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# A
# TREATISE
# ON
# ELECTRICITY,
# IN
# THEORY AND PRACTICE.

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# PREFACE.

SCARCELY a century has elapsed since Electricity was but a modest chapter in treatises on Physics. The Leyden jar, then, had just been discovered; and the power of the electric spark had already presented itself to our notice. But Franklin had not as yet established the identity between lightning and Electricity. It was merely known that certain bodies, after having been rubbed, become capable of exercising an attraction around them, — that some substances are conductors, and others non-conductors of Electricity, — that in Electricity there are two different principles, which attract each other, whilst those which are similar repel each other, — that the uniting of the two opposed principles gives rise to sparks, the power of which may attain to a remarkable degree of energy, by means of proper apparatus.

The philosophers of 1750 knew very little beyond that of the nature and properties of Electricity. Who, at that time, could have supposed that Meteorology would ere long discover in Electricity the cause of the grand phenomena of the atmosphere? — that Heat would borrow from it its most perfect instruments, and the means of manifesting its most important laws? — that Molecular Physics would have employed it for the purpose of penetrating into the intimate constitution of bodies; and would have caused it to concur with polarised light in the manifestation of the relations that exist between ponderable matters and the imponderable ether? — That Chemistry would have been indebted to it for the discovery of new elements, the formation of new compounds, its most powerful means of analysis and synthesis, and its most satisfactory theories? — That Mineralogy and Geology would in a great measure have found in it the explanation of the origin of their crystals and of their strata? — that Physiology would have deduced from it a more intimate knowledge of the forces that rule over animated matter, and the secret of acting on such matter almost as life acts? — that Medicine would have discovered in it resources against maladies hitherto assumed to be incurable? — that the Metallurgic Arts would have found in it new processes for extracting, moulding, and applying metals? — that, finally, it would have furnished to Mechanics a force, as prompt as thought, equally independent of time and space, — would have enabled intelligence to escape from its limited envelope, to dart at pleasure with the rapidity of lightning into the most distant regions.

Such, however, are the marvels that Electricity has accomplished in less than a century; such are the links that now unite it in an indissoluble manner with all the parts of the physical sciences. And hence the study of it has become indispensable to all who cultivate these sciences, — to the chemist, as well as to the natural philosopher, — to the geologist, as much as to the physiologist, — to the engineer, as well as to the physician. All are compelled to meet Electricity in their path; all consequently have need of becoming familiarised with it. I have been induced to think that a work designed to satisfy a want which is universally felt, would be received with favour. The very abridged manner, and the unmethodical style in which Electricity is for the most part treated in the treatises on Physics is not at all calculated for attaining that end; and, on the other hand, the special works that are devoted to it, enter too much into detail for persons who do not desire to make it the principal object of their labours. To initiate into the study of Electricity all the category of men of Art and Science, to whom it is necessary, an exposition is required that shall be at once substantial and elementary, — complete and abridged; the subject must be presented in a logical order, and not, as has been hitherto the case, in an order that is almost purely historical; in a word, the character of a true science must be given to this, as to the other branches of Physics, of which character it will always be deficient so long as it shall remain a simple, and, as is generally the case, a confused compilation of hap-hazard theories and disconnected facts.

I have endeavoured to express the spirit with which I have been actuated, while preparing the Treatise that is now submitted to the public. I have not attempted to make it a treatise for men of the world, although I have endeavoured to render it comprehensible to all who have received a reasonable amount of intellectual culture. I have endeavoured to address myself essentially to men who cultivate science, and who consequently are already acquainted with its language and its processes; but, at the same time, I have not assumed them to possess previously any profound knowledge of this or that particular branch of science. On this account, I have collected in some final notes, placed at the end of each volume, the mathematical developments, of which certain particular points are susceptible; but which are in no degree essential to the knowledge of the whole.

It remains for me to explain the order that I have followed, and to justify it, by a rapid glance over the vast subject to which the *Treatise on Electricity* is devoted.

When viewed in relation to the successive progresses that it has manifested, Electricity offers so prodigious a variety of scientific features, that the mind runs a risk of being lost when, by following the historic order, it is most commonly obliged to contemplate them all at once. Whilst it is following with Coulomb the researches of the laws, to which static electricity is subjected, it is called upon to scrutinise with Galvani the mysteries of animal electricity, and to travel with Volta to the discovery of the pile. Then again, whilst it is endeavouring to comprehend the beautiful calculations, on which Poisson has founded the theories of electricity, it is seized with admiration at the magnificent as well as unexpected results that Davy obtained from the Voltaic pile. But it is when setting out from the year 1820, which Oersted's discovery has made so remarkable in the history of the sciences, that the task of him who wishes to follow day by day the movement impressed upon electricity, becomes still more difficult. In the first place, it assists in the creation of that new branch of the science, which includes under the name of *Electro-dynamics* the general laws of electricity in motion:—the very interesting study, to which it leads, of the works of Arago, of Ampère and of Faraday, the founders of this part of physics, is constantly interrupted by discoveries of a very different order. Here is Seebeck, who discovers thermo-electric currents, here is Becquerel, here is Nobili who analyse them, at the same time that they are laying the foundations of electro-chemistry. Here are Marianini, Matteucci and Dubois-Reymond, who, in taking up the labours of Galvani and of Volta on animal electricity, give to this part of physiology a development, which threatens entirely to usurp it. Then there are the works upon the theory of the pile and its effects, which have called into the field very many philosophers, as Ohm, Pouillet, Fechner, Faraday, &c., and amongst whom is included the author himself of the present treatise. Then, again, there is an uninterrupted succession of new researches — the magnetic, the chemical, the calorific, and the luminous phenomena that are produced by currents and electric discharges, and on the application of which these properties of electricity are susceptible. Finally, there is the study, that is being prosecuted at once by many philosophers, of the sources of electricity, and of the laws by which they are regulated. Every day there are new names, introducing into the science of electricity their contingent of discoveries; and old names which are far from ceasing to furnish theirs. There is Becquerel continually reappearing with the results, as various as they are numerous, which he derives from his galvanometer; there is Faraday astonishing the scientific world, after his induction currents, with diamagnetism, and all the other productions of his creative genius.

This very imperfect and rapid sketch of the features that would be presented by a chronological exposition of the theories on the phenomena with which electricity has been enriched during the past century, is sufficient to show the confusion that would be created in the best organized brain, by this mode of studying. In order, therefore, that this study may be conducted in an intelligent and sound manner, it is indispensable to introduce into it a methodical classification, which, by grouping under the same head phenomena of the same order, facilitates the explanation of them and their retention in the memory. To the attainment of this end, have my endeavours been directed.

The examination of electric phenomena very soon leads us to discover two very distinct points of view; one of which comprehends the general laws to which electricity is subjected, whether in a state of rest or in a state of motion; and of which the other comprehends the various effects that arise from the action of different bodies upon electricity, and the action of electricity upon these bodies. In the first point of view, as the ponderable substance only serves for the manifestation of the general properties of the electric agent, its particular nature is of no importance; it is sufficient that it be an insulating or a conducting body. In the second point of view, the body plays the principal part; consequently its physical and chemical constitution exercise a preponderating influence over its relation with electricity. From these two very different objects, under which the study of electricity may be viewed, arises evidently the necessity of studying separately the facts that appertain to the one, and those that are comprehended under the other. The sources and the applications of electricity also form two parts, that are very distinct from each other, and from the preceding. These few words will suffice to explain the division that I have been very naturally led to adopt.

A First Part, which serves as an introduction, contains a general exposition of fundamental phenomena, and to a description of the principal instruments that are employed, either in producing or in detecting and measuring electricity. The theoretical aud complete explanation of these apparatus, it is true, can only be given further on; but it is quite necessary to become acquainted with them at the very outset of the descriptive part, on account of the services that are constantly being required of them.

The Second Part, entitled *Static Electricity*, is devoted to the exposition of general phenomena, that is to say, the laws presented by electricity in the state of rest or tension, —attraction and repulsion, distribution, induction, disguised electricity, theories on the nature of electricity.

The Third Part comprises the general laws of electricity in motion, which constitutes *Electro-Dynamics and Magnetism,* which is considered to be nothing more than a particular form of dynamic electricity. Different chapters are successively devoted to magnetism, properly so called, to the mutual action of magnetism and dynamic electricity, to magnetization by electricity, to electro-dynamic induction, and to the action of magnetism and of dynamic electricity upon all bodies. A distinct chapter is appropriated to magnetic galvanometers, on account of the importance of being well acquainted with these instruments, and of knowing how to manage them, employed as they so frequently are in the physical sciences.

The Fourth Part includes under the title of *Transmission of Electricity through different Media*, first the description of the phenomena, relating to the mode itself of the propagation of electricity in the interior of bodies, of conductibility, &c.; then a detailed study of the calorific, luminous and chemical effects that accompany this propagation; and finally the examination of the physiological phenomena, to which it gives rise in organized bodies.

The Fifth Part has for its objects *the Sources of Electricity;* a subject which can only be conveniently treated of after the study of the general laws which regulate electricity, whether static or dynamic, and of the various phenomena, by which it manifests its passage through bodies. The successive examination of the different physical, mechanical, and chemical actions, which liberate electricity is preceded by a glance into the general causes that produce this liberation, and is followed by a theoretic explanation of electromotor apparatus. The natural sources are studied in their turn, both in their origin and in their effects; animal electricity, atmospheric electricity, terrestrial electricity, which comprehends terrestrial magnetism, are the three forms, under which nature of itself produces electricity; and they consequently form three distinct chapters in this part of the Treatise. Each source is considered not only in respect to the development of the electricity to which it gives rise, but also in the relations that unite it with effects analogous to the producing cause, and which effects the electricity itself is capable of originating; a connection that leads to general considerations on the forces of nature, which are replete with interest. Thus heat, chemical action, physiological action are at once the cause and the effect of electricity; and this double form, under which electricity manifests its relation with these three great forces, is a proof of the intimate union by which they are connected both with electricity itself and with each other.

Finally, the Sixth and last Part is devoted to all the various applications of which electricity is susceptible;— electro-chemical applications (gilding, galvanoplastic, &c.), electro-magnetic applications (telegraphy, clocks, &c.), electro-calorific and electro-luminous applications, electro-physiological applications to medicine.

The simple enumeration I have been making of the different points that are treated in my work, though dry and abridged as it may be, is sufficient to enable every mind that is in the least degree inspired with a love of philosophic truths, to perceive the vast extent that electricity occupies in the domain of the physical sciences. It may seem matter for surprise, therefore, to find no place assigned in my division to the study of the great questions which concern the constitution of matter, and the nature of physical forces; and the more so as electricity appears to be the most general form, under which is presented the link that exists between ponderable bodies and immaterial forces. But considerations of that kind, which are more metaphysical than physical, could not be treated with that development which they command in a work of this kind. However, although I have not devoted to them a separate chapter, I have not failed to enter upon that subject, whenever an opportunity presented itself; convinced as I am that, independently of the interest which they offer of themselves, they possess the immense advantage of elevating the mind, by bringing it nearer to the Almighty, whose power is more fully recognized, in proportion as we examine more closely the works of creation.

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Geneva, November, 1852.

P. S.—Private circumstances had occurred to the author, which compelled him to suspend his labours for a very long time, whence it happened that the printing of his work was interrupted; on which account it has been decided no longer to delay the publication of the first volume, which has been printed for upwards of a year. The publication of the second volume shall not be delayed, and will take place in the spring at the latest.

The French manuscript of this volume was entrusted to the care of Mr. Charles V. Walker, by whom the present translation has been made, and who has carried the work through the press. He will translate the second volume.

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## RELATIVE TO MATHEMATICAL DEVELOPEMENTS OF CERTAIN PARTICULAR POINTS.

### Note A. (p. 12.)

### Note B. (p. 103.)

### Note C. (p. 179.)

### Note D. (p. 186.)

### Note E. (p. 217.)

### Note F. (p. 246.)

# ERRATUM AND ADDITION.

P. 437. l. 19. Instead of *inductive* read *induced.*

P. 321. At the end of Chap. III., add "M. Wertheim has shown that the torsion and detorsion of a bar of soft iron, magnetized by an electric current, produce a change in this magnetization; sometimes an increase, at other times a decrease, according as they occur in the direction in which the bar has been already twisted, or in a contrary direction. These experiments prove the fact that magnetization and demagnetization are accompanied by a molecular change in the iron; and that there is an intimate relation between the magnetization of this metal and the arrangements of its particles."

# TREATISE ON ELECTRICITY

IN

# THEORY AND PRACTICE.

## PART I.

## PRELIMINARY NOTIONS.

## CHAPTER I.

### MANIFESTATION OF ELECTRICITY.

### *Electricity developed by Friction.*

WHEN a stick of wax, a piece of amber, or a glass rod, is rubbed with very dry cloth, these bodies are observed, by the effect of the friction, to acquire the property of attracting small fragments of paper, small balls of elder pith, and light substances in general which are placed in their neighbourhood. This attraction occurs at a distance; and the substances upon which it is exercised remain adhering to the surface of the rubbed body by which they are attracted; or rather are alternately repelled and attracted by this body (*Fig.* 1.). The bodies, upon which the friction has developed the property that we have just explained, are said to be *electrised*; and the property itself, and the agent to which it is supposed to be due, is named *electricity*. This name *electricity* is derived from the Greek word *ἤλεκτρον*, signifying *amber*, the first substance, it is said, upon which electrical properties were observed.

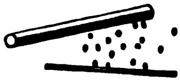

*Fig.* 1.

The substances that can be electrised by friction are numerous; in addition to those we have named there are sulphur, the different species of resin, gum-lac, the majority of crystals, wax, the skin of a cat, &c. However there are some, and the metals are of this number, on which it is impossible for us to develope the same property. On this account, the former have been named *Idio-electrics* and the latter *An-electrics.* But it was soon discovered that this distinction was not fundamental, and that the difference that had been observed between bodies, in respect to their susceptibility of being or not being electrised by friction, was only apparent. Another property, *electric conductibility,* is the true cause of this difference.

### *Electric Conductibility.*

A metal rod is to be fixed to one of the extremities of a stick of glass or wax, and to be adjusted carefully; the stick of glass or wax is then rubbed, especially in the portion nearest to the metal, care being taken not to touch the metal either with the hand or with the rubber. Small light bodies are then brought near; they are immediately attracted by the metal rod, as they would have been by the glass or the wax itself; and this attraction is exercised by every point of the rod, whatever be its length. From this experiment we must conclude that the agent which has been developed by friction upon the glass or wax has passed into the metal, and is there diffused; since the latter is found to be electrised, without its having been rubbed, and merely because it is in contact with a body that is itself electrised. Were a glass rod, a piece of wax, in a word, any one of the idio-electric substances, put in place of the metal rod, it would not have acquired electricity by its simple contact with the electrised body. This property, which is possessed by metals and in general by the bodies that had been designated by the name of *an-electrics,* of acquiring and propagating through their whole extent the electricity possessed by the part of an electrised body with which they are placed in contact, is termed *conductibility for electricity* or *electric conductibility*. Bodies possessed of this property are termed *conductors*, and those which possess it not *insulators*.

The human body, wood, especially damp wood, and in general animals, vegetables, and a great number of mineral substances, are, like the metals, conductors of electricity. The globe of the earth is equally so; on the contrary, atmospheric air, especially when it is very dry, is not so.

### *Consequences of Electric Conductibility.*

Many important consequences follow from the property, that we have designated by the name of electric conductibility.

1. An electrised surface that is put in communication with the ground, by means of one or of several conducting bodies, must lose its electricity. In fact, this electricity passes into the conducting bodies, and thence into the terrestrial globe, where it is diffused, and consequently becomes insensible, on account of the immensity of the mass in which it is distributed. Thus the terrestrial globe is termed the *common reservoir*, in order to indicate that to it is carried the electricity of bodies placed in communication with it.

2. The atmospheric air, being an insulating body, electrised bodies do not lose their electricity by their contact with it. Were the air a conductor no body could preserve its electricity, for it would be dissipated immediately into the whole mass of the atmosphere. This does take place when the air is moist: it then loses its insulating property, and the electricity of the body, that is in contact with it, is dissipated more or less rapidly, according to the greater or less degree of humidity. When, therefore, we wish that experiments made with the electricity developed by friction should succeed well, it is necessary to dry the air carefully when it is not naturally dry.

3. When a conducting substance, a rod of metal for example, is held in the hand and rubbed, we must not conclude, from the absence of all electrical signs, that this substance is

incapable of acquiring electricity by friction. In fact, supposing that it could acquire it, it would allow it to escape immediately into the ground, by means of the hand and the body of the operator. On the contrary, when an insulating body is held in the hand, and is rubbed, it preserves its electricity, not being able to conduct it; and, in order to deprive it of that electricity, we must touch successively with the hand or with a conductor communicating with the ground, all the parts of the insulating substance that have been electrised. So also, in order to show that a conducting body can be electrised, we have only to insulate it; that is to say, instead of holding it immediately with the hand, it must be fixed to a handle of glass, of wax, or of any insulating substance, by means of which it is to be held. This body is then rubbed, and it becomes capable, like every other electric substance, of attracting light bodies. To perform this experiment well, we have only to procure two perfectly similar balls or cylinders of metal, one fixed at the extremity of a glass handle, the other at the extremity of a metal handle; and to rub them successively with cloth, holding the handles in the hand; the former attracts these light bodies, the latter never attracts them. Only great care must be taken not to rub the glass handle at the same time that the metal, which this handle is intended to insulate, is being rubbed.

### *Electric Conductibility not absolute.*

The conductibility of bodies for electricity is not, however, an absolute property; that is to say, we cannot classify bodies into bodies of which some conduct electricity perfectly well under all circumstances, and of which others never conduct it in any case, in other terms, into *perfect conductors* and *perfect insulators.*

The metals are almost perfect conductors; however, they present among themselves differences relatively to their degree of conductibility; and the same metal conducts better or worse, according to its dimensions and its temperature. Resinous substances, vitreous substances, silk, oils, caoutchouc, gutta percha, are substances that insulate very well, but not all to the same degree; thus, a very fine filament of gum-lac insulates better than a filament of silk or glass of the same diameter. Gum-lac and the resins insulate better, as they are drawn out into finer filaments; this is the reverse in glass, which, when drawn into fine threads, becomes a tolerably good conductor. Finally, wood, pure water, the human body, a great number of minerals, conduct imperfectly, that is to say, they conduct powerful electricity well, but feeble electricity not so well, and sometimes not at all.

### *Causes which influence electric Conductibility.*

The conducting property of bodies appears to depend essentially on their chemical nature; thus we see all the metals are good conductors; all hydrogenated substances are bad conductors. However, in many cases the physical constitution also exercises an influence upon conductibility; ice does not conduct, while water does conduct; tallow and wax become conductors only when they are melted; it is the same with several salts. Glass is a good conductor when it is heated to redness. M. Matteucci has moreover lately remarked that sulphur and gum-lac lose a portion of their insulating power by an elevation of temperature incapable of changing their cohesion. Diamond is a perfect insulator, whilst mineral carbon is a good conductor, if it has been strongly heated. Carbon in general conducts better or worse, according to the manner in which it has been prepared, and according as it has been more or less baked. Air and gases are less insulating, as they are more rarified, which is the same as saying that vacuum is a good conductor of electricity. We shall have occasion hereafter to examine into the important question of the conductibility of vacuum.

Finally, there is one circumstance, independent of the chemical nature and the physical constitution of bodies, which renders them better or worse conductors; it is their degree of affinity for the humidity of the air. We have already seen that moist air and gases cease to be insulators. Glass, which is of itself a good insulator, easily becomes a conductor as soon as it is exposed to humidity; it attracts to its surface the aqueous vapours of the atmosphere; they form there a thin film of water, by which the electricity passes away. Thus, in order that glass rods shall well insulate the electricity accumulated upon the conductors to which they serve as supports, care is taken to cover them with a thin coat of varnish, made with gum-lac dissolved in alcohol, a coating which protects the surface of the glass against the deposition of moisture, and which at the same time itself insulates very well.

It is probably to the hygrometric property of glass that we must attribute the conducting faculty which it acquires on being drawn out into thin filaments; because it presents more surface to the moist air.

### *Means of determining the Conducting Faculty.*

It is difficult to determine the differences of conductibility between bodies when these differences are slight; for this purpose delicate methods must be employed, of which we shall speak hereafter. But, when the question is to determine whether a body must in general rank in the class of insulating bodies or in that of conducting bodies, the method is easy. Let us take, for example, a silk thread and a metal wire; we select them of the same length, and of the same diameter, and fix at one of the extremities of each of them a conducting ball, a metal one for example; we then suspend them vertically by their other extremity to the two ends of a horizontal metal rod supported itself by an insulating glass rod (*Fig.* 2.). The different parts of the surface of a piece of glass or electrised wax are moved about the metal rod; the electricity thus passes into the metal, and is thence diffused into all the conducting substances in contact with it; it penetrates

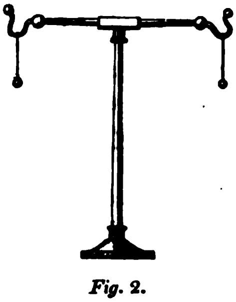

*Fig.* 2.

into the fine metal wire, and into the ball that is suspended to it, and not into the silk thread, and consequently not into the ball which terminates it; we may convince ourselves of this, by seeing that the former of the two balls attracts light bodies and the latter does not. We can operate, in the same manner, upon all substances by drawing them into rods of the same diameter and length; each rod must carry a ball at one of its extremities, whilst the other extremity is fixed to the insulated metallic support that receives the electricity.

The following is an approximative table of the conducting and insulating faculty of different bodies. This table is composed of two columns; the first contains the conducting bodies, placed in the order of their degree of conductibility, beginning by the best conductors; and the second contains the insulating bodies, placed in the order of their insulating faculty, beginning by the worst insulators. It hence follows that the second column may be regarded as a continuation of the first.

| *Conducting Bodies, placed in the Order of their Conducting Power.* | *Insulating Bodies, placed in the Inverse Order of their Insulating Faculty.* |
|---|---|
| All the metals. | Dry metallic oxides. |
| Well-burnt carbon. | Oils: the heaviest are the best. |
| Plumbago. | Ashes of vegetable bodies. |
| Concentrated acids. | Ashes of animal bodies. |
| Dilute acids. | Many dry transparent crystals. |
| Saline solutions. | Ice below 13° Fahr. |
| Metallic ores. | Phosphorus. |
| Animal fluids. | Lime. |
| Sea water. | Dry chalk. |
| Spring water. | Native carbonate of Baryta. |
| Rain water. | Lycopodium. |
| Ice above 13° Fahr. | Caoutchouc. |
| Snow. | Camphor. |
| Living vegetables. | Some siliceous and argillaceous stones. |
| Living animals. | Dry marble. |
| Flame. | Porcelain. |
| Smoke. | Dry vegetable bodies. |
| Vapour. | Wood that has been strongly heated. |
| Salts, soluble in water. | Dry gases and air. |
| Rarified air. | Leather. |
| The vapour of alcohol. | Parchment. |

*Conducting Bodies, placed in the Order of their Conducting Power.*

The vapour of ether.
Earths and moist rocks.
Powdered glass.
Flowers of sulphur.

*Insulating Bodies, placed in the Inverse Order of their Insulating Faculty.*

Dry paper.
Feathers.
Hair, wool.
Dyed silk.
White silk.
Raw silk.
Transparent precious stones.
The diamond.
Mica.
All vitrefactions.
Glass.
Jet.
Wax.
Sulphur.
The resins.
Amber.
Gum-lac.*

### *Electricity by Communication.*

Bodies, therefore, are all capable of becoming electrical by friction; but they differ among themselves with regard to the faculty they possess of transmitting electricity; some transmit it promptly and freely; others more slowly and with difficulty; others seem to be almost incapable of transmitting it. However, they are all susceptible of taking electricity from an electrised body with which they are touched; only if the touched body is an insulator, it takes electricity on that part of its surface alone which has been touched; whilst, if it is a conductor, it acquires it throughout its whole extent, although it has received it in only one point. This is a means of electrising, which is termed to *electrise by communication.*

We may further remark that, if the electrised body is an insulator, it gives the electricity it possesses to the conducting body that touches it only at the points in which the contact takes place; but, if it is a conductor, there occurs a division of its electricity between itself and the touched body, a di-

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* *Gutta Percha* appears to be of known substances one of the best insulators; its place, however, cannot exactly be assigned in this table.

vision which is subject to a very simple law, viz. that each of the two bodies, which we necessarily suppose insulated, takes a part of the total electricity proportional to its own surface. This law, which we shall demonstrate hereafter*, explains why an insulated and electrised conducting body, when put into communication with the ground, loses all its electricity; the electricity that it possessed is really divided between itself and the earth, proportional to their respective surfaces; but its surface being infinitely small in comparison with that of the earth, there must, therefore, remain to it, after contact, infinitely less electricity, or none at all.

It often happens that when we bring an electrised body near to a body that is not so, the electricity of the former passes into the latter before there is any contact between them, under the form of a spark that traverses the space of air by which they are separated. This circumstance in no degree modifies the final result, which is the same as if the communication had been made by contact.

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* This law, as we shall see further on, is not *mathematically* rigorous; but it so nearly approaches to accuracy, as to be able to be admitted, without too great an error, into the cases that are more frequently presented.

## CHAP. II.

### NATURE AND FORM OF ELECTRICITY.

### *Distinction between the two Electricities.*

We have hitherto, in a general manner, called all bodies *electrised*, whatever they may be, which, after having been rubbed or put into communication with an electrised body, exercise an attraction at a distance upon light bodies. We are now about to study this kind of action more closely; and we shall see that this study will lead us to recognise that the electricity, manifested by different substances, is not always identical.

If to a film of raw silk, which is itself fixed to a glass support that insulation may be more perfect, we suspend a conducting ball of elder pith, about a quarter of an inch or a little more in diameter[*], we shall have an apparatus which we will call a simple electroscope or electric pendulum. If we bring an electrised glass rod near to this ball, the ball will be attracted, will touch the glass, and then, after having touched it, will be immediately repelled (*Fig.* 3.). The ball will have acquired electricity by its contact with the glass; it will preserve this electricity, because it is insulated; but, if it is touched with the hand, it will immediately lose it, and be restored to the natural condition. If we have a second ball similar to the first, suspended at the same height, and electrised in the same manner, and then bring the two balls thus electrised carefully together, giving them as little movement as possible, when arrived at a certain distance from each other, they

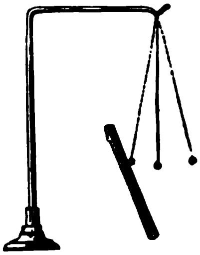

*Fig.* 3.

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[*] Balls of elder pith, covered with leaf gold, or very light hollow metal balls may also be employed.

repel each other, and do so the more strongly as we endeavour to bring them more closely together. If we make the same experiment by employing a stick of rubbed wax instead of a glass rod to electrise the two balls, we shall have exactly the same result. But, if we electrise one of the balls with the glass rod, and the other with the stick of wax, and then bring them together carefully, when arrived at a certain distance we shall see them attract and then fly to each other, and, after having touched, recover the vertical position, and give no further signs of electricity (*Fig.* 4.).*

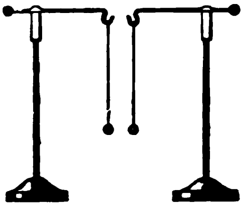
*Fig.* 4.

If one of the balls is electrised either with glass, or wax, and the other is not, they attract each other; and, as soon as they have been in contact, they repel one another; the first having communicated a portion of its own electricity to the second.

We may conclude from the preceding experiments:—

1. That there is attraction between an electrised body and a body that is not so.

2. That there is repulsion between two bodies electrised by the same source of electricity.

3. That there is attraction between two bodies electrised, the one by glass, the other by wax.

There is not, therefore, an identity between the electricity that glass acquires by friction, and that which wax acquires, since, on a body electrised in the same manner, the effect of the one is repulsive, and that of the other attractive; hence, to distinguish them, the former has been named *vitreous electricity*, and the latter *resinous electricity.*

Experiment has taught us that all bodies in nature, on being rubbed, acquire one or other of these electricities. Glass, and vitreous bodies in general, acquire the former;

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* When the balls are of pith, it sometimes happens that the contact lasts some moments, before the neutralisation is complete. This is because the elder pith, when it is dry, is not a perfect conductor; and the electricity consequently does not circulate in it freely and promptly. With metal balls or pith balls, covered with metal leaf, the same inconvenience is not presented.

wax, gum-lac, the resins, the latter. Metals also acquire resinous electricity. However, the kind of electricity that is developed upon a body, does not depend solely upon the nature of this body, but also upon that of the substance with which it is rubbed. In order to understand this influence, we should be aware that one of the electricities is never developed without the other being equally so; and that, when two substances are rubbed against each other, if the rubbed substance acquires vitreous electricity, the rubbing substance acquires resinous electricity and reciprocally, which may be proved in the following manner: —

Instead of holding in the hand the piece of cloth that is employed in producing the friction, let it be wound round the end of a glass rod, by means of which it is to be held; then another glass rod is to be rubbed with the cloth thus insulated. After the friction, the electrised glass is to be brought near the pith ball of a simple electroscope; this ball is attracted, then repelled, after having acquired vitreous electricity. The piece of insulated cloth that has served as a rubber is then to be brought near to it; the ball is immediately attracted, a proof that the cloth has acquired resinous electricity during the friction. If a piece of wax or gum-lac is rubbed with the cloth, the cloth is found to have acquired vitreous electricity; the wax or the gum-lac, on the contrary, is charged with resinous electricity.

In this case care must be taken that the resinous substance does not leave a deposit upon the cloth, which would render the result of the experiment doubtful.

The electricity that a given substance acquires is not always the same; there is nothing absolute in regard to this; thus cloth acquires resinous electricity when rubbed with glass, and vitreous when rubbed with wax. Glass itself may acquire resinous electricity if it is rubbed with a cat's skin, whilst it acquires vitreous, if rubbed with cloth. Tables have been drawn out, in which substances are placed in such an order that each acquires vitreous electricity, if rubbed by those that follow it in the table; and resinous electricity if rubbed by those that precede it.

The following is one that is generally adopted:—

Cat's skin.
Polished glass.
Woollen cloth.
Feathers.
Wood.
Paper.
Silk.
Gum-lac.
Rough glass.

However, these tables are never perfectly exact. We shall return to this subject when we are studying friction as a source of electricity. We will confine ourselves to adding that, independently of the chemical nature, certain physical circumstances may influence the nature of the electricity that bodies acquire in their mutual friction. Thus polish and temperature exercise in this respect a remarkable influence. Polish increases the tendency of a body to acquire vitreous electricity; elevation of temperature its tendency to acquire resinous electricity. Two pieces of the same glass, the one polished and the other rough, on being rubbed together acquire the former vitreous, the latter resinous electricity. Elevation of temperature not only increases the resinous tendency, but, in general, greatly facilitates the development of electricity in bodies.

### *Neutralisation of the two Electricities.*

We have seen that when two movable and insulated pith balls possess different electricities they attract each other; they come into contact; then, after contact, they regain their natural state. The two electricities have disappeared, they have become *neutralised.* In order that this neutralisation be complete, it is necessary that the two balls have each the same amount of electricity, a condition that is easy enough to fulfil, as we shall see further on. If the electricity of one is stronger than that of the other, there always remains, after the contact, an excess of electricity, vitreous or resinous, according as the vitreous or resinous was in the greater proportion. Thus, to neutralise a certain portion of *vitreous* electricity, we must always have an equal quantity of *resinous* electricity, and reciprocally. Consequently, one of the electricities, the vitreous, has often been called *positive*, and the other, the resinous, *negative*: founding these denominations upon this principle, that, like as by adding $+e$ to $-e$ we obtain 0, so, in giving to a body that is possessed of a certain quantity of resinous electricity, an equal quantity of vitreous, we have as the result, the zero of electricity, a result which may be translated mathematically, only by giving the sign + to the quantity representing one of the electricities, and the sign − to the equal quantity, representing the other. This denomination is completely independent of the ideas that may be formed of the nature of electricity; for it rests not upon a simple hypothesis but upon an experimental law.

The neutralisation of the two contrary electricities, a consequence of their attraction, may take place according to different modes. It may operate at a distance, in the case in which neither of the two balls is sufficiently movable to obey the attraction that reigns between them. Two metal balls are placed each at the extremity of a vertical glass rod, one is electrised vitreously, or positively, the other resinously, or negatively. The two insulating supports, and consequently the two balls, are made to approach each other; being retained by their supports, they cannot come together; but at a distance greater or less, according to the electric charge that they possess, an instantaneous spark is seen to shine between them, accompanied by a slight snapping; and immediately after they may be proved to have lost their electricity, and to be in their natural condition. To prove this we have only to bring near them the ball of an electric pendulum, it is no longer attracted, whilst it was so before the spark had passed. This spark, therefore, has been the manifestation of the neutralisation of the two contrary electricities, which, on quitting the bodies, where they were separately accumulated, were carried towards each other through the air by virtue of their mutual attraction — an attraction, which the electrised bodies themselves were not able to obey. This mode of neutralisation can only occur when the electrised bodies are placed at an inconsiderable distance apart—a distance that must vary with the intensity of the electricity with which they are charged, and the condition of the air comprised between them. But, whatever may be this distance, the contrary electricities may be neutralised, on making communication between the two balls, by means of an insulated conductor, such as a metal branch, held by an insulating handle.

### *Static and Dynamic State of Electricity.*

When the neutralisation is brought about either through the air with a spark or through a conductor, the electricity is said to be in the *dynamic state,* for the instant that this neutralisation lasts. Only in the case with which we have just been engaged this dynamic state is *instantaneous;* it is also called the *electric discharge.* This denomination of *dynamic* is given to the state of movement in which the two electricities are supposed to be found, when they are travelling towards each other to neutralise each other, in opposition to the *static* state, or that of rest, in which these two electricities are found, when they are separately accumulated on insulated bodies. The latter state is also named *electric tension.*

The dynamic state may be *instantaneous* or *continuous.* It is *instantaneous* in the preceding case, in which the two electrised metal balls are insulated; and consequently acquire no more electricity after that which they possess has once become neutralised. But, suppose one of the balls to be in communication with a constant source of positive electricity, and the other with an equally constant source of negative electricity, the two electricities being constantly renewed, in proportion as they are neutralised, there will be between the two balls a continual succession of sparks; and, if they communicate by a conductor, there will be through this conductor an uninterrupted neutralisation or a continued reunion of the two electricities; this is what is termed *the continuous dynamic state* or *electric current.* We then say that the conducting body, which serves to establish a communication between the two balls, is traversed by an electric current.

Bodies that serve for the passage of electricity, when it is in either the instantaneous or the continuous dynamic state, undergo, by the effect of this passage, certain modifications, some temporary, others permanent, which are extremely remarkable. For the present we will quote but two examples. If it is a very fine metal wire, and of no great length, that serves to transmit the dynamic electricity, this wire is heated, becomes incandescent, and may even melt, if the electricities, whose reunion it is bringing about, have great intensity. If the body through which the transmission occurs is water, this water is in part decomposed; and its two constituent gases, namely, oxygen and hydrogen, are seen to be set free. But this effect is manifested in a more marked degree when the dynamic state is continuous, namely, when the electricity is in the state of current; whilst the effect we have first mentioned, namely, that of heating, occurs equally, whether the dynamic state be instantaneous or continuous.

### *Theories on the Nature of Electricity.*

We shall now have to study the properties possessed by electricity, both when we consider it in its static state, and when we regard it in its dynamic state. But, before passing to this study, it is important for us to form an idea of what electricity is, and of the opinions that have been formed on this subject. The knowledge of these theories is absolutely necessary for us, even were it only to make us familiar with the established expressions, which depend in great part upon them.

The theory most generally admitted in the present state of our knowledge, consists in regarding each of the two electricities, both the vitreous and the resinous, as excessively subtile and imponderable fluids, each composed of particles that mutually repel each other, while the particles of the one attract the particles of the other. These fluids are able to travel freely in conducting bodies; and, as their particles tend mutually to repel each other, they arrange themselves on the surface of these bodies, where they remain, because they meet the air which, being an insulating body, does not permit them to go further. In non-conducting bodies the two fluids are constrained in their movements, which we attribute to their being retained by the particles of these bodies. When the two fluids unite, by virtue of their mutual attraction, they are neutralised, and form *neutral fluid* or *natural electricity*, the action of which is not sensible, because the effect of the two contrary fluids is counterbalanced. It is admitted that every body contains natural electricity; hence, to electrise a body is to decompose this electricity; one of the parts or one of the *principles* of which remains in excess on the rubbed body, and the other principle remains in excess on the rubbing body. This is called Symmer's two-fluid theory.

Franklin's theory consists in admitting but one single imponderable electric fluid, very subtle, and all the particles of which mutually repel each other. Each body has a determinate capacity for this fluid. When it contains as much as it ought naturally to have, the body is in the natural electric state. To electrise a body vitreously is to give it more electricity than it naturally contains; it is then in the *positive* electric state: to electrise a body resinously is to deprive it of a portion of its natural electricity; it is then in the *negative* electric state. We have seen that these denominations of positive and negative electricity, which follow from Franklin's theory, may be justified by considerations altogether independent of every hypothetical view, and based simply on facts.

We shall not here discuss the comparative merit of these two theories; the latter, at least in such sort as Franklin has formularised it, cannot be admitted: we shall presently see for what reason. The former, although subject to strong objections, is, however, in the present state of the science, a very convenient and tolerably exact manner of representing to ourselves this agent, that we term *electricity:* it is under this point of view that we shall adopt it. However, we may for the present say it is very probable that electricity, instead of consisting of one or of two special fluids *sui generis,* is nothing more than the result of a particular modification in the state of bodies. This modification probably depends on the mutual action exercised on each other by the ponderable particles of matter, and the subtle fluid that surrounds them on every side; a fluid that is generally designated by the name of ether, and the undulations of which constitute light and heat.

# CHAP. III.

## OF THE ELECTRICAL MACHINE AND ELECTROSCOPES.

In the same manner as it was necessary that we should make ourselves familiar beforehand with certain theoretical notions, in order to pursue a detailed study of electricity, so also it is important for us, at the outset, to make ourselves well acquainted with some of the instruments that we shall be most frequently called upon to employ, particularly the *Electrical Machine*.

### *Electrical Machine.*

An electrical machine (*Fig.* 5.) consists of a circular glass plate, from $\frac{1}{12}$th to $\frac{1}{8}$th of an inch in thickness, and the diameter of which is equally various; it is generally about 2 feet or $2\frac{1}{4}$ feet, and sometimes 3 feet; there exists at London, at the Polytechnic Institution, an electrical machine, the plate of which is as large as 7 feet 3 inches in diameter. The plate is traversed at its centre by a metal axis, fixed solidly to the glass by means of two ferrules: this axis rests upon two wooden supports, fixed vertically at the end of a solid table, and is so placed that the glass plate is situated between the two supports, and at an equal distance from either. A handle, fixed to the extremity of the axis that is situated on the outer side of the table, serves to give a rotatory movement to the plate. The greater portion of

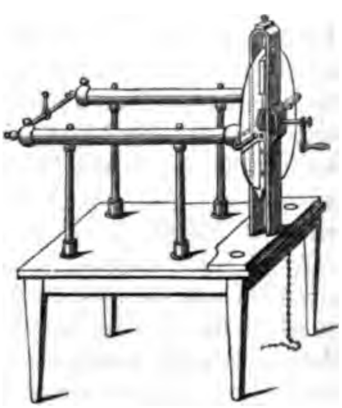

*Fig.* 5.

this handle is commonly of glass, so that the electricity of the part of the plate nearest to the axis may not be conducted into the ground by the hand and body of the person who is working the machine; which might occur, were it not for this precaution. Two pairs of horse-hair cushions, covered with leather, are placed, one in the upper part, the other in the lower part of each of the two vertical supports. These cushions are so arranged that each portion of the plate is made to pass successively between them; first above, then below, by means of the rotatory movement. It is also necessary that the cushions be sufficiently near together, and sufficiently elastic to exercise a strong pressure against the plate: this produces a friction that electrises the glass. The cushions are 4 or 5 inches wide, and are as long as possible, always, however, leaving a sufficient interval between their extremities and the metal ferrules, by which the axis of the plate is fixed.

Experience has taught us that, in order to render the liberation of electricity more considerable, the surface of the leather of the cushion must be covered with an amalgam of zinc or a coat of mosaic gold (deuto-sulphuret of tin). Without the addition of this coating, which must be often renewed, the electricity developed by the immediate friction of the leather against the glass will be excessively feeble. Finally, the vitreous electricity that is acquired by the glass plate by the effect of friction is collected by cylindrical conductors, generally of brass, which are placed horizontally on vertical glass stems, themselves fixed on the table, at one of the extremities of which the supports are placed by which the glass plate and the cushions are sustained. There are generally two parallel conductors, each supported by two glass legs, and connected by a metal stem, passing from one to the other: these two conductors are situated behind the plate, parallel to its axis prolonged, and at the same height as this axis; from which they are equidistant. Sometimes there is only one conductor, and it is situated also behind the plate, upon the axis prolonged; and bifurcates near the plate into two branches, equidistant from its centre. Each of these branches, or each of the two conductors, when there are two, carries at the extremity that is nearest to the plate a metal arm so bent as to envelope, without touching, the part of the surface of the plate situated at the height of the axis. These appendices are furnished in the part of their surface that is turned towards the glass with metal points, which approach as closely as possible to the plate, without, however, being in contact with it. These points serve to draw off, from all the parts of the plate that are successively presented before them, the electricity acquired by them in their passage between the cushions. An envelope of waxed silk serves to protect from dust and from the agitation of the air, the portion of the plate that has just been electrised against the cushions, until its arrival before the points that draw off from it its electricity. The latter then passes to the insulated conductors, where it is accumulated in a greater or less proportion, according to the power of the machine and the length of time it has been working. There is, however, a limit to this time; when the intensity of the electricity on each part of the conductor is equal to what it is on the part of the plate that has just undergone friction, and is not yet discharged, it is impossible to increase the electrical charge of this conductor, even although the machine continues to be worked.

In order to preserve the electricity on the conductors, they must not present any angular or pointed parts, except those by which the electricity penetrates; and they must be throughout of as rounded a form as possible. The supports also must be good insulators; and with this view the glass rods are covered with a coating of gum-lac varnish. When the air is moist it must be dried around the conductors by means of chafing-dishes filled with live coals; and the insulating supports must be rubbed with warm cloths. As the moisture also accumulates upon the glass itself, and as this moisture is much opposed to the development of electricity, the latter must frequently be rubbed, to get rid of it, either with a warm cloth or, which is much better, a rag impregnated with ether. The dust, that flies about in a room, is often as hurtful as moisture to the preservation of electricity on insulated conductors: we must protect ourselves from it as much as possible, and, with this view, be careful frequently to wipe the conductors and the insulating supports with clean cloths.

In the electrical machine, as we have been describing it, the cushions communicate with the ground by means of the wooden supports, and of the table, also of wood, upon which these supports are placed; sometimes a metal chain is added to facilitate this communication: thus the negative electricity which they acquire by friction is lost in proportion as it is liberated; if we wish to collect it, the cushions must be insulated by glass supports, which require a slightly different construction. By thus insulating the cushions, we succeed indeed in obtaining negative electricity, but the quantity of positive electricity collected upon the insulated conductors is reduced to one half: this is a consequence of the laws of the liberation of electricity by friction, as we shall see further on. Hence it is better, when we wish to have positive electricity alone, to make the cushions communicate with the ground by means of a metal chain. If we wish to have negative electricity alone, we must, for the same reason, put the conductors, upon which the positive is liberated, in communication with the ground, by means of a metal chain. If we want to have both electricities at the same time, we must then make neither the conductors nor the cushions to communicate with the ground.

Formerly, in the construction of electrical machines, glass muffs or cylinders were employed, instead of circular plates. There are still some powerful machines constructed after this fashion. This gives rise to a few differences, which are easy to be perceived, in the details of the construction. We shall not dwell upon them. The machine *Fig.* 6., the cushions of which are insulated, is a cylinder machine.

An important circumstance is the quality of the glass of which the plate or cylinder is made. It is impossible to point out any rule in this respect; experiment alone can decide in each particular case. In general, the best glasses are those into the composition of which the least amount of alkali enters, and the glasses with the potash base; also tolerably ancient glass, especially that of Bohemia, is preferable to modern glass. It is affirmed that exposure to the sun for a certain time, during the whole of a fine summer's day for example, gives to a glass plate a great electrical power.

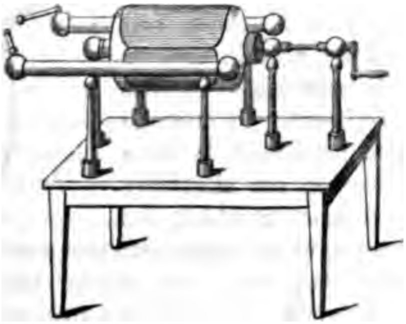

*Fig.* 6.

*Different Apparatus that accompany the Electrical Machine.*

The electrical machine is always accompanied by certain apparatus, with which we must become equally acquainted, on account of the frequent use that is made of them. They are, in particular, the *quadrant electrometer*, the *discharging rod*, and the *insulating stool.*

The *Quadrant Electrometer* (*Fig.* 7.) consists of a metal stem, which is fixed vertically on a foot, or upon the conductor of an electrical machine; the stem carries, in its upper part, a small wooden or ivory needle, terminated by a ball of elder pith, and movable in a vertical plane. It naturally acquires a vertical position, consequently parallel to that of the stem, with which the pith ball is in contact. But the electricity that is communicated to the instrument obliges the ball to recede from the fixed stem, and consequently makes the needle that carries it describe a larger or a smaller angle, which is measured upon a circular division.

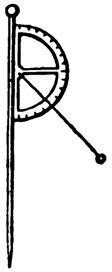

*Fig.* 7.

The *Discharging Rod* (*Fig.* 8.) is a metal conductor composed of two similar stems, united by a joint, which permits of their being separated to various distances, and each terminated by a ball; one, or more frequently two glass handles permit the experimenter to hold the metal stems with his hands, so as to use them for passing the electricity from one body to another, which, but for this contrivance, would escape into the ground.

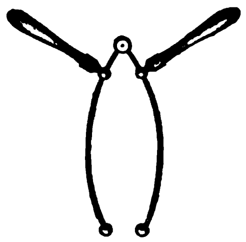

*Fig.* 8.

The *Insulating Stool* (*Fig.* 9.) is a wooden table, varying in size, supported by glass legs: all bodies that are placed upon it are thus in a state of insulation. The feet are commonly of sufficient strength to support the weight of a man. If the latter, when placed upon an insulating stool, touches with his hand the conductor of an electrical machine in action, sparks may be drawn from all parts of his body, similar to those that could be drawn from the conductor itself.

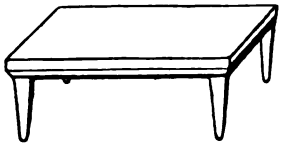

*Fig.* 9.

## *Some Experiments with the Electrical Machine.*

Among the numerous experiments that may be made with the electrical machine, we shall confine ourselves, for the present, to mentioning the following:—

If the hand is brought near to the conductor of the machine, a vivid and instantaneous light is manifested between the conductor and the hand, which is accompanied with a certain degree of painful sensation. It is the electric spark which we have already seen to be produced in the neutralization of the two electricities, and which here shows itself, when one alone of the two electricities, no matter which, is escaping from a conductor upon which it is accumulated, to pass through the air into another conductor.

Any conductor whatever, if substituted for the hand, produces the same effect.

We can compel the electric spark to traverse bodies of small conducting power, or of none at all, such as ether and alcohol, and it instantly inflames them.

It also inflames combustible gases, such as hydrogen: thus, if we bring a candle that has just been extinguished, near to the electrised conductor of the machine, so that the spark passes from the conductor to the candle, through the smoke, which is nothing more than carburetted hydrogen gas, the candle is relighted.


*Fig.* 10.

For inflaming hydrogen we often use Volta's pistol (*Fig.* 10.), which is a small sheet iron vessel, in the interior of which is situated the rounded end of a metal rod, insulated by means of a glass tube and wax, and the other extremity of which appears outside the glass. A little hydrogen, which becomes mixed with the air, is placed inside the vessel; then, by means of a cork stopper, all communication with the exterior air is intercepted. The electric spark is made to pass into the interior, by means of the insulated conducting rod. There arises a strong detonation, produced from the combination of the hydrogen with the oxygen of the air, and the cork is projected afar.

The employment of the electrical machine and of the insulating stool, enables us to demonstrate in an elegant manner the differences of conductibility of divers substances. A person places himself upon the stool; he takes successively into one of his hands rods of glass, of wood, of metal, with which he touches the conductor of a machine, the plate of which is made to revolve; he brings the other hand to a conductor communicating with the ground. According to the insulating or conducting property of the rod, there is or there is not a spark, and according to its degree of conductibility, there is a longer or a shorter spark. We may even show the presence of the spark by employing it, although it comes out from the hand, to set fire to an inflammable substance, such as ether or hydrogen gas. In the same manner is demonstrated the insulating or conducting property of threads of various substances, such as caoutchouc, gutta percha, dry or moist silk, &c., by making them communicate by one of their extremities with the conductor of the machine, and holding them with one hand by the other extremity.

### *Electroscopes.*

Electroscopes or electrometers are apparatus designed for detecting the presence of electricity, for indicating its nature, and for measuring, if possible, its intensity. We have already spoken of simple electroscopes, and of the quadrant electrometer. The others are in general founded upon the principle that two very light bodies, when freely suspended, and very near to each other, are mutually repulsive, when they are charged with the same electricity; and this to a distance greater in proportion as the electricity is stronger. The most simple is formed of a glass rod, fixed vertically on a foot, and surmounted by a small horizontal metal cross-piece, terminated at the one end by a knob, and at the other by a hook, to which is suspended a linen thread, whose two ends are stretched vertically by two balls of elder pith fixed at each of the two extremities (*Fig.* 11.). The metal cross-piece is to be touched with the electrised body, and the electricity is immediately communicated through the linen thread, which is a conductor, to the two balls, which recede from each other. To know the nature of the electricity, we touch the metal cross-piece, whilst the electroscope is charged, with a stick of electrised wax: we thus give to the instrument negative electricity. If the two balls approach, we conclude that the electricity with which the instrument was charged was positive; if they separate further, we conclude that it was negative.

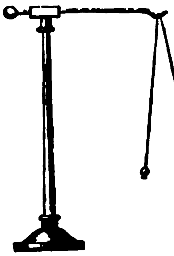

*Fig.* 11.

To render the instrument more sensitive and more accurate, the two light bodies are inclosed in a bell-glass, whence there arises a metal rod that sustains them, and which is to be touched with the electrised substance. The light bodies themselves are then either the two pith balls (*Fig.* 12.), or two blades of straw, as in Volta's electrometer (*Fig.* 13.), or two gold leaves beaten very thin, as in Bennet's electrometer (*Fig.* 14.); in this latter two small metal stems, each terminated by a knob, are placed vertically on the foot of the instrument, on each side of the gold leaves, so that, when the latter diverge too strongly, they come in contact with the stems, which are in communication with the earth, and are thus discharged. We thus avoid the tearings resulting from the adhesion to the sides of the bell-glass, to which the gold leaves would be subject by the effect of too strong a charge of electricity. Finally; in all electroscopes a circular division enables us to measure the angular separation of the two light bodies, the pith balls, the blades of straw, or the gold leaves. The metal stem, in the gold leaf electrometer, carries, at its lower extremity, which penetrates into the upper part of the bell-glass, pincers, by means of which the gold leaves are fixed; and its upper extremity, which is outside the bell, is terminated by a disc or a knob. In order that the electricity which is given to the knob may not be lost, and may pass onward and affect the gold leaves, care is taken to place the metal rod itself in a glass tube, which covers it entirely, except at its two extremities: this tube penetrates into the bell through a metal ferrule, to which it is cemented by means of an insulating material, such as wax or gum-lac. The ferrule is also fixed by means of wax to the tubular hole of the bell (*Fig.* 15.).

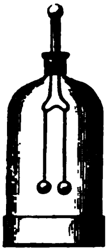
*Fig.* 12.

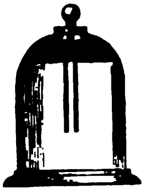
*Fig.* 13.

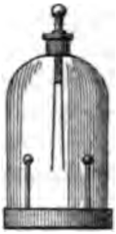
*Fig.* 14.

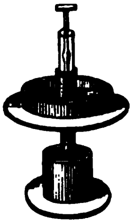
*Fig.* 15.

It is very important that the air be very dry, both in the interior of the bell and on its exterior surface, so that the electricity may not be dissipated by contact with moist air. With this view, the electroscope itself is frequently placed all entire in a glass cage, filled with chloride of calcium or quick lime, which well dries the air; care being taken to let no part be outside the cage, except the knob or metal disc, by which the electricity is made to reach the gold leaves.

With sensible electroscopes, such, in particular, as the gold leaf, it is not always necessary to touch with the electrised substance the exterior part of the metal rod which carries the light bodies, in order to pass into the latter the electricity that we wish to collect. It is sufficient to bring the substance near the rod; and, by an effect which we shall soon study, the gold leaves, while under this influence, are found to possess an electricity similar to that possessed by the substance itself. In like manner, if the electroscope is electrised, it is sufficient to bring near to it, without contact being necessary, a body whose electricity is known, in order to judge, from the greater or more feeble divergence of the two light bodies, what the nature is of the electricity with which they are charged.

Although the degree of divergence of gold leaves, and in general of all other light bodies, is in relation with the intensity of the electricity that animates them, this intensity is far from being exactly proportional to the number of the degrees of separation. Thus, to speak truly, the instruments that we have been describing deserve rather the name of *electroscopes* than that of *electrometers*, which latter name must be reserved to apparatus, such as Coulomb's balance, of which we shall speak in the following Part, and which give indications proportional to the intensity of the electricity with which they are charged.

# CHAP. IV.

## OF THE VOLTAIC PILE AND VOLTAMETERS.

### *Volta's Column Pile.*

THE voltaic pile, like the electrical machine, is an apparatus in constant requisition in the study of electricity; but it is based upon another mode of developing the electric fluids. Friction is, indeed, not the only mode of producing this development: there exist others; in particular, elevation of temperature, and, also, the chemical action of one body upon another. The simple contact of two heterogeneous substances, such as that of two different metals, is also, according to some philosophers, a source of electricity. It is not the place here to study the different modes of producing electricity; this subject will be treated of in the Fifth Part.

We must here confine ourselves to saying that the Voltaic Pile is an apparatus in which electricity is developed, according to some by the contact of two metals of a different nature, and according to others by the chemical action of the liquids, with which it is charged, upon one of the two metals that enter into its formation. It presents, in fact, these two circumstances united: we shall see, in the sequel, what part must be attributed to each. This is of little consequence to us at present, since we are only concerned in the description of the apparatus. We may further add that the pile devised by Volta owed its origin to the interpretation which this celebrated philosopher gave to a remarkable experiment made by Galvani, namely, that a frog undergoes a violent commotion when one of its nerves, being exposed, is touched with one metal, and its muscles with another metal, the

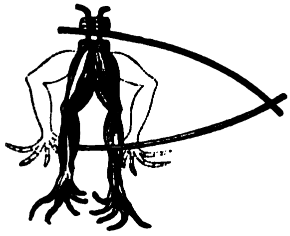

*Fig.* 16.

two metals being themselves in close contact, in one or more points of their surface (*Fig.* 16.). This effect, which is due to a liberation of electricity, has caused the electricity thus liberated to be called *galvanic*, and the part of physical science concerned in it to be called *galvanism;* but the name of voltaic must remain to the pile, since it truly originates with Volta.

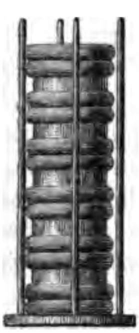
*Fig.* 17.

The first form that was given by Volta to the pile is that of a vertical column, formed of discs of copper and zinc, from 1½ to 2½ inches in diameter, arranged as follows (*Fig.* 17.). The base of the column is a copper disc, upon which is placed a zinc disc; the combination of these two superposed discs forms a pair; over this first pair a second similar pair is placed, care being taken that the copper is always below the zinc: the second pair is separated from the first by a circular piece of cloth or pasteboard, well moistened with water, or, which is better, with salt water or acid water. Upon the second pair is placed a third, arranged in the same manner, and separated also by a moistened circular piece, similar to that which preceded. In this manner a greater or less number of pairs are superposed one over the other, care being taken to retain them in their position by means of vertical rods of glass; if the precaution has been taken to insulate the pile by resting its base upon a plate of glass, it is found to be charged with negative electricity at its lower extremity, where it is terminated by the copper disc, and with positive electricity at its upper extremity, where it terminates by the disc of zinc. These extremities are termed *poles;* the former the negative, and the latter the positive pole of the pile. Had the two metals been placed in another order, namely, had we commenced with the zinc, and placed upon it the copper disc, then the moistened cloth, and then again zinc, copper, and moist cloth, and so on, the positive pole would have been below and the negative above. Two wires lead one from the extreme copper and the other from the extreme zinc, each communicating the electricity of the pole whence it originates; and when they are brought together, a spark passes between them, resulting from the neutralization of the two contrary electricities. If these wires are held one in each hand, when the number of pairs in the pile is sufficiently great, a series of shocks are felt, the sensation of which is sometimes very painful. When, instead of the human body, a very fine wire of iron, platinum, or any other metal, an inch or two in length, is employed to connect the two conductors, the neutralization of the two electricities is brought about through this wire, which rises in temperature and becomes incandescent. The length and diameter of wire that can be heated are greater in proportion as the pile is more powerful. The most remarkable circumstance is, that the incandescent condition of the wire is permanent, because the neutralization of the two electricities is continued, the pile liberating them at each of its poles, in proportion and as rapidly as they are neutralized.

The two wires, that come from the poles, may also be plunged into water, which has been rendered saline or acidulated to make it a better conductor. In this case the submerged part of the two wires must be either of *gold* or of *platinum*. It will immediately be perceived that, through the continued neutralization of the two electricities which takes place by means of the water, the latter is decomposed, and its two constituent gases are liberated, the one, oxygen, around the wire that communicates with the positive pole; the other, hydrogen, around the wire, that communicates with the negative pole; the two gases are constantly in the same proportions that constitute water, namely, one volume of oxygen to two of hydrogen. In order to collect them, the precaution is taken of placing above each of the wires, which penetrate interiorly into the vessel containing the water, and to which they are well cemented, a tube, closed above and containing the same liquid as the vessel itself; and which is driven out by the gas in proportion as it ascends (*Fig.* 18.).

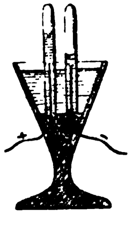

*Fig.* 18.

The phenomena, that we have been describing, are merely examples of the varied and numerous effects that are produced by the voltaic pile, or, rather, that arise from the continuous reunion of the two electricities; for the pile is in this case only a convenient and powerful means of obtaining this continuous reunion, but it is not the only means. These examples will suffice for the present; for they will already have enabled us to discover, in the effects of the pile, the means of measuring its power, and of constructing apparatus which have been termed *Galvanometers*, or, better still, *Voltameters.*

### *Instruments intended for measuring the Power of the Voltaic Pile, or Voltameters.*

The first Voltameter, founded upon the calorific effects of the pile, was contrived by M. Gaspard de la Rive; it consists of a fine platinum wire, stretched vertically, the two extremities of which terminate at pieces of metal, separated from each other by a sufficiently insulating body, such as ivory or ebony (*Fig.* 19.). The wire, at its lower extremity, is secured to a needle, movable in a vertical plane round one of its extremities, while the other extremity traverses the divisions of a graduated circle. The point, where the wire and needle are united, is very near its centre of rotation; whence it follows that very small variations in the length of the platinum wire make the needle traverse comparatively large arcs on the scale. The conductors from the poles of the pile are put into communication by means of metal pincers, one with the lower and the other with the upper part of the wire. The latter becomes more or less heated in proportion to the power of the pile, and its dilation is appreciated by the number of degrees traversed by the needle on the scale. Platinum wires of different sizes may be adjusted to the instrument to render it more or less sensible: the choice of these wires depends upon the force of the

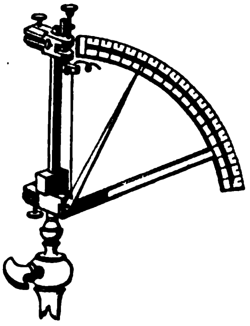

*Fig.* 19.

apparatus, whose power is by these means to be appreciated. It is easy to determine the expansion that the wire has undergone, and consequently the approximate temperature to which it has been exposed, by means of the sines of the arcs that have been traversed, and by knowing the absolute length of the wire.

A still more sensible voltameter, founded also on the same principle, is that in which the platinum wire, that is to serve as the channel for the continuous reunion of the two electricities, traverses the ball of an air thermoscope, in such a manner that its two extremities come outside, and thus may each be placed in communication with one of the poles of the pile (*Fig.* 20.). The wire must be hermetically sealed to the glass at the two points where it traverses the ball. As soon as it is heated it expands the air contained in the ball,—an effect which is immediately made manifest by the rise of the thermoscopic liquid. There are often in the same ball two different and independent wires, the one finer than the other; so that, according to the force of the electricity, an apparatus of greater or less sensibility may be employed.

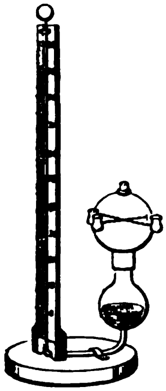
*Fig.* 20.

Another, which is no less sensible, and whose indications are more comparable, is a voltameter that I described even before the preceding one had been contrived. It consists in using the helix of a Breguet's metallic thermometer, instead of a platinum wire, to appreciate, by the calorific effects, the energy of the dynamic electricity (*Fig.* 21.). Breguet's helix is composed of three superposed metallic plates, so narrow and so thin that the slightest change of temperature makes it twist and untwist by means of the unequal

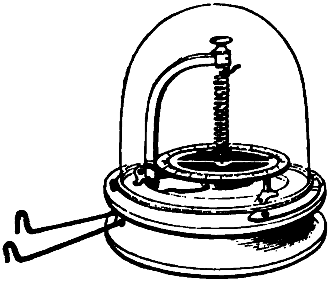
*Fig.* 21.

dilatability of the three metals, *platinum*, *gold*, and *silver*, of which it is formed. The helix is fixed by its upper extremity to a metal support, which is placed in communication with one of the poles of the pile. To its lower extremity, which is free, is soldered a small vertical platinum wire, that is lightly plunged into a capsule filled with mercury, into which the other pole enters by means of a wire. This same free extremity carries the horizontal needle, which, by the number of degrees it traverses on a circular division, indicates the elevation of temperature that the helix has undergone.

These are the three principal forms that have been given to *calorific* galvanometers, or rather voltameters, which, as their name indicates, are founded on the effects of the heat to which the electricity produced by the pile may give rise.

Voltameters that are founded upon the chemical effects, have for their basis the exact measure of the quantity of gas liberated during a given time (one minute, for example) in the decomposition of water; or, which is still better, the appreciation of the time necessary to liberate a given quantity of gas. It is hence necessary that these gases be collected with care, no portion being allowed to escape, and their volume being accurately estimated, taking into the account the atmospheric pressure and temperature. This is not all: the quantity of gas liberated in a given time, in the decomposition of water, depends not only upon the force of the pile employed, but also on the degree of purity of the water subjected to experiment, and on the nature and size of the wires that are immersed in it, in order to place it in communication with the poles of the apparatus, and also on the distance which separates these wires or plates; so that, in order that experiments may be comparable, it is necessary to employ throughout the same apparatus or apparatus perfectly similar. With regard to the water, distilled water is selected, to which has been added a certain portion of very pure sulphuric acid, in order to render it sufficiently conductible;—about $\frac{1}{10}$th in volume, or $\frac{1}{20}$th in weight, is employed. By means of an areometer it is easy to have water always acidulated to the same degree. The metal employed is always platinum, either in wires or in plates.

These wires are placed vertically in a glass, and near to each other; their lower extremity comes out at the bottom of the vessel, so that a communication may be established between them and the poles of the pile. The gases are collected, either in two tubes (*Fig.* 18.), or in a single one placed equally over both wires (*Fig.* 22.). The tubes must be carefully graduated. The gases are also collected in graduated test tubes, placed on the pneumatic trough, and beneath the voltameter (*Fig.* 23.). When, on the contrary, the liberation of gas is very feeble, the gases are measured by the displacement they produce upon the liquid. With this view, there comes from the lower part of the vessel, wherein the decomposition is carried on, a lateral tube in which the liquid that is driven out by the gas ascends, and is itself lodged in the upper part, which is hermetically sealed (*Fig.* 24.). With this apparatus it is necessary to take into account the influence which the pressure, exercised by the column of liquid raised in the lateral tube, may have upon the volume of the gas.

*Fig.* 22.

*Fig.* 23.

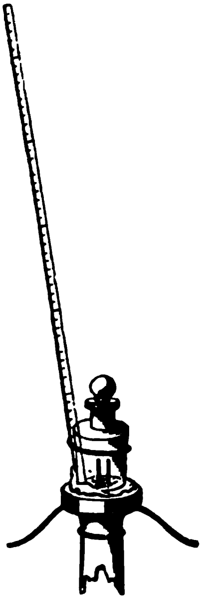

*Fig.* 24.

All these voltameters, both the chemical and the calorific, are far from being perfect instruments: for there is nothing to prove that their indications are exactly proportional to the intensity of the cause which they are intended to measure; and, moreover, these indications themselves are often variable by reason of circumstances of various kinds, which we shall be called upon to study and to appreciate hereafter.

We may add, that there is one galvanometer, the most perfect of all, which we have not mentioned, because we shall have occasion to devote ourselves to it in a very special manner in the Third Part of this work: it is the one founded upon the property possessed by every conductor that is traversed by an electric current,—to deflect a magnetic needle from its natural direction of North and South, when it is placed parallel, either above or below the needle. This instrument has received the name of *magnetic galvanometer* or *multiplier*.

### *Different Forms given to the Voltaic Pile.*

The form of a column, which Volta gave to his apparatus, was soon abandoned; it had many inconveniences, without reckoning the very long time that must needs be devoted to putting the apparatus together, whenever it was required to be used. The principal inconvenience was the rapid drying up of the pieces of moistened cloth or pasteboard, whence arose a great diminution in the power of the pile.

To remedy this, it was proposed to substitute for these discs a bed of liquid, which necessarily required that what was a vertical pile must be rendered horizontal, and that each pair should then be composed, not of two circular discs, but of two rectangular plates in contact, and should be cemented one after the other in the grooves of a wooden trough, so as to leave between them vacant spaces or cells, to be filled with liquid (*Fig.* 25.). It is essential that caution be taken that the plates are carefully cemented against the sides of the trough, that there may be

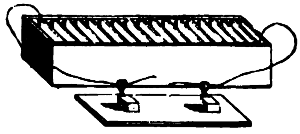

*Fig. 25.*

no communication between the liquid of one cell and that of the following. This mode of construction, which was first pointed out by Cruikshanks, was adopted in establishing the great voltaic pile that was given to the Polytechnic School by the Emperor Napoleon, and with which MM. Gay Lussac and Thénard made their experiments in 1808.

This form possessed, however, several of the inconveniences of the primitive form, especially that of requiring a long time to fit up the apparatus; and of allowing a communication between the liquid of the cells, when the plates were not well cemented, which notably diminished the electrical effects. A return was then made to a form that Volta had previously pointed out, in constructing his pile called *Couronne de Tasses*, —a pile in which the liquids are placed in vessels independent of the metal plates, and the sides of which, of glass, porcelain, or pipe-clay, allow them to be placed one after the other, and even in contact, without there arising any communication between the liquid strata contained in them. With this view, either a series of ordinary cylindrical glasses are employed, as in the couronne de tasses pile, or a porcelain trough, divided off, by partitions made with the trough, into a certain number of cells (generally ten), in equal and successive compartments of a rectangular form, into each of which the liquid is poured, care being taken not to fill them completely. The liquids are thus totally insulated from each other. With regard to the metal plates, as it was very quickly perceived that it was not necessary for the zinc and copper to be in contact throughout their surface, but that it sufficed them to be so in certain

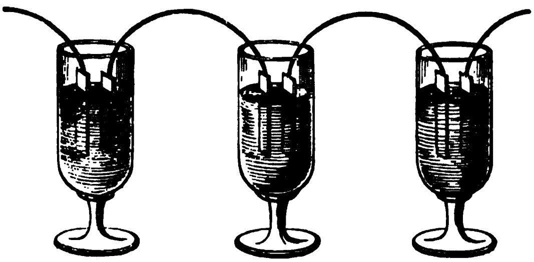

*Fig.* 26.

points only, this enabled us to plunge into the liquid of each compartment a zinc and a copper plate, and to make a communication by means of a small plate of copper in the form of an arc, between the zinc of one compartment and the copper of the following one, and so on. This is done in the couronne de tasses (*Fig.* 26.). By this method the liquid stratum, as in the primitive pile, occurs between the zinc, on the one hand, and the copper on the other; and the zinc and copper that are plunged in the same liquid are never in metallic contact, which is as it ought to be. But, to facilitate operations, care is taken in the trough piles (*Fig.* 27.) to fix the pairs, which are the same in number as the compartments of the trough (eight, for example), to a rod of glass or varnished wood: they are held there by means of the copper arc, which forms the means of communication between the metals of the pair. The metal plates must be arranged one after the other in the proper order, and at such distances that, by holding in the hands the two ends of the rod to which they are fixed, they may be plunged all together into their respective troughs, and so that each occupies the place prescribed for it; namely, that there shall be found in the same liquid only the zinc of the preceding couple, and the copper of the following one, or reciprocally.

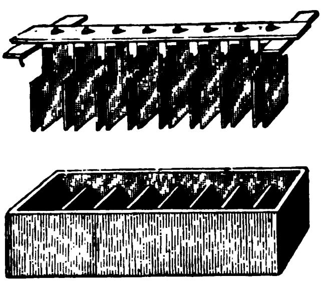
*Fig.* 27.

In the pile we have been describing, each trough contains ten compartments, and consequently ten pairs; but several of these troughs may be placed one after the other, care being taken that the zinc of the pair whose copper is plunged in the last compartment of one trough shall itself be placed in the first compartment of the following trough, and so on. The Royal Institution of London, the laboratory of which has been the scene of the brilliant labours of Davy and Faraday, possessed a pile constructed according to the method we have just described, and composed of 2000 pairs. It was with this pile that Davy made his splendid experiments, and especially the one of the luminous arc, that escapes between two charcoal points placed very near together, and each communicating with one of the poles of the pile.

Wollaston found that the effect of this pile was augmented if a greater surface was given to the copper than to the zinc; a modification that is easily introduced, without making any change in the form of the apparatus or in the size of the cells, by enveloping the zinc plate of each pair with the copper plate of the preceding one, at the same time taking great care to avoid all metallic contact between these two plates (*Fig.* 28.).

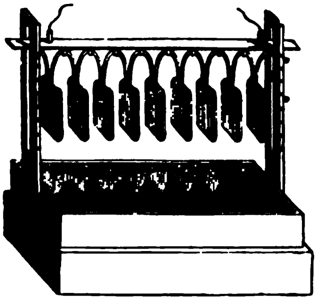

*Fig.* 28.

In this manner the copper plate has a surface double that of the zinc plate. Berzelius suggested making use of the copper itself, by which the zinc is enveloped, without being touched, as a cell or vessel for containing the liquid (*Fig.* 29.). This arrangement possessed great advantages in increasing the power of the pile; but, in manipulation, it presented many inconveniences, which prevented its being generally adopted.

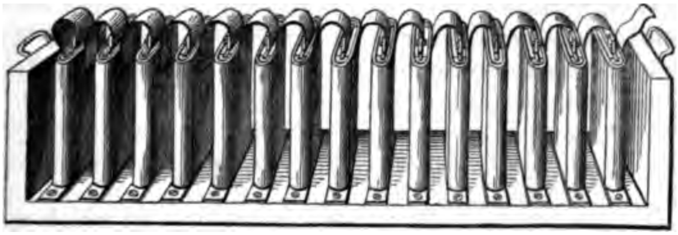

*Fig.* 29.

Two forms of the pile, that have been long in use, are those

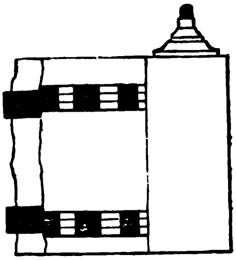

*Fig.* 30.

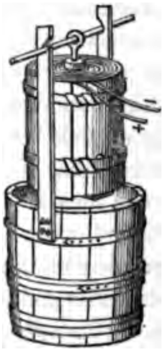

*Fig.* 31.

of the helix (*Fig.* 30.) and the concentric cylinder (*Fig.* 31.). The former was employed by Dr. Hare; the latter by M. Pouillet, in the construction of the great pile of the Faculty of Sciences at Paris. The zinc and copper, when wound into a helix or arranged in concentric cylinders, are plunged into a glass vessel, and must have no contact one with the other; but the helix or cylinders of zinc of the one vessel are in metallic communication with the helix or cylinders of copper of the following one, and so on. By this arrangement a great surface may be given to the two metals of each pair, without there being the necessity of having very large troughs. The employment of cylindrical vessels possesses a further advantage, on account of the facility with which they may be procured.

With regard to the liquid conductor, experiment had shown that the best one to be employed in charging the pile we have described above was a mixture of water with $\frac{1}{40}$th in volume of sulphuric acid, and $\frac{1}{60}$th of nitric acid.

### *Daniell's, Grove's, and Bunsen's Constant Piles.*

The piles that we have been describing, and which were for a long time exclusively used, all possess one inconvenience, which is, that after a short time they lose their power; and, in general, their force is very variable during the progress of the same experiment, even when the duration does not exceed ten or fifteen minutes. This gradual, and, in the majority of cases, rapid, diminution is due to several causes, the principal of which is that the liquid, placed between the pairs, is decomposed when the poles of the piles are connected by a conductor, in the same manner as the liquid is decomposed that is interposed between the poles themselves; it hence results that the copper of each pair is covered with hydrogen, and even with oxide of zinc, arising from the decomposition of the water, and from that of the sulphate of zinc, which is constantly formed from the action of the sulphuric acid upon the zinc. This deposit, by altering the surface of the copper, and rendering it almost similar to that of the zinc, which latter, on its own part, is very rapidly oxidized, destroys in great part one of the conditions essential in the construction of a pile, the heterogeneity of the two metals; and, consequently, very notably reduces its power. Hence it was necessary to clean the plates of a pile every time it was used, before putting it into action again.

In 1836, Daniell, in order to avoid the inconvenience that we have just pointed out, conceived the idea of plunging the copper of each pair into a different liquid from that in which the zinc was plunged: he placed the former of these metals in a solution of sulphate of copper, and the latter into a diluted solution of water and sulphuric acid, or into a solution of sea-salt. The difficulty was to separate these two liquids by a substance which, while preventing the mixture, should not alter the conductibility of the heterogeneous liquid conductor interposed between the plates of the pairs. A metal diaphragm could not be thought of, for this would have violated one of the fundamental conditions of the construction of the pile, which requires that there should be a conductor totally moist between the pairs. Daniell had recourse to an organic substance, according to the method which Becquérel had first pointed out; and he made some diaphragms with bladder, with stout paper, with very thin wood, or with very closely woven linen cloth. Experience has given the preference to diaphragms of thin wood, lime-tree wood, for example, as well as to those of bladder, only care must be taken to preserve them from flaws, or in general from all solution of continuity. With this in view, it is necessary to keep the wooden diaphragms constantly in water when they are not in use, and to place those made of bladder under protection from the attacks of insects, and from the contact of every foreign body. The difficulty experienced in taking these precautions has induced several philosophers to adopt, as indeed Daniell himself did, diaphragms of unglazed porous earth; but the pile loses much of its power, especially for calorific and chemical effects. Daniell gave the cylindrical form to the pairs of his pile, on account of the greater facility there is of procuring diaphragms of this form. In his pile (*Fig.* 32.) a hollow copper cylinder is plunged into a glass vessel filled with a solution of sulphate of copper; in the interior of the cylinder is placed either a bag made of bladder, or a wooden tube, or a hollow cylinder of porous earth, which is filled with either acidulated or saline water; finally, in this water is plunged a zinc cylinder, which is in metallic communication with the copper of the succeeding pairs by means of a little cup filled with mercury, into which dip two pieces of copper, attached the one to the zinc, the other to the copper. The zinc cylinder may be solid or hollow: in the latter case it is simply a sheet of zinc rolled into a cylindrical form. This latter mode is preferable, because the zinc is found to have

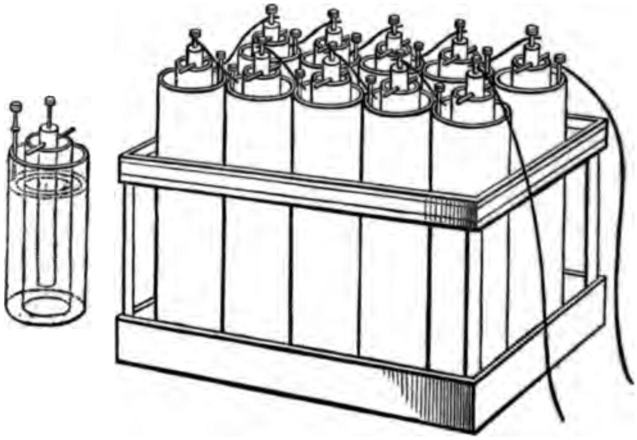

*Fig.* 32.

more points of contact with the liquid; but it is consumed more rapidly.

Another great amelioration introduced into Daniell's pile, as well as into those of which we shall speak hereafter, consists in amalgamating the zinc, that is, in covering it with a coat of mercury, which is easily done by pouring mercury upon the zinc, and, at the same time, sulphuric acid diluted with about twenty times its volume of water, in order that the surface of the zinc may be well oxidized, and sufficiently clean that the mercury may adhere to it. The advantage of this operation, which was suggested by an English philosopher, Mr. Kemp, is, that, without in any way changing the effect of the zinc in the production of electricity by the pile, it is prevented being attacked; and it consequently does not dissolve in pure loss in the acidulated water when the pile is not in action; that is to say, when its poles are not united by a conductor. But as soon as this union takes place, the zinc is attacked, notwithstanding the mercury with which it is covered; only the oxide that is formed does not remain adhering to the surface, which always continues brilliant and metallic: a circumstance in other respects eminently advantageous, for the film of oxide that covers the zinc plates when they are not amalgamated contributes notably to the weakening of the pile. With regard to the copper, as it is plunged in sulphate of copper, it becomes covered with metallic copper by the decomposition of the sulphate whilst the pile is in action: its surface is therefore not altered.

It may be conceived that the power of Daniell's pile is constant, at least for a moderate length of time; but it must follow that, at the end of an hour or two, the solutions are exhausted, and they must be renewed: they also finish by mixing one with the other, and more or less rapidly, according to the nature of the diaphragm. It is then necessary, not only to change them entirely, but to wash the diaphragms carefully and to clean the surfaces of the metals. It is preferable not to wait for this mixing to take place before taking the pile to pieces and renewing the liquids.

A second constant pile, and one in which two different liquids are also employed, is that of Grove. In this pile the zinc is amalgamated, as in the preceding one, and is plunged into sulphuric acid diluted with 10 or 20 times its volume of water. The other metal is platinum and not copper, and is plunged into nitric acid, either pure of 40° or diluted with half its volume of water, or mixed with one fourth concentrated sulphuric acid. The diaphragm by which the two liquids are separated is not in this case of an organic nature; for it would be immediately destroyed by the action of the nitric acid: it is of unglazed porcelain or pipe-clay: in this state these substances have the advantage of being sufficiently porous to permit communication between the liquids, at the same time of entirely preventing their mixture.

In Grove's pile (*Fig.* 33.) the pairs are not generally of a cylindrical form, although some have been constructed of this form: they are plates of zinc and platinum plunged into cells of glazed porcelain or glass. Each cell contains dilute sulphuric acid, in which the zinc is immersed, and a small cell of porous earth filled within with nitric acid. In this acid is placed the platinum plate in metallic contact with the zinc of the succeeding or following cell. This contact is established between the two edges of the zinc and platinum plates, which are carefully cleaned, by means of pincers either of metal or simply of wood. Experiment has shown that the power of these piles is much increased by giving to the zinc plates a very large surface in respect to the platinum plates. With this view they are bent so that they form in each cell two vertical and parallel surfaces united by a lower and horizontal surface which is much smaller: the porous trough that contains the nitric acid and the platinum plate is placed in the interval that is left between the two parallel surfaces.

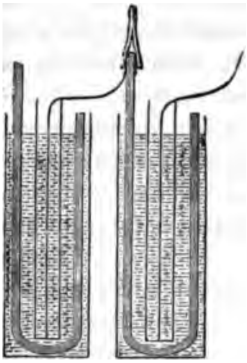
*Fig.* 33.

When Grove's pile is in action — that is, when its poles are united, — the hydrogen, arising from the decomposition of the acidulated water in which the metals of the pairs are plunged, is not developed upon the platinum, but changes the nitric acid into nitrous acid: the oxide of zinc remains, as before, in the liquid, where the zinc itself is, and does not penetrate through the porous partition to the platinum. The latter then retains a perfectly clean surface; and it is this circumstance which contributes essentially to this pile's maintaining for a greater or less length of time, according to the use that is made of it, that power which is at once so constant and so energetic, and which renders it so valuable in practice. The nitric acid, however, as it changes into nitrous acid by the action of the hydrogen, passes into reddish brown, and then into green, and finishes by acquiring a temperature so elevated that it enters into ebullition: in this case it is necessary immediately to arrest the action of the pile.

Bunsen's pile differs from Grove's only in that carbon supplies the place of platinum. This substitution arose essentially from the high price of platinum, which, on this account, is used in sheets so thin that they are frequently torn. Bunsen's pile has the cylindrical form of Daniell's; in fact, if, in the latter, a hollow cylinder of carbon is put in place of the hollow copper cylinder, and pure or diluted nitric acid in place of solution of sulphate of copper, and a cylinder of porous earth in place of the porous cylinder of organic matter in which are contained the diluted sulphuric acid and the cylinder of amalgamated zinc, we obtain Bunsen's pile (*Fig.* 34.). Each carbon cylinder carries at its upper part a collar of copper, furnished with an appendix, which is placed in contact, by means of pincers, with a similar appendix carried by each zinc cylinder; care, however, must be taken that the carbon cylinder is sufficiently high, that the part which carries the copper ring shall rise above the glass vessel, and consequently shall in no way be in contact with the nitric acid. However, as the charcoal is very porous, the capillarity causes the acid finally to attain to the top of the cylinder, and to alter interiorly the copper ring. Therefore, every time this pile is used, it is necessary to move these rings and wash and carefully clean them.

A more convenient arrangement,—inasmuch as it is free

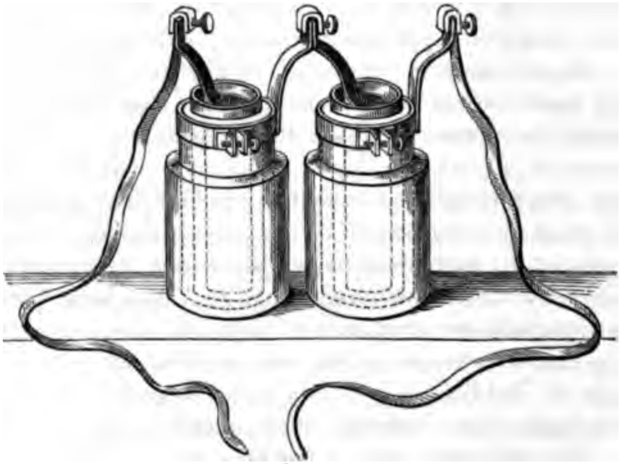

*Fig.* 34.

from the kind of inconvenience that we have just pointed out,— is that which was contrived by M. Bonijol (*Fig.* 35.). This

*Fig.* 35.

skilful artist employs, instead of hollow cylinders, solid cylinders of carbon, in the top of which is thrust a stout copper rod, bent so as to be put into communication, by means of a cup filled with mercury, with a similar rod soldered to each zinc. The top of the carbon cylinder around the place in which the copper rod is inserted is covered with a coating made of wax, prepared so as to penetrate to a sufficient depth into the pores of the portion of the carbon which it covers and to which it adheres strongly. The consequence of this is, that the nitric acid cannot ascend as far as the copper rod. It is evident that in this pile the amalgamated zinc is outside the carbon: it is a hollow cylinder plunged into the glass vessel that is filled with diluted sulphuric acid: the porous tube is placed in the interior of the zinc cylinder, and itself receives the carbon and the nitric acid into which the latter must be plunged.

The preparation of the carbon is difficult when hollow cylinders, such as in Bunsen's pile, are in question. For this purpose, it is necessary to have iron moulds, and then coke in fine powder, which is brought by one or two operations to a high temperature after having been mixed with sugar or molasses to cause a cohesion, that gives consistence to the whole. In Bonijol's pile the cylinders may be prepared of carbon in the same manner, which is the easier, as they are solid. But it is a much more simple plan to procure pieces of well-baked coke of good quality and of sufficient dimensions. They are cut, as well as may be, into the form of cylinders, without, in truth, its being possible to give them exactly this form, which, however, is of little importance.

M. Deloeil is at the present moment constructing in Paris piles of this kind, in which the carbon is perfectly cylindrical, and has been prepared according to the process mentioned. A very simple arrangement enables us beforehand to establish a contact between the carbon or zinc of each pair; and to attach the pairs themselves upon fixed frames in such a manner that, in order to put the pile in action, it is only necessary to raise a wooden table that sustains the vessels filled with their liquids, and into which the carbon and the zinc are to be plunged, each in that which appertains to it.

Such are the different kinds of piles that are generally used, and all of which are more or less to be found in physical cabinets and in chemical laboratories. There are, however, some others that are used only in certain practical applications, and of which we shall speak again, when we are engaged in these applications.

We will not occupy ourselves farther at present with certain voltaic combinations, which have a purely theoretical interest, and the description of which will find its place when we are treating upon the theory of the pile. However, we will mention here, as it is very generally used, Smee's pile, the pairs of which consist of amalgamated zinc and plates of platinised silver, namely, silver covered with a coating of the black powder of platinum, plunged into one and the same liquid, diluted sulphuric acid, and which, notwithstanding, preserve a remarkable constancy.

### *Enumeration of the different Voltaic Piles, and the general Consideration that is common to them all.*

To sum up, the voltaic piles that we have described are:—

1. Volta's column pile, celebrated because it was the first, and because it represents the form under which its illustrious inventor realised his idea;

2. The wooden trough pile with fixed metal pairs,—the form under which was constructed the great pile given in 1806 to the Polytechnic School by the Emperor Napoleon;

3. The pile, with independent cells of glass or porcelain and movable metal pairs,—the form under which the pile of 2000 pairs belonging to the Royal Institution of London was constructed, and which was used by Davy in making the great discoveries that have immortalised his name;

4. Berzelius's pile, with copper cells, which was of essential service in the first experiments upon electro-magnetism;

5. Daniell's constant pile, with porous organic diaphragms, and two liquids, sulphate of copper for the copper, and acidulated or salt water for the zinc, a form eminently useful in experiments of long duration, and in particular those in which the study of the chemical effects of the current is concerned.

6. Grove's constant pile, in which, as in that of Daniell, two liquids and a diaphragm are employed, with this difference, that platinum supplies the place of the copper, and nitric acid the place of sulphate of copper; and the porous diaphragm is of unglazed not glazed earthenware;—a pile, the

best suited of all for the production of the effects of the electric current, on account of its enormous powers, united with a constancy, which, although less than in Daniell's pile, is sufficient in the majority of cases, and especially in public lecturing.

7. Bunsen's constant pile, which is only a modification of Grove's by the substitution of carbon for platinum; it is constant for a longer time, but is less energetic in its effects than Grove's. It is also very much used, especially in Germany, and it is found, as well as Daniell's, both in the workshop of the artizan and in the cabinet of the savant and the professor. Bonijol's pile and Deloeil's differ from Bunsen's only in the form and place given to the carbon.

This is the place to offer a general remark, which is common to all piles; and the importance of which will not escape those who employ these apparatus. It is to know accurately what determines in each of them the place of the positive pole and that of the negative. The employment of certain faulty denominations, joined to prejudices arising from certain theories, have cast upon this point, so simple in itself and so essential, an obscurity which ought not to exist, and which it is indispensable that we should dissipate.

There enter into the construction of all the piles of which we have spoken (which contain one or two liquid conductors), two solids of a different nature, the one more oxidisable than the other, almost always the zinc; the other less oxidisable, the copper, the platinum, the carbon. These solid bodies, which, for greater facility in explanation, we will suppose to be zinc and copper, are connected together two and two, so as to form pairs, which follow each other, and are separated from each other by *the one* or by *the two* liquids. Care is always taken to place the two solid bodies of the pair in the same order, so that, for example, in each pair every zinc is above the copper, if the pile is a column, or on the right of every copper if the pile is horizontal. The inverse order may equally occur; but it is necessary that the rank, whatever it may be, occupied by the two metals in respect of each other remain the same in all the pairs. It follows from this, that in horizontal piles, which are the only kind now used, each cell contains, besides the liquid, the two solid bodies of a different nature, and never those of the same kind. With regard to the two extreme cells, one of them contains, besides the copper of the pair whose zinc is plunged in the preceding cell, a zinc to which a conductor is soldered; the other contains, besides the zinc of the pair whose copper is plunged in the cell that follows it, a copper, to which a conductor is also soldered. It is these two conductors that carry away the two electricities produced by the apparatus and accumulated at the two extremities or poles, and which are called the *electrodes* of the pile; one the positive, the other the negative electrode.

In the column pile the extreme zinc is also in contact with a copper, which is itself not in communication with any conducting liquid, and the extreme copper with a zinc that is in the same condition; but in the horizontal pile this copper and zinc are suppressed, as experience has shown them to be of no utility. This suppression does not, in the least, change the nature of the poles; so that whilst, in the column pile, a plate of copper is the negative pole and a plate of zinc the positive, in the horizontal piles the negative pole is found at the last zinc, and the positive at the last copper. From this circumstance some confusion has often arisen, especially when, instead of employing the words positive and negative, we have wished to designate the poles by the names of the metals, as the *zinc pole* and the *copper pole*. The nature of the electricity that is accumulated, must not be associated with the nature of the substance that terminates the pile at each extremity; for, as we have seen, this may lead to grave errors. It must be connected with the order according to which the solid substances are placed; and we must remember that the positive pole is always at that extremity of the pile towards which the zincs of each pair are turned; the negative pole at that toward which all the coppers are turned; and this, whatever be the manner in which the pile terminates, whether by a plate of zinc or one of copper. If the zincs of each pair are turned to the left of a person who is looking at the pile, and the copper consequently to the right, the positive pole will be at that extremity of the apparatus which is to the left of the observer, and the negative at that which is at his right. If the pile, instead of being arranged in the same right line, returns upon itself, and is arranged in any direction whatever, we have merely to see on which side the zincs are turned, and to remember that the positive pole is on that side; as also that the negative pole is on the side to which the coppers are turned. In this way we are sure never to make an error.

Finally, it is well to know that, for dynamic effects, a pile composed of a single pair may be sometimes employed: thus, Mr. Hare's first helix pile (*Fig.* 30.) consisted of but a single pair with large surfaces, and, as this pair was eminently fitted for producing the effects of the incandescence of wires, the author called it a *Deflagrator.* In the case of a single pair there is but one cell, into which are plunged separately the two solid bodies which are not in immediate contact. From each of them proceeds a metallic conductor; and the conducting substance placed between these two conductors is traversed by an electric current. If this substance is fine wire, it is heated, and it can be made red hot if the pair is sufficiently powerful; if it is acidulated water, it is decomposed; but this latter phenomenon cannot occur unless the single pair is one of Grove's or Bunsen's. In the case of the decomposition of water by a single pair, the hydrogen is seen to accumulate around the platinum wire coming from the zinc of the pair, and the oxygen around that proceeding from the platinum or the carbon. Thus the negative electricity comes from the zinc, and the positive from the platinum or the carbon. This equally takes place, as we shall presently see, in a pile of many pairs, if care be taken to suppress the copper in contact with the last zinc and the zinc in contact with the last copper, which Volta had thought necessary, and which occurred in his column pile, but which, as we have said, are perfectly useless, and never exist in the trough piles.

It is important to bear in mind, when occupied upon a pile composed of many pairs, that what we call *the pair* is not the association of the two metals plunged into the same cell, but is formed of the two metals in metallic contact, each immersed in different cells, so that the same cell contains two metals belonging to two different pairs; whilst, when the pile is composed of a single pair, the two metals of this single pair are necessarily plunged into the same cell, and contact is established between them by the conductor, which is traversed by the two electricities as they unite with each other.

In what has been said, we have not given any accurate estimate of the comparative merit of each kind of pile. This estimate, which will find its place further on, if it were effectively made, would in fact require that we should take account at once of the intensity of the effects and the expense of the operations, an expense which is estimated by the more or less rapid consumption of the zinc and the acids. There exists another important element which must be taken into this calculation—it is time. The same quantity of electricity the developement of which corresponds to the same expense of apparatus, may produce very different effects, according as it is liberated in a longer or shorter space of time. This difference depends upon the nature of the effects. So that the point to which we would arrive cannot at present be treated on; but it will be developed with fuller knowledge of its causes, when, after having described in detail the different phenomena produced by dynamic electricity, we shall enter, more profoundly than we have been able to do in this First Part, into the actual sources of electricity, and, consequently, into the theory of the apparatus by which it is produced.

### *Tension Piles, the Dry Pile, and the Dry Pile Electroscope.*

The dynamic effects of electricity do not require for their production the employment of a great number of pairs; many of them are manifested in a very energetic manner even with a single pair. But it is not the same with static effects: in order that there may be a tolerably strong accumulation of positive and of negative electricity at each of the poles of a pile, it is necessary that the pile be composed of a considerable number of pairs, and that the different parts be as much insulated as possible. This insulation is often difficult to be obtained on account of the presence of the liquid with which the pile must necessarily be charged; indeed, unless great precautions be taken, there is a risk of the liquid establishing, between the cells that contain it, a communication in addition to that resulting from the contact of the metals of each pair; and which is the only one that should exist. Mr. Gassiot, by employing glass cells supported on glass stems, so as to render the insulation more complete, succeeded in obtaining, with a Grove's pile of 100 pairs, very considerable effects of tension. He also constructed a pile of 3520 zinc and copper pairs, charged with pure water, and the cells of which are ordinary glass covered with a coat of gum-lac varnish so as to render the insulation more perfect.

This pile, during the several years it has been set up, constantly gives electric sparks at each of its poles which are insulated: the only precaution to be taken is to pour water occasionally into the cells, to replace that which is lost by evaporation. We shall see hereafter that the air dissolved in the water plays an important part in these piles, where, to a certain point, it supplies the place of acids in oxidising the zinc plates.

The water battery, for it has been thus named by Mr. Gassiot, gives but very feeble dynamic effects, as compared with the static or tension effects. The same is the case with the dry pile, which manifests electricity in a state of tension alone. In this pile, paper supplies the place of the liquid conductor; a circumstance that has led to its being termed the dry pile. However, this name has been improperly applied to it, for it acts only because the paper, a very hygrometric substance, is always more or less moist: it would not act at all if it were absolutely dry. Tin supplies the place of zinc in this pile, and peroxide of manganese the place of copper. It is constructed by taking paper tinned on one side only; on the untinned surface of the paper is spread, with a camel's hair pencil, a coat of the powder of peroxide of manganese, of which a paste is made as fluid as possible by dissolving it with milk, and which is made to adhere by a little gelatine or starch. When this coat is well dry, the sheets of paper thus coated are cut into equal discs by means of a punch. These discs are then all placed one above the other, care being taken to arrange them all in the same order, so that there may always be tin and peroxide of manganese in contact, then paper, and then again tin and peroxide of manganese, and so on. Many thousands are built up in this manner; and thus a column or pile is constructed similar in form to Volta's first pile, and the extremities of which are, the one negative, and the other positive. The pile necessarily terminates at its two extremities by an insulated metallic surface; at the one, the negative extremity, by the coating of tin; at the other, the positive extremity, by that of peroxide of manganese.

The dry pile cannot in general develop any electric current, when its poles are united by a conducting body; it can only produce a series of small sparks, arising from the reunion of the two electricities that slowly accumulate at each of its extremities. However, by giving a great surface to the discs, and employing only a determinate number, M. Delezenne obtained with these piles some effects of the current, in particular the decomposition of water: he employed a pile of 300 pairs, each having about 106 square inches of surface.

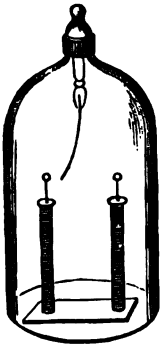
*Fig.* 36.

The principal use made of dry piles is to apply them in the construction of an electroscope, which is the most sensible of all, and which has the advantage over all others of indicating the nature of the electricity at the same time as its presence. This, which is called Bohnenberg's electroscope, from the name of its inventor, consists of two dry piles (*Fig.* 36.), placed vertically upon a wooden stand at a distance of 4 or 5 inches apart: each of the piles terminates above by a metal ball, of a diameter equal or superior to that of the discs of which they are formed. This ball is charged with the electricity accumulated at the pole of the pile above which it is placed: the piles are so arranged that the upper pole is positive in one and negative in the other. The two piles are covered with a bell-glass, having a hole pierced in its upper part. Through this hole is introduced a metal rod sustaining a single gold leaf, the lower extremity of which can oscillate between the two positive and negative balls of the dry piles. The precautions for insulating the metal rod that carries the gold leaf and the other parts of the apparatus are the same as for other electroscopes. As soon as the gold leaf is electrised by the approach of a source of electricity, it is carried toward one or other of the balls, according to the nature of the electricity with which it is charged,—toward the negative ball if the electricity which it possesses is positive, and reciprocally. We thus perceive immediately both the presence of electricity and its nature.

The instrument is so sensitive that it is affected at a distance of more than a yard by the electricity of a glass rod or of a stick of wax: if care is not taken there is even sometimes a risk of giving false indications by the very excess of its sensibility. Indeed, if the two dry piles are too near together, and if the gold leaf is not exactly between the two balls, the slightest movement that brings it nearer to one than to the other is sufficient to cause it to be attracted by this ball, even although it be not electrised, just as any other light body would be. We may therefore easily be led into error, and believe in the presence of an electricity that does not exist, unless the greatest precautions are taken. We have even succeeded in obtaining a continuous movement by these means; for, when once in movement, the gold leaf, or any other light body, having touched one of the balls, becomes charged with its electricity: it is then repelled, to be attracted by the other, which it touches, and of which it acquires the electricity: it is then repelled, and returns to the first, and so on. To obtain this continuous oscillatory movement it is better to employ a light body, such as a small, very light ball, or a disc of tinsel, suspended to a film from a cocoon: there is a risk of the gold leaf sometimes remaining adhering to the ball with which it comes in contact, notwithstanding the repulsive force of its electricity and that of the ball, which is not sufficient to overcome the cohesion.

The expectations that were founded on the dry piles, first devised by Deluc in 1810, then perfected by Zamboni, who has given his name to the one now described, have not been realised. Not only are they very limited in their application, since they only give rise to static electricity,—except the exceptional case, and which is difficult of realisation, that we have cited, in which they produce a barely sensible current,—but, moreover, they do not possess even the advantage of being of very long duration. At the end of some years they no longer work, and their place must be supplied by others in apparatus, into the construction of which they are made to enter. This defect of duration, as we shall see when we are engaged in the general theory of voltaic piles, is due to the paper's finally losing in part its hygrometric faculty, and especially to the tin's becoming oxidised.

# PART II.

## STATIC ELECTRICITY.

## CHAPTER I.

### ELECTRICAL ATTRACTIONS AND REPULSIONS.

AFTER having unfolded the general phenomena presented by electricity, and having familiarised ourselves with the study of this agent, let us examine more closely its properties, commencing by those that relate to static electricity.

Let us first occupy ourselves with the repulsions and attractions manifested by electrised bodies. It is easy to perceive, by means of the apparatus that we have employed in demonstrating the existence of these repulsions and attractions, that the energy with which they occur is greater in proportion as the two bodies between which they are exercised are nearer together. Thus, in the case of attraction, we first see the two electrised balls approach each other slowly, then acquire a more rapid movement, and finally rush upon each other. It is the same with regard to repulsion; we see the two balls, when they are charged with the same electricity, avoid each other with the more vivacity, the more we endeavour to bring them near to each other.

This influence of distance is subjected to a law which was discovered by Coulomb. It consists in this, that *two electrised bodies attract or repel each other with a force which is inversely proportional to the square of the distance that separates them;* that is to say, that if the distance becomes half, the force becomes quadruple; if it becomes the third, the force becomes nine times greater; and so on.

### *Electric Balance.*

The demonstration of this law is founded upon the employment of an instrument contrived by Coulomb, and with which it is necessary to become acquainted, in order to be able conveniently to study static electricity. This instrument is the electric balance, or rather the torsion balance (*Fig.* 37.). It consists of a cylindrical or cubical glass cage, surmounted in its upper part by a vertical tube from 15 to 20 inches high: the cage itself may be 12 or 15 inches in diameter, or even more. The top of the tube is closed by a brass piece, which, like the lid of a tobacco-box, may turn tightly round the cap; which is also of brass, and fixed to the tube itself. A circular division enables us to measure how many degrees the movable piece has been turned, and which may thus describe several circumferences of the circle.

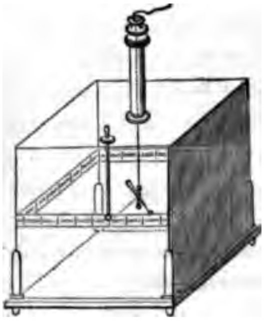
*Fig.* 37.

This piece carries interiorly a vertical metal pincer adapted exactly to its centre, and to which is fixed, by one of its extremities, a very fine silver or platinum wire, which is stretched at its other extremity by a brass weight. The wire must be sufficiently long, that its lower extremity may reach to about half of the height of the glass cage; it is generally about two feet. The brass weight by which the wire is stretched, is traversed by a horizontal needle of glass or gum-lac, one of the branches of which is very short, and the other, which is from 3 to 5 inches long, according to the size of the cage, carries at its extremity a little gilt ball of elder pith, or a small metal disc of tinsel. A circular division, traced round the glass cage, serves to measure the angular spaces traversed by this needle. The deviation that it assumes, when not urged by any force, depends on the position that is given to the movable lid that sustains the wire to which it is suspended. Care is taken that the 0° of the division that is traced on the cage shall coincide with the direction assumed by the needle, when the lid itself is at the 0° of the division, traced on its own circumference. In this manner the starting points, or the 0° of the two divisions, correspond. Finally, an insulating stem of glass or gum-lac, carrying a ball or disc perfectly similar to the ball or disc at the extremity of the movable needle, is introduced vertically by an opening made in the cover of the cage: the place of the opening of the cage and the length of the stem are so combined, that the ball or disc which is at its extremity shall be in contact with the ball or disc of the needle, when the needle itself is in the direction corresponding to the 0° of the division.

The insulating stem may be easily taken away and returned to its place, by means of the piece, to which it is fixed by its upper extremity, and which at the same time serves to adjust it to the opening formed in the cover of the glass cage.

### *Determination by the Electric Balance of the Law that Electric Attractions and Repulsions obey according to Distance.*

To make the experiment, we begin by removing the insulating stem, then giving to the ball, by which it is terminated, either vitreous or resinous electricity, by touching it with an electrised body. It is immediately to be restored to its place: it at once divides its electricity with the ball of the movable needle. The latter is then repelled, and the needle describes a larger or smaller arc of the circle, according to the energy of the repulsion. After a few oscillations, it settles in a certain position, at 36° for example, from the point of departure, namely from the 0° of the division. If the needle stops at this distance, and does not describe a greater arc, it is because, at 36° of distance, there is equilibrium between the two forces, the repulsive force existing between the fixed electrised ball and the movable one, and the torsion force of the metal wire, to which the needle is suspended, and which tends to bring it back to its starting point. Since the needle acquires a fixed position, after having described an arc of 36°, this proves that the force, with which the wire, when twisted to an angle of 36°, tends to untwist itself, is precisely equal to that with which the two balls repel each other at the distance of 36°.

Let us now inquire what would be the force that would produce equilibrium, and that consequently would be equal to that with which they were repelled if they were at a smaller distance, at 18°, for example, instead of 36°; namely, at a distance one half less. For this purpose, let us turn the metal lid, to which the upper extremity of the wire that carries the needle is fixed, so as to compel this needle to approach nearer to its starting point; to compel, consequently, the movable ball to approach the fixed one. We shall see that, in order that there may be an arc of only 18° between the two balls, the lid above must be turned 126°, which causes the wire to be twisted 126° from above; but since the needle is not at the 0° of its division, but remains fixed at 18° beyond, it follows that the wire is twisted 18° below and 126° above, which makes in all a torsion of 144°. The force, then, that produces equilibrium, or that is equal to that with which the two balls are repelled when they are 18° apart, is the force with which a wire, twisted to 144°, tends to untwist itself. We operate, in the same manner, to determine the force with which the two balls are repelled when the arc by which they are separated is no more than 9°. We should find that it would be necessary to twist the wire from above 567°, which makes 576° of torsion in all, by adding the 9° that it is twisted below; for the needle is maintained 9° beyond its 0° of torsion: thus the force with which the wire tends to untwist, when it is twisted to an angle of 576°, is equal to that with which the two balls are repelled when they are only 9° apart.

Experiment had proved to Coulomb that the forces of torsion are proportional to the angles of torsion; in other words, that the force, which must be employed to twist a wire to a certain angle, or that with which it tends to untwist, is proportional to this angle; that is to say, that if the angle becomes double, triple, half, or quarter, the force in like manner becomes double, triple, half, or quarter of what it was. Thus the forces that produce equilibrium, or that are equal to the forces with which the electrised balls are repelled at the distances 36°, 18°, 9°, are to each other as the angles of torsion 36°, 144°, 576°. But these angles are to each other as 1 : 4 : 16; whence we may conclude that, if the distances are to each other as 1 : $\frac{1}{2}$ : $\frac{1}{4}$, the repulsive forces are to each other as 1 : 4 : 16. *It is therefore correct to say that the force with which two electrised bodies repel each other, is inversely proportional to the square of the distance by which they are separated.*

In the same manner we prove that *the force with which two bodies that possess different electricities attract each other, is inversely proportional to the square of the distance by which they are separated.*

In this case, after having given to the ball of the movable needle, by means of the other ball, a certain electricity, we must take away this latter, and give it the contrary electricity. But, before restoring to its place this ball that is intended to remain always fixed at the 0° of the division, it is necessary to give the movable needle another position, which prevents the contact taking place immediately between the ball that terminates it and the fixed ball that has a contrary electricity; for, without this precaution, as these two balls would be touching, the two electricities would be neutralised immediately, and no effect would take place. For this purpose we turn the metal cover, to which the torsion wire is fixed; and, in this manner, we induce the movable needle to remain at 40° or 50° from the 0° of its division, when it is not acted upon by any force, and when the wire consequently is without torsion. It is then we introduce the ball, which is to remain fixed at the 0°, and which is charged with a contrary electricity to that which has already been given to the movable ball before it was made to change its place. There is immediate attraction between the two balls; but they are prevented from coming into contact in consequence of the torsion of the wire resulting from the displacement of the movable ball; they remain, therefore, at a certain distance from each other, a distance at which there is equilibrium between the force of torsion that tends to separate them, and the attraction that reigns between them and that tends to bring them together.

We augment or diminish the torsion so as to maintain equilibrium at other distances. We thus obtain variable distances between the balls, and angles of torsion corresponding to these distances; and it is from the relations that exist, on the one hand between these distances, and on the other between these angles, that we deduce, as in the case of repulsion, the law that we have laid down. We must only take care that, in making the torsions vary, we do not bring the two balls at so feeble a distance from each other that, attraction getting the better of the force of torsion, they may come suddenly into contact, in which case, the two electricities being neutralised, all would have to be done over again.* In all the preceding experiments the electricity that is possessed by the balls runs the risk of being dissipated, with greater or less rapidity, by means of the imperfect insulation of the supports and the humidity of the air. To avoid this inconvenience, we must dry the interior of the torsion balance as much as possible, by placing in it chloride of calcium or other bodies that absorb moisture, by making the experiment as rapidly as possible, and finally by taking account of the loss of electricity, by taking the mean between the results of the same experiments made at slightly different periods.†

### *Influence of the absolute Quantity of Electricity upon Attractions and Repulsions; and general Expression of the Attractive and Repulsive Force.*

After having found the laws by which electric attractions and repulsions are connected with the mutual distance of two electrised bodies, it remained to determine the law according to which the attractive or repulsive force depends on the

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* For the calculations, see note A at the end of the volume.

† Coulomb confirmed the laws that he had found by the torsion balance by a totally different method, which consists in oscillating before an insulated and electrised globe, a horizontal needle terminated by a small ball, charged with the same electricity as the globe, or with a different electricity; the number of oscillations in a given time at different distances are counted; and, by the formula of the pendulum, is deduced the influence of distance upon the intensity of the force.

We shall develope this method more in detail when we come to magnetic attractions and repulsions.

quantities of electricity accumulated upon each body. To arrive at this, Coulomb set out from the self-evident principle that if two bodies, for example, two insulated conducting spheres, of the same size and perfectly similar in every respect, are placed in contact, they share equally in the electricities that they possess; in such sort that if one of the insulated spheres is electrised and the other is not, they have, after contact, each the same quantity of electricity, namely the half of that possessed beforehand by the one only that was electrised. This point being admitted, we observe the force of torsion that at a certain distance is in equilibrium with the repulsive or attractive force of the two balls of the balance, that are similar and charged with the same quantity of electricity. We have a third ball perfectly similar to the two others, insulated as they are, but not electrised. With this ball we touch the 'fixed ball of the balance; this contact takes from it the half of its electricity according to the principle we have just laid down, the movable ball retaining the whole of its own. We then look again for the force of torsion necessary to cause equilibrium, at the same distance, to the attractive or repulsive force of the two balls of the balance, and we find that this force is now only the half of what it was before. By then reducing to a half, by the same process, the electricity of the movable ball, we find that the force of torsion is now only the fourth of what it was in the outset. It is the same if, without making any change in the electric state of the movable ball, we diminish a second time by a half the electricity of the fixed ball, namely, if we reduce it to a fourth of what it was at the first.

These experiments therefore prove that, *the distance remaining the same, the attractions and repulsions are in compound ratio to the quantities of electricity with which the two bodies are charged;* or, which amounts to the same thing, that *the attractive or repulsive force is the product of these two quantities.*

It is easy indeed to see that there is simply a product which may become half less when one of the factors diminishes by a half, and become four times less when the two factors each diminish by a half, or when one alone of the two becomes a fourth of what it was, the other not changing. This result has been verified by Coulomb, by means of a great number of experiments, made with absolute quantities of electricity, and very different one from the other.

The law that we have just established, connected with that which regulates the distance, enables us to give to the expression of the attractive and repulsive force reigning between two electrised bodies this very simple form: $F = \frac{EE'}{D^2}$, calling F the force, E and E′ the quantities of electricity with which the two bodies are charged, and D the distance existing between them.

## *Torsion Electrometers.*

The knowledge of the two laws to which electric attractions and repulsions are subjected, has furnished philosophers with an excellent electrometer in the torsion balance. To apply it to this use the fixed ball is made to communicate, by means of a metal rod situate in the axis of the insulating tube that sustains it, with a small metal sphere situated on the outside of the glass cage that contains the whole apparatus. This sphere, as in ordinary electroscopes, is placed in communication with the source of electricity. The electricity arrives at the fixed ball and at the movable one that is in contact with it at the 0° of torsion and charges each of them. Repulsion immediately takes place; by means of torsion they are to be brought back to a determinate distance, always the same for comparative experiments. The angles of torsion, necessary to bring back the balls to the constant distance, represent in each experiment the repulsive forces that are proportional to these angles. But these forces being the product of the two equal quantities of electricity with which the balls are charged, it is clear that each of these quantities themselves is proportional to the square roots of the repulsive forces or of the corresponding angles of torsion. We have, in fact, in this case, $F = \frac{E^2}{D^2}$, and in the other $F' = \frac{E'^2}{D^2}$, whence $E : E' :: \sqrt{F} : \sqrt{F'}$. Thus, if the angle is four times greater in one experiment than in the other, it signifies that the quantity of electricity possessed by each of these balls, and consequently that of the source which was put in communication with them, is twice greater. Care must be taken after each experiment, and before commencing another, to discharge the two balls of the balance, by putting them in communication with the ground by means of a metal rod held in the hand. Without this precaution, the electricity that would remain after one experiment would complicate and falsify the results of the following one. It is true we need not discharge the movable ball, but leave to it a constant quantity of electricity, taking care to avoid its coming in contact with the fixed ball. Then this latter alone is placed in communication with the source; and the angles of torsion or the repulsive forces are then simply proportional to the quantities of electricity with which it is charged, quantities which are variable in this ball alone. This mode of operating is easier, and it requires no calculation; hence it is more adopted, although it is less sure on account of the loss of electricity which the movable ball always experiences, to a greater or less extent, during the experiments, notwithstanding our carefully taking the precautions that we have already pointed out when referring to the torsion balance.

Coulomb's electric balance, when employed as an electrometer, does not, it is true, immediately indicate the nature of the electricity; a determination, however, which may easily be obtained by the same means employed for other electroscopes. But the great superiority of this instrument is that it is the only one which can give an exact measure of electric forces; in addition to which, it is susceptible of great sensibility. When necessary to increase this sensibility, the metal wire, by the torsion of which the forces are to be measured, must be as fine as possible, and as long as the construction of the apparatus permits. Care is taken at the same time that the glass or gum-lac needle that carries the movable ball as well as this ball itself, are of great lightness. By these means we succeed in obtaining an apparatus of remarkable delicacy. It may even become the most delicate of all electroscopes, except, perhaps, that with dry piles, if a film unwound from a cocoon is put in place of the metal wire that carries the movable needle: we then give it a slightly different and more simple form (*Fig.* 38.). But as the waxed filament of silk does not obey the laws of torsion as the metal wires do, the apparatus is no longer an electrometer; it becomes a simple electroscope. In this case a force equal to $\frac{1}{60000}$th of a grain is sufficient to make the needle traverse an entire circumference; consequently, an arc of one degree, if traversed by this needle, corresponds to a force equivalent to only $\frac{1}{21600000}$ of a grain. We see, by this example, what a minute force we can contrive to measure, and, consequently, to what extent we may succeed in discovering the slightest traces of electricity.

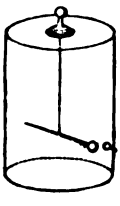

*Fig.* 38.

### *Objections to the Generality of the preceding Laws.*

Before terminating this chapter, we must add that the generality of the two laws discovered by Coulomb has been contested by an English philosopher, Sir Wm. Snow Harris. This philosopher has made a great number of observations by means of an apparatus of his invention, termed a *Bifilar balance,* in which the movable needle is carried by two waxed silk threads, the points of support of which are very near to each other, and at an equal distance from its centre of gravity. As soon as the movable needle is driven from its position of equilibrium, the two threads can no longer preserve their vertical position, and they incline in opposite directions to a greater or less degree, according to the intensity of the force by which the needle is driven; and it necessarily follows that the latter is raised. The new position that it acquires is, therefore, that at which there is equilibrium between the electric force and the force with which gravity tends to bring it back to its normal position, a force which it is easy to calculate. In Sir W. Harris's bifilar balance, gravity takes the place of the force of torsion in Coulomb's balance. With regard to the slight torsion that the silk threads may undergo, it is not necessary to take it into account, experiment having proved that its effect is completely null. The same philosopher has also employed a very delicate simple balance, in which, by means of weights placed in one of the scale pans, he produced equilibrium to the electric attractions acting upon a disc fixed to the other scale pan.

It is with these apparatus, and by greatly varying his experiments, that Sir W. Harris found that the law of the inverse of the square of the distance is not exactly sustained, except when the balls or the discs are charged with an equal quantity of electricity; when this quantity is not too feeble; and, finally, when the angular distance that separates them is greater than 9°. Otherwise, and especially if the electric charges of the two bodies are very different, the force becomes the inverse of the simple distance, within certain limits. The same causes equally modify the second law, which establishes the relation existing between the quantities of electricity, and the attractive or repulsive forces. Thus, in one experiment, the respective quantities of electricity being successively, on each of two discs, in turn 1 and 2, the corresponding repulsive forces, instead of being 1 and 4, were 1 and 5. This deviation from the law was due to the absolute intensity of the electricity being too feeble. But it is much more sensible when there is inequality in the electric charges of two bodies, and when this inequality is very great.

These numerous exceptions to Coulomb's laws are in great part due to there occurring to electrised bodies, when in presence of each other, important modifications in their electric state, by the effect of influences whose action we shall study further on,—influences which are the more sensible as the electric charges are more different. They depend also upon its being very probable that the laws in question are general only for points almost mathematical, and not for bodies of any forms and dimensions. Now we conceive that they must be so when we employ, as Coulomb did, small equal spheres for electrised bodies; for, as is demonstrated in mechanics, the action of a sphere is always the same as that which would be exercised by its centre, supposing all the forces with which the sphere is endowed were concentrated in this centre. We see, therefore, that Coulomb's laws may be regarded as general by restricting them to the cases of electrised molecules or points; and that, in other cases, they may be regarded as deviating less from the truth, as the bodies are of smaller dimensions, and as the forms approach more or less the spherical form.

Sir W. Harris has also found that, when a quantity of electricity is constant, the attractive force is inversely as the square of the surfaces upon which the electricity is diffused; and that, when the surfaces are constant, the force is proportional to the squares of the quantities of electricity. What is very remarkable is, that the distance at which a discharge between two balls, charged with contrary electricities, may take place, is simply proportional to the quantities of electricity, whilst the attractive forces are proportional to the squares of these forces.

The same philosopher has also established that the attractive force between electrised bodies depends only on the form of the two opposed surfaces, and not at all on that of the rest of the body: thus two cones, opposed by their base, attract each other, as would two circular discs equal to these bases; two hemispheres, as two spheres of the same diameter; the attraction between two circular surfaces, one greater than the other, is the same as between two surfaces equal to the smaller of the two; it is also the same between a ring and a disc, as between two rings of the same diameter. All these different results may be summed up in the following law: it is, that the attraction is directly proportional to the number of points immediately opposed to each other, and inversely to the square of their respective distances. But we should remark that these consequences are true only in the cases, in which the electric forces are equally distributed.

## CHAP. II.

### DISTRIBUTION OF ELECTRICITY ON THE SURFACE OF INSULATED CONDUCTING BODIES.

### *Electricity arranges itself on the Surface of insulated conducting Bodies.*

WHAT characterises a conducting body, is the facility with which electricity is propagated in it. As soon as an insulated conductor is touched at any point with an electrised body, all the points of the conductor are themselves instantly electrised; and, as soon as communication is made with the ground, by touching with the hand or in any other manner any point of an insulated and electrised conductor, immediately this point and all the others cease to possess any electricity. But this electricity, which is thus spread over all the points of the surface of an insulated conductor, does not penetrate into the interior; and its diffusion depends upon the surface of the body alone. Coulomb proved this by a series of experiments, in which he observed the repulsive force between the two balls of the torsion balance before and after having touched the fixed ball with a third ball insulated and unelectrised, and of exactly the same size. Whether the latter were solid or hollow, of copper, of lead, or of any metal whatever, of wood, or cork, or elder-pith, it always carried away from the one with which it had been put in contact the same quantity of electricity, namely, the half of what it possessed; and the proof is, that the repulsive force was reduced to the half of what it was before. Thus, then, in the contact of two insulated spheres, the electricity is equally divided between them, providing they are both made of conducting matter, whatever their density may be, and whether they be solid or hollow. This is a proof that electricity is only disposed upon the surface of bodies; for were it also disposed in the interior particles, the solid ball must have acquired more than the hollow one; and were it disposed in greater proportion in particles of one kind than in those of another, the metal ball would not have acquired the same quantity of electricity as the elder-pith one.

If, instead of touching the fixed ball of the balance with a sphere of the same surface, it is touched with a sphere of double the surface, its electricity is reduced to one third of what it was before, as is proved by the diminution of the repulsive force. This experiment is a new proof that the electric charge is all disposed upon the surface in insulated conducting bodies; for the little ball lost the two thirds of its electricity only because it was in contact with a globe having a surface double its own, and because the total amount of its electricity is distributed between the two spheres of unequal size, proportionately to their respective surfaces.

A still more direct experiment points out this tendency of electricity to arrange itself upon surfaces. An insulated metal sphere is electrised; it is enveloped with two hollow metal hemispheres (*Fig.* 39.), which cover it exactly, so as to become its veritable surface. These hemispheres are fixed to insulating handles, by means of which they are held. After having enveloped the sphere with them, they are removed, when not the smallest trace of electricity is to be found upon the sphere, as may be proved by touching it with a sensible electroscope. On the other hand, the hemispheres are electrised, although they were not so before the experiment; they have therefore taken from the sphere all the electricity it possessed. To remove the hemispheres is to take away the surface of the sphere; and, since in taking away the hemispheres all the elec-

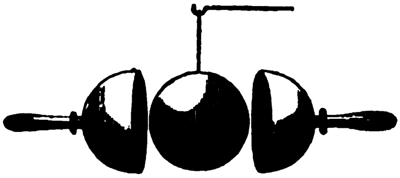

*Fig.* 39.

tricity is taken away, we have the proof that all the electric charge is entirely arranged at the surface.

To show this important principle in a more general and complete manner, we employ a small apparatus, termed a *proof-plane.* It consists of a small disc of tinsel or gilt paper, fixed at the end of a stem, or rather an insulating thread of gum-lac or glass. The length of this stem, and of the support by which it is sustained, are so calculated that the small disc may supply the place, in the torsion balance, of the fixed ball of the apparatus, and act like it, when it is electrised, upon the disc or the ball fixed at the extremity of the movable needle. A point of the surface of a body is touched by the proof-plane, and, if this point is electrised, it is immediately perceived, because the proof-plane, when carried to the balance, acts upon the movable needle. By this mode of operating we prove, that, however thin its envelope may be, a hollow metal sphere does not present the slightest trace of electricity upon its inner surface, even when its outer surface is strongly electrised. The proof-plane is in like manner introduced into a hollow cylinder or body of any form, so as only to touch its interior surface; it comes out without any trace of electricity; whilst, if it is put in contact with the exterior surface, it acquires a very decided electric charge.

The following are some of Faraday's experiments, which in an elegant manner demonstrate the same principle. A cylinder, made of metal gauze, or a trellis of iron wire with meshes not too close together, is placed upon a horizontal metal disc, resting on an insulating support; electricity is communicated to it by its interior surface:—the proof-plane indicates that the exterior surface alone is electrised, notwithstanding the facility with which the two surfaces may communicate with each other. An animal, such as a mouse, when placed in the interior, does not experience any shock, even when the entire apparatus is very strongly electrised, and vivid sparks are drawn from it.* A hollow metal cylinder is placed

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* Mr. Faraday, in his lectures, covers his most sensitive gold-leaf electroscopes with cotton or linen nets, having loose meshes, to protect them from the influence of the ambient electricity. Notwithstanding the vicinity of powerful electric

upon an insulated metal disc, of a diameter a little larger than its own; it is electrised, and its exterior surface alone gives signs of electricity. It is surrounded exteriorly with small brass columns, higher than itself, and which rest by their base upon the same metal disc; all the electricity is immediately disposed upon the exterior surface of these small columns. A third experiment consists in fixing to an insulated metal wire, bent into the form of a ring, a conical muslin bag, which forms in fact a butterfly net. It is to be electrised: no electricity is found upon its interior surface by the proof-plane. By means of two insulated silk threads, fixed to the apex of the cone, one withinside and the other without, the bag is turned inside out without being deprived of the electricity with which it is charged, so that the surface which was exterior becomes interior, and reciprocally: and it is always the surface that is outside which is alone found to be charged with electricity (*Fig.* 40.).

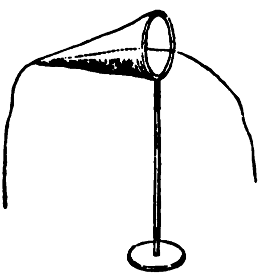

*Fig.* 40.

### *Electric Reaction of the Points of a Surface.*

It is therefore fairly proved, that upon the exterior surface of a conducting body is disposed all the electricity with which it is charged. Each point of this surface will have a certain quantity of electricity, which is termed a certain *electric reaction;* an expression by which we designate the condition of an electrised point or surface that, in the static state, does not exercise any action, but would virtually be capable of exercising one. The electric reaction of each point of the surface of a conducting body must depend, for the same quantity of electricity given to this body, upon the extent of its surface, and must be inversely to it, because all the electricity is disposed upon the surface alone. We may

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machines in action, the electroscopes experience no effect, the electricity that reaches them being entirely disposed upon the exterior surface of the tissue by which they are enveloped.

prove directly by experiment this self-evident principle, by means of a metal riband wound around an insulated metallic axis. An electroscope composed of two elder-pith balls, suspended to linen threads, is fixed at the extremity of the metal axis (*Fig.* 41.). The whole is to be electrised; and the electroscope diverges powerfully. We then unroll the riband by means of an insulating silk thread fixed at the free extremity; the balls of the electroscope approach and come almost into contact. The riband is then wound up again by means of an insulated handle fixed at the end of the axis; the balls of the electroscope immediately begin again to diverge. This double operation, which may be repeated several times without the electricity being dissipated, if the air is tolerably dry and the supports good insulators, shows that the electric reaction of the point of the surface to which the electroscope is fixed is less according as the total surface is greater, and, reciprocally, is stronger, as the surface is smaller. The mass of the body remains the same, its surface alone is varied; but as the electricity is disposed upon the surface alone, it is clear that the same quantity of electricity, in distributing itself over a greater surface, will give to each of the points of which it is composed a less electric reaction than would be possessed by each of the points when the surface was smaller.

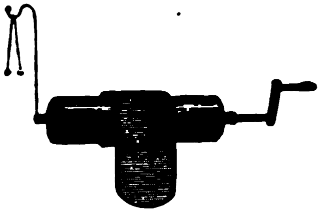

*Fig.* 41.

### *Distribution of Electricity upon the Points of different Surfaces.*

The electric reaction of a point, for the same surface, does not depend simply upon the absolute intensity of the electricity, but also upon the general form of the surface to which this point belongs. The influence of this form on the manner in which the electricity distributes itself over a surface, has been the object of numerous and interesting researches by Coulomb. It was also by touching successively with the proof-plane the different points of the surface of an electrised conducting body, and bringing it each time to the torsion balance, that he succeeded in determining the laws which the distribution of electricity obeys. In fact, when the proof-plane is tangent to a point of the surface, it is confounded with the point that it touches; it becomes itself part of the surface, and consequently takes the same charge of electricity that was possessed by the element that it covers. When the plane is taken away, it is as if there had been cut from the surface an element of the same extent as itself, and it had been conveyed to the balance with the electricity that it possessed, when it formed part of the surface. Consequently, when we wish to operate, we begin by charging the disc of the movable needle with the same electricity as that of the body subjected to experiment; we then touch with the proof-plane a point of the surface of the electrised conductor, and carry the plane to the torsion balance; we determine the angle of torsion necessary to establish equilibrium at a constant distance; we now take it away, and discharge its electricity, and then convey it to another point of the same conducting body; it takes electricity from it, is carried over to the balance; we determine the angle necessary to produce equilibrium still at the same distance. The relation existing between this angle and the preceding one, expresses the relation that exists between the two electric charges taken successively by the plane, consequently, between the electric charges of the two portions of the surface that have been successively touched.

By applying the method to determining the distribution of electricity over the surfaces of insulated conductors of different forms, we arrive at the following results: —

*Sphere.* — We find that the angles of torsion are all equal, whatever point is touched; whence we conclude, that the distribution of electricity is uniform on a spherical surface.

*Ellipsoïde.* — This uniformity ceases to exist so soon as the spherical surface becomes slightly spheroidal; experiment gives the angles of torsion greater when the proof-plane has touched a point of the surface of an ellipsoïde of revolution near to the ends of the longer axis, than when the point touched is near to the ends of the short axis. The electric reaction is greatest at the very extremities of the great axis, and least at the extremities of the small one; and the difference between the two reactions is the more considerable as there is a greater difference between the length of the two axes.

*Cylinders.*—A cylinder of 2 in. in diameter and 33½ long, terminated by two hemispheres, when touched successively by the proof-plane at the middle, or at one of its extremities, manifests electric reaction, of which the first is to the second as 1 is to 2·30. By comparing the middle point of the cylinder with a point taken at 9·8 in. from the extremity, the relations of the electric reactions were found to be as 1 to 1·25. It follows from this that the electric reaction varies but little from the middle of the cylinder to 2 in. from its extremities; and that it increases from this distance to the very extremity, where it is at its maximum.

### *Plane Surfaces and Prismatic Bodies.*

Thin plates, whose length is at least double their width, present an electric reaction which is very nearly constant from the middle to about an inch from the extremity; this reaction goes on increasing, from this distance, to the extremity itself. At the extremities of the plate, the reaction is double of what it is in the middle; and, if the proof-plane is placed on the prolongation of the plate, it is quadrupled. In a circular plate the electric reaction goes on increasing from the centre to the edges; however, this increase does not become very sensible till about an inch from the edge: at about a third of an inch from the edge the reaction is double what it is at the centre; it is triple at the edge itself. The increase of the electricity towards the extremities is found in prismatic bodies, especially when they are very elongated. It exists, in like manner, toward their edges.

### *Spheres in contact.*

If the spheres are equal, the distribution of the electricity greatly resembles what it is upon a cylinder. Thus in a series of twenty-four globes, placed in contact in a straight line, the electric reaction varies very little in the middle globes from those which précede the latter ones, but considerably between the two extremes and those which immediately follow. Thus the electric reaction of the extreme globes is to that of the middle globes as 1·75 : 1·00. With two equal spheres in contact, the electricity goes on increasing from the point of contact, where it is null, to the extremities of the common diameter that passes through this point,—extremities where it is at its maximum. If the spheres in contact go on diminishing in size, from one end to the other, the electric reaction goes on increasing from the largest to the smallest, where it is most considerable.

### *Power of Points.*

The electric reaction is so considerable at the extremity of a point that the electricity escapes from it, to be carried through the air to the nearest bodies, or to diffuse itself simply in the atmosphere. This effect of points is a consequence of the distribution of electricity. We have seen, indeed, that in an ellipsoïde the electric reaction is greater at the extremity of the greater axis than at the extremity of the small one; and that the difference is the more considerable as the two axes differ the more from each other. It is the same with respect to a cylinder, which, when it is extremely long in regard to its diameter, presents at its extremities a very great electric reaction. In this case, as in that of the very elongated ellipsoïde, this reaction may become such that the electricity escapes. This is exactly what happens with a point, which may be regarded as being the extremity of a very elongated ellipsoïde or cylinder, or rather of a series of spheres in contact, whose dimensions go on gradually decreasing.

### *Methods for taking account of the Loss of Electricity.*

The experiments upon the distribution of electricity are subject to a source of errors, which we must know how to take into account, and which arise from our not being able to touch, at the same moment of time, the two points of an electrised conductor whose electric reactions we are desirous of comparing: now, during the time that has elapsed between the instant when one of the points was touched, and that when the other was touched, a portion of the electricity with which the body was charged has escaped, either by the air, which is always more or less moist, or by the supports, which are never perfectly insulating. It follows that the experiment gives, for the second point touched, an electric reaction relatively more feeble than that which should have been recognised.

Coulomb endeavoured to take into account this cause of error by estimating beforehand what the loss should be. With this view he distinguished the part of the loss that is due to the ambient air, from that arising from the imperfection in the insulating property of the supports. With regard to the influence of the former cause, he found that it depended on the degree of the humidity of the air; and he succeeded in drawing out tables, which give for each degree of the hygrometer the corresponding loss of electricity; namely, the relation existing between the quantity which the body loses in one minute, and that which remains to it after this minute. In order to estimate the part played by the supports in the loss of electricity, he made various experiments with threads of different substances, such as silk, glass, wax, gum-lac, &c., all of the same diameter and of variable lengths. He discovered that the insulating property of these threads varies for each with the intensity of the electricity and with their proper length, —that there exists consequently a certain degree of intensity of electricity, for which they are perfectly insulating: but that this degree depends upon their length and their nature. Thus, a thread of gum-lac insulates a quantity of electricity ten times greater than can be insulated by a silk thread of the same diameter. A thread of any nature whatever insulates a quantity of electricity which is proportional to the square root of its length.

These laws are not general, for they are only verified if the supports are long and slender like threads; moreover, they are often altered by the property that supports of a certain nature possess, such as those of glass, to attract moisture from the air upon their surface, which notably diminishes their insulating property.

To take account of the loss of electricity, it is therefore better to employ another method, which is that employed by Coulomb in preference in his experiments; it is the method of alternatives or means. It consists in this: we first touch one of the points of the surface of the electrised body with the proof-plane, and convey it to the torsion balance; then, at the end of a certain time, as short as possible, we touch another point and operate in like manner: we touch a second time the first point at the end of a time equal to that which elapsed between the two experiments. We take the mean of the two angles of torsion that were obtained by touching the first point of the surface twice: this mean angle is the same as that which would have been obtained directly by experiment, had we been able to touch the first point at the same instant that we touched the second. In fact, the loss of electricity being approximately uniform during a certain time, the same quantity must have been lost in the interval that separated this third experiment from the second, as in that which separated the first from the second. The mean of the results of the first and the third experiments represents, therefore, an experiment made with an electric state similar to that under the influence of which the second was made.

Among the experiments of Coulomb, of which we have already spoken, I choose the following, which will very well enable us to understand the method of alternatives. It refers to an insulated steel plate, 12 inches long, 1 inch wide, and $\frac{1}{25}$th inch thick. The proof-plane was 1 inch wide. Coulomb first applied the proof-plane to the middle of the plate, then to 1 inch distance from the extremity; and he obtained the following results:—

| | | |
|---|---|---|
| Touched at the middle | 370° | |
| 1 inch from the end | | 440° |
| the middle a second time | 350° | |
| 1 inch from the end a second time | | 395° |
| the middle a third time | 320° | |
| mean | 347° | 417°·5; |

whence we conclude that the relations between the electric reactions of the middle of the plate, and of the part 1 inch from the edge, are as 347° to 417°·5, or as 1 to 1·20.

### *Employment of the Proof-plane in the preceding Experiments.*

The employment of the proof-plane for determining the relative quantities of electricity that are found on the different points of the surface of the electrised conductor, has given rise to various remarks and to certain objections, which we cannot pass by in silence. We have admitted that as this plane becomes, so to speak, a part of the surface upon which it is superposed, to take it away is virtually to take away this part of the surface, and also the electricity with which it is charged. This manner of regarding the part played by the proof-plane is contested. Coulomb admits that it is charged in all with a quantity of electricity double that possessed by the part of the surface with which it is placed in contact, so that each of its two faces has as much. He bases his assertion upon the fact, that if an electrised and insulated sphere is touched with an insulated but unelectrised disc, of which one of the two surfaces is equal to that of the sphere, the latter, after the contact, has only one third of the electricity that it had before; the disc, therefore, has taken the double of what remained, an effect that is due to its two surfaces, which are each equal to that of the sphere, becoming each charged equally with electricity. This is exactly the case with the proof-plane, which is itself merely a disc. We must observe, however, that if this disc is sufficiently small to be confounded with the element of the surface upon which it is applied, the former mode of regarding its effects is more accurate than the latter, which supposes a disc of the same surface as the body with which it is placed in contact.

But whatever may be the absolute quantity of electricity that the proof-plane takes, the important matter is, that it always takes a quantity proportional to the electric reaction of the part of the surface with which it is placed in contact. But this actually does take place, as is proved by many of

Coulomb's experiments, especially the following. We take two insulated conducting cylinders, perfectly similar. We electrise one of them, and determine with the proof-plane the relation existing between the electric reaction of a point situated at the middle of its length, and that of a point situated at its extremity. We then touch the electrised cylinder with the one that is not electrised; it is evident that the total electricity must be divided between the two with perfect equality; consequently, the one that was electrised has in each of its points only one half of the electricity that it had formerly; but the relation between the electric reaction of the point taken at the middle and of the point situated at the extremity, must still remain the same. The proof-plano confirms this conclusion; a proof that, whatever may be the absolute quantity of electricity, it takes from it a quantity proportional to that possessed by the part of the surface upon which it is applied.

We may add, that the absolute quantity of electricity that the disc carries away is always very small in relation to what the electrised body possesses: so that, without sensible error, we may affirm that the contact of the plane, when it has only been repeated for an inconsiderable number of times, in no degree modifies the electric state of the body.

More serious objections have been made by Sir Wm. Snow Harris to the employment of the proof-plane: numerous experiments have proved to him that the quantity of electricity, taken away from the surface of a body by means of a small and thin insulated disc, may be influenced by the position of the point of application, independently of the quantity of electricity possessed by this body at the point touched; so that the same quantity may exist in two different points, and yet the proof-plane may be charged unequally when it is put in contact with these two points. It may even happen that, by the effect of the action of the neighbouring points, the proof-plane is not at all charged, even when the element of the surface with which it is placed in contact is strongly electrised. These singular anomalies are due to the effect of action at a distance, or the induction exercised by the electrised bodies upon those that are not so; phenomena, the study of which forms the subject of the following chapter.

But before terminating this, we may add that Sir W. Harris's objections cannot shake the confidence that philosophers place in the results obtained by Coulomb, at least in the more simple cases, such as those which concern the distribution of electricity in conducting bodies of a regular form. Perhaps where bodies of irregular form, or where many bodies in contact, are concerned, there might be a new study to make; but what process can we employ if we must reject this of the proof-plane? I will permit myself to point out one, which, if it has not the precision nor the sensibility of the latter, has at least the advantage of manifesting to the eye in a direct manner the law that is followed in the distribution of electricity. It consists in taking a simple electroscope or electric pendulum, the very small and very light ball of which is charged with the same electricity as the body to which it is brought near. We then see, in presenting it to the different points of the surface of the body, that it is more or less repelled, according to the points in front of which it is placed. Thus, with an ellipsoïde, the distance to which it is repelled goes on increasing from the extremity of the small axis to the extremity of the large. With a sphere, it is everywhere equally repelled. The slightest differences in the electric reaction are shown in a very sensible manner by this process, which, although it is not in itself free from all the objections presented by the employment of the proof-plane, would perhaps be susceptible of being usefully perfected.

# CHAP. III.

## ELECTRICITY BY INDUCTION.

### *Developement of Electricity by Induction in an insulated Conductor.*

If an electrised body is presented to an insulated conducting body, signs of electricity are developed in the latter, even though the two bodies are at a greater or less distance apart. These electric signs disappear as soon as the electrised body is withdrawn. This phenomenon constitutes the developement of electricity at a distance by influence or by induction.

To make this experiment carefully, we take an insulated metal cylinder, B (*Fig.* 42.), and attach small pith ball electroscopes to different points of its surface. We gradually bring another electrised body, the sphere A for example, near to this cylinder, taking care that the cylinder is placed so that one of its extremities faces the electrised body. When the cylinder is not more than an inch or so distant from the electrised body, the electroscopes are seen to diverge, at least those that are placed at its two extremities; for the electroscopes that are attached to the intermediate points diverge the less as they are more distant from the two ends, and there are even some that do not diverge at all. If the electrised body is withdrawn, the balls of the electroscope fall back into a natural position, and all trace of electricity

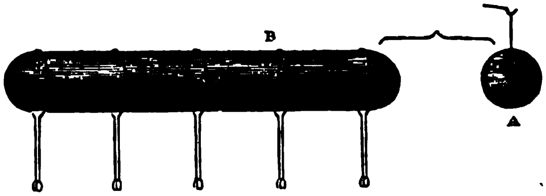

*Fig.* 42.

disappears. If the electrised body is again brought near, the divergence recommences in the same manner.

This is not all. If, whilst the electroscopes are diverging, the electrised ball of a simple electroscope is brought near them, we perceive that the electricity which they manifest is not the same at one of the extremities of the cylinder as it is at the other. At the extremity nearest to the electrised body, it is of the contrary nature to that of this body, negative if the former is positive; at the more distant extremity it is of the same nature. To become better acquainted with the electrical state of the cylinder, whilst it is under the influence of the electrised body, we must touch successively the different points of its surface with the proof-plane, that we employed in studying the distribution of electricity. We thus find that the two contrary electricities are at their maximum at the two extremities of the cylinder; that, setting out from these extremities, they go on each diminishing in intensity up to a point where they are null, and which on this account is named the *neutral point.* The neutral point is never in the middle of the cylinder; its position depends on the distance at which the two bodies are placed with relation to each other, and on the intensity of the electric charge; but it is in every case nearer to the extremity that is contiguous to the electrised body.

The following is an experiment by a German philosopher, Mr. Mohr, who has studied this subject with much care, a subject on which much light had been already thrown by the researches of Coulomb. The insulated cylinder was 65 c. m. long; the electrised body was placed at the distance of 1 c. m. from one of the extremities of the cylinder; the neutral point was found on the surface at a distance of only 1 c. m. from this extremity. Thus the negative electricity (the electrised body being positive) occupied a portion of the surface of the cylinder equal to only 1 c. m. in length, whilst the positive occupied the other part, 64 c. m. in length. An increase in the respective distances of the two bodies, as also a diminution in the electric charge of the electrised body, would have changed these proportions, and would have augmented the space occupied by the negative electricity, and consequently diminished that occupied by the positive, without, however, this latter ever ceasing to be superior to the former.

In the preceding experiments care must be taken to place the electrised body at a sufficient distance from the insulated conductor, so that no portion of the electricity of the former shall pass into the latter. If, indeed, this distance is too small, a spark is seen to pass between the two bodies, a proof that a part of the electricity of one has passed into the other. It may even happen, if the air is moist, that this passage of electricity takes place gradually, in an invisible manner; the insulated conducting body is then electrised by communication and not by induction, which may be easily recognised; for, after having been withdrawn from the influence of the electrised body, instead of returning to the natural state, it is found charged with an electricity of the same nature as that of this body.

But if, on taking the necessary precautions to prevent this transmission of electricity from taking place, we connect the insulated conductor with the ground whilst it is subjected to induction, we find it, after the induction has ceased, to be charged with an excess of electricity of a contrary nature to that of the electrised body: negative, for example, if the latter is positive. Only we must take care to cut off the communication of the insulated conductor with the ground, before withdrawing it from induction; for, without this precaution, its negative electricity would pass away, as its positive had done.

An important remark to make is, that whilst the electrised body electrises a conductor by induction, it does not itself experience any other loss of its electricity than what results from the imperfection of the insulating supports and from the contact of the air; and, consequently, what it would have undergone had it been alone. This may be easily proved by touching the electrised body with the proof-plane at the same point both before and after it has exercised its inductive action.

The phenomena that we have just described are a natural consequence of the theory of two electric fluids, that we have laid down in the First Chapter. These two eminently subtil fluids are endowed with the property that the molecules of the one attract the molecules of the other, whilst the molecules of the same fluid mutually repel each other. We must admit that they both pre-exist in a conducting body; because we can make them appear there without communicating any electricity to this body. But they pre-exist there in such proportion that, when abandoned to themselves, they are mutually neutralised, without, however, destroying each other. They constitute what is called *neutral fluid;* and the body that is possessed of this neutral fluid only, is said to be in the *natural electric* state; whilst it is positive, or vitreous, if it possesses an excess of positive electricity; negative, or resinous, if it possesses an excess of negative electricity.

When a body, positively electrised, is presented to an insulated conductor that is in the natural state, the positive electricity of this body decomposes the neutral fluid of the conductor, attracting the negative fluid and repelling the positive. The two electricities being able to travel freely in the conductor, the negative goes into the part nearest to the electrised body, which attracts it, and the positive is repelled into the more distant part. But the moment the electrised body is removed, the two electricities that are developed in the conductor are no longer subject to any thing but their mutual attraction; and, as they are in equal proportions, they are neutralised, and again constitute the neutral fluid. If the conductor is touched whilst under the influence of the electrised body, its positive electricity, being driven into the ground by that of the same nature possessed by the electrised body, is not regained after the influence has ceased, to constitute again with the negative the neutral fluid. On this account it is that the conductor presents an excess of negative electricity.

After having shown how the phenomena of induction enter into the theory, we will return to it again, either to study them under different forms, or to explain some particular facts that depend upon them.

### *Developement of Electricity by Induction in several successive Conductors.*

We may observe first, that, by means of a single electrised body, we are able to develop electricity by induction in a very great number of insulated conductors, such as metal cylinders. We have only to place them one after the other in the same line, so that the extremities of each of them shall be at the same distance from the extremities of the one that precedes it and of the one that follows it. The electrised body, for example, a positive metal sphere, is brought near to the anterior extremity of the first. Each metal cylinder is immediately found to be electrised positively in the extremity that is most distant from the sphere, and negatively in the nearer extremity.

If we touch the last of the cylinders with the hand, we enable its positive electricity to pass into the ground; and it commonly happens that the negative electricity of this latter, being rendered more free by the departure of the positive, by which it was kept back, unites through the air under the form of a spark with the positive of the last but one; the negative of the latter with the positive of the following one; and so on to the first, whose negative electricity combines with the positive of the electrised sphere. These sparks, which thus escape simultaneously through the air, are a sign of the neutralisation of the contrary electricities; whence it follows that each of the bodies, after the phenomenon has taken place, has returned to its natural state. If we take away the electrised sphere, without having made any of the cylinders communicate with the ground, the neutralisation of the two cylinders, instead of occurring from one to the other, takes place in each of them separately, and they are thus also found in the natural state, without there having been any sensible exterior effects.

### *Effects of Points in the Phenomena of Induction and in the Electrical Machine.*

The effect of points in the phenomena of induction is very remarkable. We have seen that the pointed form determines, in the part of the conductor that possesses it, a charge or electric reaction so much more considerable than in the rest of its surface that the electricity most frequently escapes from it to go either into the air, or upon the nearest conductors. So, when an electrised body is presented to a conductor, that is terminated in a point and insulated, the electricity of the contrary nature, that is developed by induction in the conductor, by accumulating at its point, escapes from it to neutralise through the air that of the electrised body: thus it is that the conductor of an electrical machine may be discharged, or may be prevented from charging, by presenting to it at a distance of eight or ten inches, or even further, a metal point, held in the hand. In the working of the electrical machine a phenomenon of the same kind takes place. Each part of the glass plate that has been electrised by friction passes successively before the points of the insulated conductor of the machine, whose natural electricity it decomposes by induction, attracting the negative and repelling the positive. The negative, being accumulated at the points, escapes from them to neutralise the positive of the plate, which, on passing anew between the cushions, regains, by the friction it there undergoes, the positive electricity it has lost. With regard to the positive electricity of the conductor: being deprived of the negative that has escaped from it by the points, it is no longer able to produce the neutral fluid, and remains consequently in excess; on this account it is, that after a certain number of turns the insulated conductor of the machine is found to be charged with positive electricity. It is not, therefore, as has often been erroneously said, the positive electricity of the glass plate that has passed into the conductor: it is the negative of the conductor that has passed out by the points, and has left there the positive, with which it formed the neutral fluid, and from which it has been separated by the influence of the plate. This inductive action continues to accumulate positive electricity in the conductor until each point of the surface of the latter has a reaction equal to what each point of the surface of the glass acquires by its friction against the cushions. Indeed, when this limit is obtained, there is no reason why the electricity of the conductor should not act just as much upon the plate, as the electricity of the plate upon the conductor. There is, therefore, equilibrium; and the conductor takes no further charge: we can therefore understand that the charge of the conductor must be higher according as the friction determined upon the plate is more energetic; an energy which itself depends on the quality of the glass, on that of the rubbers, on the manner in which they are more or less properly adjusted, on the degree of dryness of the air, and on the greater or less care that has been taken to dry and clean the surface of the plate itself.

### *Action at a Distance by Induction upon Electroscopes.*

It is also to the developement of electricity by induction that we must connect the fact of its not being necessary to touch an electroscope with an electrised body in order to act upon it, but that it is sufficient to approach it with this body at some distance. Indeed this body, by its influence, decomposes the natural electricity of the metal parts of the electroscope situated exteriorly, attracts near to it the electricity of the contrary name to its own, and repels that of the same name into the gold leaves, the blades of straw, or other light substances that are in communication with this metal part. The electroscope is thus found charged, while under the influence of the electrised body, with the same electricity as that possessed by this body, but, in order to preserve it, it must then be touched with the body itself. However, if, whilst it is subjected to the inductive action, we touch it with the finger on any part of its exterior metal part, it is then found charged with an electricity contrary to that of the electrised body, provided we have taken care to remove the finger before withdrawing this body. The fact is, the electricity of the same name, in obeying the repulsive action, instead of having been driven into the gold leaves, has escaped away into the ground by the intervention of the body and finger of the observer. There therefore remained in the instrument, when it was withdrawn from the inductive action, an excess of the contrary electricity; which caused its gold leaves to diverge. This is a more expeditious and more convenient mode of charging the electroscope: but we must not forget, when we adopt it, that the electricity which it indicates is of the contrary nature to that of the body with which we acted upon it.

## *Electrophorus.*

An instrument, founded upon the principle of the developement of electricity by induction, and which may in many cases advantageously supply the place of the electrical machine, is that contrived by Volta, the *Electrophorus.* It is composed of a cake of resin poured into a circular mould of wood or metal of any diameter. A disc of metal, or of wood covered with tin, and of a less diameter than that of the cake, is furnished with an insulating handle fixed at its centre perpendicularly to its surface. This disc is bounded by a rounded edge, so as to avoid sharp corners, by which the electricity would run the risk of escaping (*Fig.* 43.). The cake of resin is electrised by beating its surface with a cat's skin; the metal disc is then placed upon it, holding it by the ~~metal~~ handle; we touch it with the finger, and, when it is raised, we find it charged with positive electricity. We may repeat the experiment a very great number of times, and even at several days apart, without its being necessary to electrise the cake anew. The latter preserves the resinous electricity that has been developed upon its surface for a very long time, on account of its insulating property, and its small tendency to attract moisture from the air. We must only take care to let the metal disc remain upon it, the presence of which prevents the loss of electricity that would result from the contact of the air. It is not necessary to add that it is the negative electricity of the cake which, by decomposing the natural electricity of the metal disc, drives the negative into

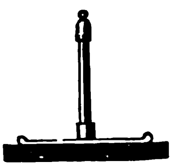

*Fig.* 43.

the ground by means of the finger, and attracts the positive, which is found in the disc, as soon as it is raised. If we raise it without having previously touched it with the finger, we then find it charged, not with positive electricity, but with a certain quantity of negative electricity, which it has taken from the cake by simple communication. This quantity is always very feeble on account of the difficulty the electricity experiences in quitting the resin.

The positive electricity with which the disc is charged is sufficiently energetic to give strong sparks; and hence it is used for inflaming gases and for a great number of experiments. There is also an apparatus called the *electric lamp*, wherein a jet of hydrogen is inflamed by the spark given by an electrophorus, the metal disc of which, by means of a silk cord fixed to a stop-cock whereby the gas escapes, is detached from the cake of resin by the same movement that opens the stop-cock. An insulated conductor, that just touches the disc when it is raised by the movement of the stop-cock, is terminated, towards the jet of hydrogen, by a fine point placed opposite, and at a very small distance from a similar point communicating with the ground. It is between these two points that the electric spark passes, which thus meets and inflames the jet of hydrogen gas. This gas is itself produced afresh in the apparatus, in proportion as it passes away, by means of a zinc rod, which is acted upon by water acidulated with sulphuric acid (*Fig.* 44.); care, however, must be taken, in order that the instrument may work well, to electrise the cake of resin from time to time with a cat's skin.

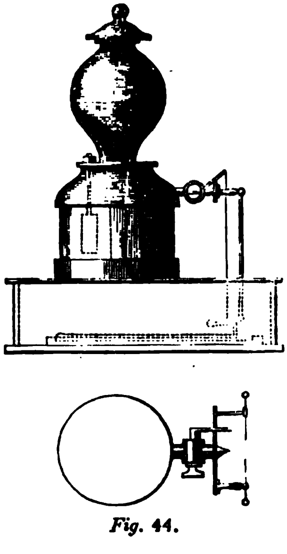
*Fig.* 44.

### *Explanation of the Attraction of light Bodies by electrised Bodies.*

The primitive phenomenon of electricity, that of the attraction of light bodies by an electrised body, is less simple than is commonly supposed. It is a true phenomenon of induction. There is no attraction, neither is there any repulsion, between an electrised body and a body that is not so; there is none except between bodies both electrised. Thus when a stick of rubbed wax is presented to light bodies, such as bits of paper or pith balls, the stick of wax decomposes their natural electricity, repels into the ground their negative electricity; they, still retaining an excess of positive electricity, obey the attraction which a negatively electrised body must exercise on a body positively electrised.

In support of this manner of interpreting the phenomenon, we may quote the following facts: —

The first is that, if the light bodies are of an insulating material, such as resin or glass, they are not attracted by an electrised body, because their natural electricity cannot be decomposed so easily as when they are conductors. The second fact is, that if the shreds of paper or the other light bodies rest upon an insulating surface, such as a plate of glass or resin, they are no longer so easily attracted, because the one of their two electricities that is repelled, cannot quit them to pass into the ground: then the other electricity cannot but with difficulty overcome by its attractive power the repulsive force of the former. That there may be no attraction at all, it is necessary that the light bodies be thin and small; pith balls, if their diameter exceeds the tenth of an inch, are attracted when the electrised body is brought very near to them, even when they are placed upon an insulating surface because the contrary electricity to that possessed by the body is, in a portion of their surface, that is sensibly nearer than is that portion in which the electricity of the same name is accumulated.

### *Movements produced by Electric Induction, and the Electric Bells.*

A very interesting and very elegant experiment consists in placing upon a metal disc, provided with a foot communicating with the ground, small pith or cork balls, and covering the whole with a bell-glass, whose upper part is open, and provided with a collar of leathers, through which a rod passes tightly, and carries at its lower extremity a disc of metal similar to the former. The disc is placed at a distance of six or eight inches from the former: — in each case we determine by trial the most convenient distance. The rod, and consequently the upper disc, is put into communication with the conductor of an electrical machine in action (*Fig.* 45.); by the effect of the induction that we have described, the positive electricity attracts the small pith balls, which, on arriving into contact with the lower surface of the disc that is constantly positive, discharge themselves of the negative electricity, which they had acquired by induction, and take from it positive by communication, which, as they are immediately repelled, causes them to fall on the lower disc; and, as this is in communication with the ground, it takes away from them their positive electricity. Being restored to their natural state, their natural electricity is again decomposed; they are again attracted and repelled; as long as the electricity of the machine arrives at the upper disc, they continue to execute these alternate movements, bounding against each other in a thousand ways. This experiment, which seems to be nothing more than a simple toy, owes the celebrity it has enjoyed to its having given rise to a theory of hail, conceived by Volta, and which we shall have occasion to set forth hereafter. We may make the experiment more simply by using a bell-glass, whose interior surface is to be electrised by touching its different points with the conductor of an electrical machine in action. We then

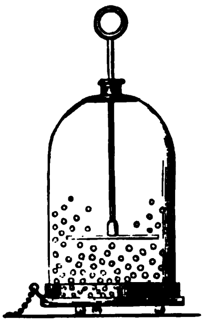
*Fig.* 45.

invert it upon a table over a heap of small pith balls; and they immediately begin dancing, being attracted and repelled as they successively are by its surface, which, on account of its insulating property, preserves for a long time the electricity that has been given to it (*Fig.* 46.).


*Fig.* 46.

The place of the pith balls is sometimes supplied by pieces of cork, to which any form is given, for instance, that of little men: this is called the "dance of puppets." It suffices in this case to place two discs, one of which is in communication with the conductor of the machine, and the other with the ground, parallel with each other, at a distance of about six or eight inches, but which may be greater or less according to the power of the machine; it is between these discs that the movement takes place. In place of the puppets we may, in like manner, introduce a gold leaf, that will be seen to fly about between the metal discs (*Fig.* 47.).

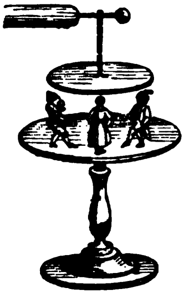
*Fig.* 47.

An apparatus, founded upon the same principle, and which has some importance because it is employed in several countries to detect the presence of an electrised cloud, is the *electric bell* (*Fig.* 48.). A small metal ball affixed to the end of a silk thread, the other end of which is attached to a horizontal support forming part of the apparatus, is suspended between a bell communicating with the ground, and a similar bell placed in communication, by its support, with the source of electricity, for example, the conductor of the electrical machine. The small ball oscillates between the two bells, as the pith ball did between the two discs, and, by its repeated blows, it gives rise to a succession of musical sounds. The same apparatus sometimes carries several metal balls,

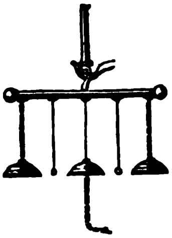
*Fig.* 48.

similar to the preceding and similarly suspended, and also the number of bells necessary for the backward and forward movements to operate. The whole is so arranged that there is alternately a bell and a metal ball, and that one of the two bells, between which each ball is placed, communicates with the ground, and the other with an insulated support for transmitting the electricity to it.

### *Effect of Electricity by Induction upon a Jet of Water.*

Among the numerous experiments to which the developement of electricity by induction gives rise, we shall quote one or two more that are interesting in their application.

At a short distance from the conductor of an electrical machine in action, we cause drops of water to fall upon an insulated plate, communicating with an electroscope, from a metal receptacle which is held in the hand, or which is made to communicate with the ground in some other manner. The drops of water, after they fall, indicate an electricity of a contrary nature to that of the conducter. This same effect is produced in a still more sensible manner by directing upon the metal plate the jet from a pressure fountain, which is held in the hand; taking care that the jet passes near the conductor of the machine. In these experiments, the drops of water that come out from the vessel have their natural electricity decomposed, by the influence of the conductor, before separating from the jet; their positive electricity is driven into the ground, the negative remains in the water, and consequently affects the electroscope. Professor Balli obtained the same result by substituting, for the electricity of the machine, the positive electricity with which the atmosphere is constantly charged. He collected in an insulated receiver in communication with an electroscope alone, the drops of water that fell from a very elevated jet, and he always found them charged with negative electricity: this was an effective induction produced by the positive electricity of the air. It is probable that the negative electricity, which Volta, Trallis, and other philosophers have found in the water that falls from natural cascades, has the same origin, and that it is not due, as they appear to have believed, to the terrestrial globe whence these drops came being itself negative. At least we cannot draw this conclusion from the observation that we have just related, because it is very naturally explained by the simple intervention of the positive electricity of the atmosphere.

### *Action of Electricity by Induction on organised Bodies.*

A very remarkable effect of electric induction is that which is presented by organised bodies, when exposed to it. Galvani was the first to remark that a frog, whether living or killed less than four or five hours previously, when suspended at a certain distance from the conductor of an electrical machine, but not in direct communication with it, experiences strong commotions when the conductor is charged, and still stronger when, after it has been charged, we discharge it by drawing a spark. These commotions are due, the former to the decomposition of the natural electricity, which takes place in the body of the animal by the influence of the positive electricity of the machine; the latter, which is much the more energetic, to the sudden recomposition of the two electricities which is brought about in the frog itself when the cause of the induction suddenly ceases by the discharge of the conductor of the machine. The commotions of this kind, which are impressed upon the body of the animal as a sort of convulsion, are called the *return shock.*

In presence of a powerful machine, a man experiences similar shocks. When two persons are placed near the conductor, if one of them draws sparks, the other each time experiences at the same instant a violent shock, without any trace of electricity passing between him and the conductor; this is also the effect of the return shock. When we shall be referring to the effects of lightning, we shall see that a storm cloud may act in the same manner and strike by lightning, as well by the *return shock* as by the *direct shock.*

Independently of this effect, a person placed near the conductor of an electrical machine experiences extraordinary sensations in the face and hands whilst it is being charged, his hairs stand up more or less strongly, a spider's web seems to cover his face: these effects are all due to the decomposition of the natural electricity of the observer by induction at a distance, and to the escape of the two separated electricities, the one into the ground, the other through the air towards the electrised conductor.

# CHAP. IV.

## DISGUISED ELECTRICITY.—CONDENSERS AND LEYDEN JARS.

### *Principle of disguised Electricities.*

IN the preceding chapter we have studied the effects of induction, by directing our attention only to the body upon which it operates. But the body that produces it itself undergoes a kind of induction, resulting from the action exercised upon its own electricity by the electricity, that it has developed in the neighbouring conductor. This double mutual influence of the two electricities gives rise to the phenomena of disguised electricity. In studying them we shall make use of an apparatus composed of two perfectly similar metal discs eight or ten inches in diameter, placed vertically each on an insulating glass support; the two supports are themselves fixed by their lower extremity to a piece movable in a slide, so that, with a handle or by any other means, we can separate the two discs or bring them as near as possible; the two faces always remaining perfectly parallel. Each disc carries a pith-ball electroscope. We shall call one of the discs A, and the other B (*Fig.* 49.). We electrise A, and bring towards it B, whose natural electricity is immediately decomposed by the influence of A, which we will suppose positive. We touch B with the finger, in order to allow of the escape of its positive electricity; the electroscope of B immediately ceases to diverge, and that of A gives now only a very feeble divergence. But if A and B are withdrawn from each other,

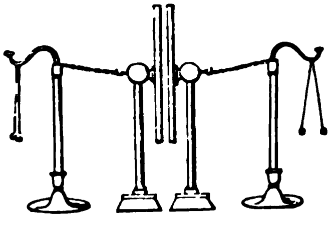

*Fig.* 49.

taking care not to touch them, we immediately perceive the two electroscopes to diverge strongly; that of B indicates negative electricity, that of A positive. We again bring the discs near to each other, and the divergence of the electroscope of B again ceases, and that of the electroscope of A diminishes. The same phenomenon may be produced several times, if the air is very dry and the supports are good insulators; for, without this precaution, the loss of the electricity, with which the discs are charged, would be brought about rapidly, and the effects would very quickly cease. The total disappearance of the electricity of B, and of the greater portion of that of A, is only apparent, since we have merely to separate the two discs from each other, for the two electricities to appear again with all their intensity; they are called *disguised* when they are in that latent state resulting from the proximity of the discs. This state is attributed to the tendency that the two electricities would have to go towards each other by virtue of their mutual attraction, a tendency which they cannot obey on account of the resistance opposed to their union by the interposed body of insulating air. This tendency carries them entirely to the portions of the surfaces of the two discs that are contiguous; and then they are neutralised, as it were, the one by the other: we say *as it were*, because if they were actually neutralised they would no longer re-appear separately when the two discs are separated. This circumstance it is that establishes the difference between the two states, and which has caused the name of disguised electricities to be applied to the phenomenon on which we are engaged, to distinguish it from the state of neutralised electricities.

We have said that, whilst in the disguised state, not any of the electricity of B was sensible, and a small portion only of that of A remained apparent. This portion is named *free electricity*. It arises because A, on account of the distance that separates it from B, has not been able to develope by induction in B a quantity of negative electricity as considerable as that which it possesses itself. It follows from this, that, whilst the latter, notwithstanding the distance and because it is the stronger, is able to disguise all the negative of B, the latter, being more feeble, is not able in its turn to disguise all the positive of A; there remains therefore upon A a certain proportion that is not disguised, but which serves, with that which is so, to disguise all the negative electricity of B. We touch A with the finger; immediately the small quantity of free electricity that it possessed disappears; the disguised does not pass away into the ground, being retained by the action of B; at the same instant when the electroscope of A ceases to diverge, that of B diverges in its turn,—a proof that the electricity of B is no longer disguised *in toto;* and which takes place because A has lost a portion of its electricity. One part of the electricity of B has thus become free in its turn, without, however, there having been a diminution in the total quantity of electricity that was possessed by the disc, a quantity which continues to disguise the same proportion of that of A. This proportion has become the total, since its free portion has been taken from A. If B is now touched, or the part of the electricity that had become free on this body is removed, then a portion of that which was disguised on A by the action of the total of the electricity of B, becomes free: this double effect is made manifest by the absence of divergence in the electroscope of B, and the appearance of a slight divergence in that of A. We may again take away from A this new dose of free electricity, and make one arise immediately upon B; then touch B, and so on, until, having gradually made all the electricity pass away from each of the discs into the state of liberty by successive small doses, we have completely discharged them. This is what we term the *slow recomposition* of the two electroscopes. The *sudden recomposition* is that which takes place when, on uniting the two discs by the two branches of a discharging rod, we allow the two disguised electricities to unite immediately through a thin stratum of air, which they do by giving rise to a spark, that darts with much brilliancy and noise.

The disguise of the electricities is the more complete when the discs are nearer to each other, which is due to the mutual attraction of the two electricities becoming stronger as the distance is feebler. But we must leave a stratum of air sufficiently insulating, and consequently sufficiently thick, to oppose the direct reunion under the form of a spark of the two opposed electricities: thus the distance at which the two discs may be brought in respect to each other, depends on the intensity of the electric charge that is given to A, and on the degree of humidity, and consequently on the insulating faculty, of the air.

However, much more decided effects may be obtained by putting, in place of the stratum of air, a substance, such as glass or resin, which is perfectly insulating, even when it is in a very thin plate. It is then an easy matter to bring the discs to a very small distance from each other, without running the risk of producing the neutralisation of the two electricities. It hence follows that A developes by induction in B a much greater quantity of negative electricity; and, in its turn, a much higher proportion of the electricity of A is disguised. In practice, the choice of this insulating substance, and the distance to be given to it, depends upon the object in view. This object is two-fold, and has given rise to two apparatus, known under the name of the *Condenser* and the *Leyden Jar*. We will commence by explaining the common principle upon which they depend; and will then pass on to the differences, by which they are characterised with regard to the object, and consequently with regard to the form, that is given to them.

### *Theory of the Condenser and the Leyden Jar.*

We have seen that, with any electrical machine, a conductor cannot acquire a stronger charge of electricity than that which is impressed upon the different points of its surface by an electric reaction equal to that of the plate. It is the same with every source of electricity. The charge, therefore, varies with the electric reaction of the source; but the total quantity of electricity accumulated upon an insulated conductor may be increased by the effect of the same source, by extending the surface of this conductor. In fact, as the electricity with which a conductor is charged is able to move freely in it, it is enough to touch it in one point, in order that the whole may enter it; and, as each element of the surface has the same electric reaction, namely, that of the source, the more this surface shall be extended, the more elements there will be having the same electric reaction; the greater, consequently, will be the sum total of electricity. It was on this principle that Volta contrived a system of electric conductors terminated by hemispheres, and suspended by means of insulating silk cords. He put them in communication with the conductor of an electric machine in action, and he thus accumulated, by means of the same machine, a quantity of electricity as much greater as the sum of these conductors presented a more considerable surface. He named these conductors *secondary conductors*. This process possessed the inconvenience of requiring an embarrassing developement of conductors, besides that of spreading a given quantity of electricity over a very great surface, and of exposing it by this means to a rapid loss by the contact of the air.

The principle of disguised electricities has furnished the means of attaining the same end, avoiding also the inconveniences, that we have pointed out; and this by permitting a greater quantity of electricity to accumulate upon a given surface than that with which it would be charged naturally.

In order that we may obtain a better idea of the manner by which this result is obtained, let us return to the apparatus that we employed when demonstrating the principle; and let us put the disc A in communication with the source of electricity. Each of the points of this disc will acquire an electric reaction equal to that of the source. Let us bring the disc B near, and touch it with the fingers. Immediately, in conformity with what we have seen, the greater portion of the electricity of A will be disguised, a certain quantity only will remain free, which, by diffusing itself throughout the surface, will determine in each of its points an electric reaction much inferior to the primitive; but A, being in communication with the source, will be able to regain electricity in sufficient quantity, that the electric reaction in each of the points of its surface will again become equal to that of the source. A new decomposition of the natural electricity of B is brought about, and a new disguise of that of A; but at each operation the quantity that remains free will become greater, because it is the same proportion of the total electricity for the same distance of the two discs: the greater the total amount of the absolute quantity becomes, the more also does the proportional quantity increase. When this free quantity shall have become such that of itself alone it gives at each of the points of the disc A an electric reaction equal to that of the source, it will then have arrived at the limit of possible accumulation. The disc A will contain, at this moment, a total quantity of electricity, composed of two elements, namely, the disguised portion and the free portion, the electric reaction of which latter is equal to that of the source, and will be that with which the disc would be charged, were it not under the influence of B, namely, had it remained in the ordinary conditions.

We have therefore succeeded in condensing into A a much more considerable quantity of electricity than would have been accumulated in it by simply placing it in communication with the source. We have then merely to remove A from B, in order to make the disguised part free, which then adds itself to that which is not so; and then to obtain, on each element of the surface of A, an electric reaction very superior to that of the source, from which, however, it had been charged. The condensing power of the apparatus is the relation existing between the total quantity of electricity with which the plate is charged, when it is under the influence of B, and that with which it is charged when it is not under this influence. In order to obtain this relation, we have merely to determine with the proof-plane and the torsion balance the electric reaction of a point upon the surface of A when, being under the influence of B, there is only a feeble portion of its electricity that is free, and when, being out of this influence, the whole of the electricity with which it is charged has become free. This mode of determination cannot be applied to the case in which the electricity possessed by the apparatus is very feeble, — the case, too, of most importance; for the portion that is free is too inconsiderable for the proof-plane to be sensibly affected by it. In this case it is better, when the two discs are separated, to touch them successively with the proof-plane, and so to determine the relation existing between their total charges. By means of this relation, and by a very simple calculation, we are enabled to arrive at that existing between the total electricity with which the disc A is charged, and the quantity of electricity that it retains in the free state, when it is under the influence of B; which was what we wanted to know.

The condensing power is the greater as the insulating stratum by which the discs are separated is thinner; but it must not be sufficiently thin to allow the two electricities to unite through this stratum. And here it is that we must distinguish between the two ends proposed with condensing apparatus. One of these ends is to endeavour by their action to make manifest on the electroscope amounts of electricity, whose reaction would be too feeble to act directly upon it; we must therefore have as thin an insulating stratum as possible; because, on the one hand, the condenser must be as powerful as possible, and, on the other hand, there is no risk, if the material of the stratum is very insulating, of the two electricities being sufficiently intense to overcome its resistance. This kind of apparatus has acquired the especial name of *condenser*. The second end is to accumulate, with as powerful a given source as possible, as large a quantity of electricity as we can, in order to produce great effects. The insulating stratum must in this case be thick enough and of sufficient insulating power to oppose an adequate obstacle to the energetic tendency to unite, possessed by the two electricities. In this case glass is employed, because its homogeneous structure prevents our running the risk, as in a thin stratum of insulating varnish, of solutions of continuity; and because also, even when it is very thin, it preserves its insulating property.

This second kind of apparatus is named, according to the form that is given to it, the *magic picture* or the *Leyden jar*.

### *Condenser.*

The condenser was invented by Volta; it was originally formed of a wooden disc covered with gummed silk, and of a metal disc furnished with an insulating handle, and which is placed on the wooden disc. The metal plate is put in communication with the source of electricity, it plays the part of the disc A; the wooden plate plays that of the disc B; and the gummed silk is the thin insulating stratum which prevents the immediate recomposition of the two electricities accumulated upon the two plates. When the metal plate has been charged it is raised and is carried to the electroscope, which indicates the nature and, up to a certain point, the intensity of the electricity of the source.

The *gold-leaf* condenser is the one most generally used, and it is so named because it is adapted to a gold-leaf electroscope (*Fig.* 50.). It is composed of two metal plates, nicely adjusted, of not less than 6 inches, nor more than 1 foot in diameter. One of these plates is screwed on the exterior extension of the metal stem of the electroscope by which the gold leaves are supported; the other is provided with an insulating handle, fixed vertically at its centre, and is placed upon the former, so as exactly to cover it. The two plates have been coated on their surface in contact with several layers, successively applied, of a very liquid varnish formed of a solution of gum-lac in alcohol. This varnish, in drying, forms a pellicle, whose thickness does not exceed $\frac{1}{250}$th part of an inch, but which is sufficient to prevent the recomposition of the electricities, when they are not very strong. The plates are thus almost in contact, and the disguise of the

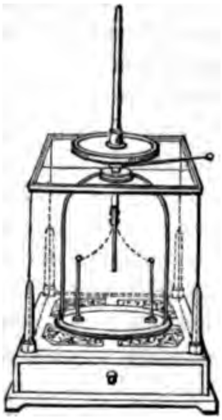

*Fig.* 50.

electricity is as complete as possible; and the condensing power of this apparatus is very considerable, but it can only support very feeble charges, which, indeed are all it is intended to receive. It is important that the two plates be fitted to each other as accurately as possible, and, consequently, that their surfaces be very even. For this reason there is a limit to the size of these surfaces that cannot possibly be exceeded, because their construction would become too difficult, in consequence of the condition we have pointed out: the manipulation also would be very troublesome; for it is essential that we should be able to raise the upper plate easily, and should take care to raise it perpendicularly, without exercising any friction against the other, which of itself would be a source of electricity, and would consequently interfere with the results. This reservation being once made, it is advantageous to have the largest possible surface, because the quantity of electricity accumulated is proportional to this surface. Experiment has demonstrated that we cannot exceed a foot in diameter without falling into the inconveniences, that we have just now pointed out. The plates are generally of brass, and, if possible, of gilt brass, so as to be protected against the chemical action of the moist air, and of the vapours and liquids, with which they may have occasion to come in contact. Electrical signs are sometimes found on separating the two plates, even although there may be no electrical source in communication with either of them. This error is due to a small quantity of electricity arising from preceding experiments, which has penetrated into the layers of varnish, and which is not got rid of without some difficulty. In order to remove it, we must place a very thin sheet of tin-foil between the two discs, and leave it there until we have satisfied ourselves that, after having been placed in immediate contact with each other, the plates liberate no trace of electricity by the mere fact of their separation. It is essential always to determine this absence of spontaneous electrical signs, before making an experiment.

For greater convenience, the source of electricity is generally placed in communication with the upper plate of the condenser, which is termed the collector; and the lower plate is touched with the finger. When the two plates are separated, it is the electricity of the lower plate, now become free, that affects the electroscope; but we must not lose sight of the fact of its being of a contrary nature to that of the upper one, and consequently to that of the source subjected to experiment. Before beginning a second experiment, we must not forget to discharge both the plates by touching them with the fingers; and, generally, we must never leave them charged, especially when they are in contact, because the electricity, that they retain, penetrates into the layers of varnish, from which, as we have seen, it is a very difficult matter to expel it.

We have entered into minute details of the condenser, because it is an electrical apparatus most commonly in use, and is at the same time one of the most delicate: by its assistance Volta succeeded in showing that a plate of zinc, when held in the hand, and put into contact with the upper plate, charged it with negative electricity,—an experiment that was the origin of the discovery of the voltaic pile. When this experiment is made, care must be taken that the zinc plate be well cleansed, especially in the points where it touches the disc. In like manner, we can charge the plate with positive electricity by interposing between the plate and the zinc plate, which is still held in the hand, a disc of cloth or paper slightly moistened with salt water. In each case we must not neglect to touch the lower plate with one of the hands, whilst the zinc plate is held by the other in contact with the upper plate.

The experiments that we have just quoted, and the other delicate experiments in which the condenser is used, require the air of the room in which the operation is carried on to be as dry as possible, or at least the electroscope and all the pieces of which it is constructed to be well protected from moisture. With this view, the whole is covered with a glass cage, in the interior of which chloride of calcium is placed, in order to produce the dryness (*Fig.* 50.).

M. Peclet has still further increased the sensibility of the condenser by adding to it a third plate, interposed between the other two; and he has named his apparatus the *multiplying condenser* (*Fig.* 51.). The lower plate, as before, is screwed

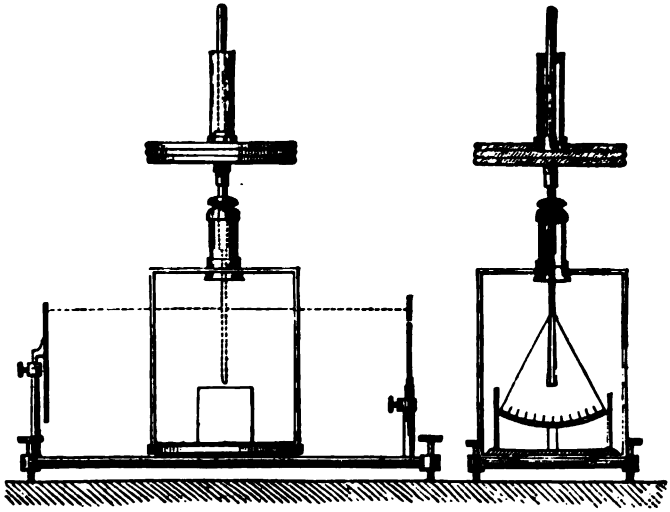

*Fig.* 51.

upon the electroscope; the second is furnished with an insulating handle, and is varnished on its two faces; the third, which is varnished only upon its lower surface, is pierced at its centre with a hole, within which is sealed a glass tube that serves as an insulating handle, and at the same time affords a passage to a glass rod, forming the insulating handle of the second. We can thus easily superpose the three plates, and successively raise the third and the second. In operating, we put the source in communication into the third, and touch the second with the finger by means of a small metal appendage that forms part of its border. Then, this being charged, we raise the third and touch the first with the finger: the electricity of the second is thus found almost entirely disguised; it is charged again by replacing the third, which is still in communication with the source; the third is then to be removed, and the first to be touched, and so on, until the electricity of the second can no longer be disguised by the first. We then remove first the third, and then the second, and the first is found to be charged with a considerable amount of free electricity, and of the same nature in this case as that of the source; for it is of the contrary nature to the electricity of the second plate, which is itself different from that of the third, which receives its charge directly from the source. It is easy to comprehend that this apparatus condenses a second time the product of a former condensation; and thus very feeble sources of electricity may be rendered sensible. But, like all the instruments, it is too delicate and rather dangerous in its use, and is moreover very tedious and inconvenient in manipulation. It must therefore be reserved for exceptional cases, and be only used with the greatest precaution. We should add, that the plates employed by M. Peclet for the construction of his condenser are made of roughened glass, ground with great care, and covered with gold-leaf, which is applied without cement, it being sufficient to moisten the surface of the glass slightly with the breath. It is not necessary to remark that the same apparatus that serves as a multiplying condenser may be employed as a simple condenser. For this purpose, we have merely to remove the third plate, and the second, being furnished with its insulating handle, is put in direct communication with the source by means of the appendix affixed to its edge.

### *Magic Picture and Leyden Jar.*

The magic picture, called also the sparkling pane, consists of a pane of glass, the two faces of which are coated with a sheet of tin-foil (*Fig.* 52.), care being taken to leave bare upon each of the faces of the glass pane an edge of 2 or 3 inches in width, so that the contrary electricities accumulated on the sheets of tin-foil cannot unite immediately by the edges of the sheets. One of the sheets of tin-foil is put into communication with the source of electricity, and the other with the ground. Then, when they are charged, the two plates may be connected by means of a dis-

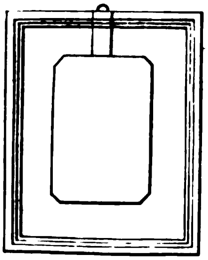
*Fig.* 52.

charging rod, and a very vivid spark is obtained. This apparatus is termed the sparkling pane, because metal filings, secured to the glass by gum, are sometimes substituted for one of the metal sheets: now, when the charge is made in the dark, there arises on the face so coated a brilliant light, produced from the sparks which escape between all the grains of metal, at the moment of the neutralisation of the two electricities.

The Leyden jar is nothing more than a magic picture made into a cylinder; the insulating stratum is also of glass; but, instead of being a plane surface, it has the form of a cylinder or bottle (*Fig.* 53.). One of the sheets of tin-foil is on the outside of the bottle, and is termed the outer coating of the Leyden jar; the other is withinside, and is termed the inner coating. This latter receives electricity by means of a metal rod, terminated on the exterior by a knob, and in the interior by a cluster of wire, which, diverging by virtue of their elasticity, come thus into contact with the metal coating. The rod is fixed by means of a plug of wood or cork, through which it passes tightly, and which is itself inserted firmly into the neck of the jar. A thick coating of wax covers the cork and the exterior part of the glass, surrounding it so as altogether to prevent the possibility of a reunion between the electricity of the exterior coating and that of the inner coating and of the rod that is in connection with it. In order to charge the jar, it is held in the hand by the outer coating, and the knob is presented to the conductor of the electrical machine. The positive electricity of the machine penetrates to the inner coating, decomposes through the glass the natural electricity of the outer coating, the positive of which goes into the ground through the hand and the body of the operator, and the negative of which is disguised. At the end of the operation there remains a small quantity of free electricity upon

*Fig.* 53.

the inner coating, as an electroscope indicates. If, after having carefully placed the jar upon an insulating support, we draw this away with the fingers, it is manifested under the form of a small spark; and, as soon as it is gone, the balls of the electroscope fall down, while the electroscope, placed in communication with the outer coating, indicates the presence of free electricity upon this coating (*Fig.* 54.).

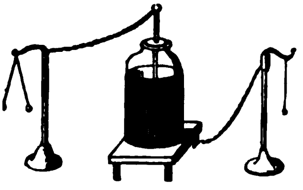

*Fig.* 54.

The free electricities of contrary natures, possessed by the two coatings, may be made manifest by placing between the two knobs, with which they are each in communication, the pith ball of an electric pendulum; being attracted by the free electricity of one of the knobs, this ball comes into contact with it, and is electrised by contact; being immediately repelled, it goes to the other, charged with a free electricity of a contrary nature; then it loses its own electricity, and is charged with that of the second knob, by which, being repelled, it returns to the former, and so on (*Fig.* 55.) Thus the ball executes between the two knobs a series of oscillations, which may be prolonged for several hours, at the end of which, the two coatings having lost their electricity by this succession of small discharges, the phenomenon ceases. The pith ball is sometimes constructed in the form of a spider, of which it is itself the body, and small very fine wire are the limbs; on which account this apparatus is called *the electric spider.* If, instead of employing the pith-ball, the two knobs of the jar are touched successively with the finger, the discharge is brought about by a series of small sparks arising from the portion of electricity alternately made free on each of the

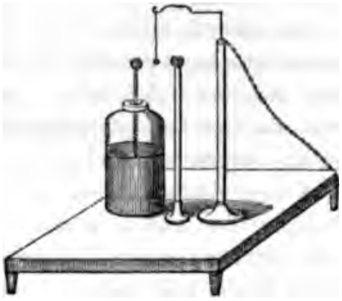

*Fig.* 55.

coatings; but it is only after having drawn a very considerable number of sparks that we succeed in completely discharging the jar. It is important in this experiment to take care never to touch the two knobs of the jar at the same time, which might easily happen if both hands were employed; we should, under such circumstances, ourself serve as the course for the reunion of the two electricities that are accumulated upon the two coatings, and we should experience a violent, and often a dangerous, shock. It is also with a view of avoiding this inconvenience that it is essential to place the Leyden jar, when it is charged, upon an insulating stool; for, if we merely place it on an ordinary table, we are in the route that the two electricities of the two coatings would pursue at the moment we touch the knob; as they are now separated by conducting bodies alone.

To show the different electricity with which the two coatings of a Leyden jar are charged, Faraday employed two concentric cylinders made of metal gauze, separated by a stratum of air about $\frac{1}{3}$ in. thick, and resting on a base of resin. The exterior is put in communication with the ground, while the interior is charged with electricity. They are touched successively with the proof-plane, and are found charged each with a different electricity. Care must be taken not to touch the exterior cylinder on its inner surface, nor the interior on its outer.

The inner coating of a Leyden jar is easily charged with negative electricity. For this purpose we have merely to hold it by the knob, and let the electricity of the machine arrive on its outer coating; but in this case we must take care, after the jar is charged, to place it upon an insulating support; for if, while holding it by the knob, we were to place it upon a table, we should receive the whole of the discharge.

There is a very elegant experiment, for which we are indebted to Lichtenberg, and which is called *Lichtenberg's figures*, that makes manifest without an electroscope, and in a directly visible form, the nature of the electricity with which the inner coating of a jar is charged. This experiment consists in slowly passing over a cake of resin the knob of a Leyden jar, while the outer coating is held in the hand; we may even trace figures with the knob. The free electricity of the inner coating, which is constantly renewed in proportion as it escapes, because the other coating is held in the hand, remains adhering to all the points of the cake which the knob has touched. If, after having thus traced out lines with the knob of a jar charged interiorly with positive electricity, we trace others beside them with the knob of another jar charged with negative electricity, we may render each of them visible and distinct by powdering the cake with a powder formed of a mixture of sulphur and red lead, that have been rubbed together. We perceive that all the particles of sulphur place themselves upon the positive lines, and all those of red lead upon the negative; and they remain adhering there, even when we blow them, or shake the cake strongly, so as to make the portion of the powder disappear, which is not upon the parts of the surface, that had been touched by the knob. The effect that we have just described arises from the molecules of sulphur during their mutual trituration having acquired negative electricity, and those of red lead positive; and which causes the former to pass upon the positive traces, and the latter upon the negative. We also remark that the sulphur forms a small tuft round each of the positively electrised points; whilst, on each of the negative points, the red lead leaves only a circular spot. This phenomenon, establishing as it does a very remarkable difference between the two electricities, is due to a more general cause, which we shall study hereafter.

The property that we have thus recognised in resin, of retaining both electricities adhering to its surface, is not peculiar to this substance alone; all bodies that are insulators possess it in a more or less marked degree. We have already seen that it exists in glass when we electrised the interior of a glass jar to produce the dance of pith balls. A Leyden jar, the contents of which are movable, furnishes a further proof of this. The glass jar in this case has a widening or conical form; the inner coating is of tinned iron, and fits accurately into the jar; the outer coating is also of the same material, and the jar exactly fits into it. The jar is charged as usual; then, with an insulating glass handle, the inner coating is lifted away, and afterwards the glass itself is lifted out; the two coatings, being thus detached, manifest no electrical signs. The two electricities have in fact remained adhering to the glass, the positive on the interior surface, and the negative on the exterior. These two electricities are recovered again by replacing the jar within its outer coating, and placing within it its inner coating; the discharge takes place between the two coatings as if they had not been deranged.

The fact that we have just pointed out explains why a Leyden jar always retains electricity after a first discharge; even when the latter has given rise to a strong spark, we can obtain a second discharge, much weaker, it is true, than the former, but yet very sensible, and sometimes indeed exceedingly violent, if the jar is large and has been strongly charged. This second discharge arises from a portion of the two electricities having remained adhering to the glass after the first discharge, notwithstanding the contact of all the points of the two surfaces of the jar with the metal surfaces; but the second discharge is generally sufficient to make all the remaining traces disappear.

To terminate the details relating to the Leyden jar, we may add a few words on the origin of its name, which is connected with the history of its discovery. In 1746, three philosophers who were assembled at Leyden, Muschenbroeck, Allaman, and Cuneus, having endeavoured, by means of a metallic rod, to introduce electricity from a machine into water contained in a bottle (*Fig.* 56.), in order, as they said, to try and store up this agent, were very much frightened when one of them, whilst holding the bottle in his hand, and touching the metal rod that was thrust into the water, received a very violent shock. This experiment made a great stir; its effects were singularly exaggerated: adventurers, who spread themselves throughout Europe, gained their livelihood

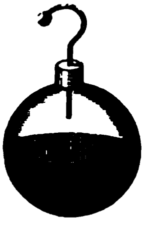

*Fig. 56.*

by repeating it under various forms. The primitive apparatus, in which it is easy to see that water filled the office of the inner coating, whilst the moisture with which glass is always covered discharges the function of the outer coating, was soon perfected and brought to the present form, which it has always preserved; and this long before its theory was discovered.

### *Electric Batteries.*

In the same manner as with the condenser, the total quantity of electricity that may be accumulated upon a Leyden jar with a given source of electricity, depends upon the extent of its surface, or rather of the surface of its coatings. In fact, the charge attains to its limit only when each of the points of the surface of the coating, in communication with the electrical machine, has a quantity of free electricity whose reaction is equal to that of the source. We have therefore endeavoured to give to Leyden jars the greatest possible amount of surface: some have been constructed which are as much as 12 or 15 inches in diameter, and from 20 to 24 inches in height. But these larger jars, besides being very inconvenient to manage, and being exceedingly expensive on account of the higher price of vessels of the desired dimensions, have this inconvenience also, that the glass will easily break if its contexture is not perfectly homogeneous. In fact, it needs but present some flaw, and consequently one part more feeble than the rest, for the two electricities that are accumulated on the two coatings to obey the powerful tendency which directs them towards each other, and unite through this point by breaking the glass. It is therefore preferable to unite together several jars of a moderate size, by establishing a metallic communication between all their interior coatings, and a similar one between all their exterior coatings. This is what constitutes an *electric battery;* which, however, must not be confounded, it is evident, with a *voltaic battery* or *pile.*

Each battery is generally composed of four jars, but sometimes of nine or of twelve (*Fig.* 57.). The jars are placed in a case lined with tin-foil, upon which they rest, and which serves to establish a communication between all the exterior coatings: the interior coatings communicate together by means of small metal rods, which connect the respective knobs. The discharge is made by means of a chain, or of a metal wire fixed by one of its extremities to the tin-foil of the case; and its other extremity is brought near to the knob of one of the jars by means of an insulating handle or a discharging rod. It is easy to understand how several batteries may be united so as to form but one, as several jars may be united so as to form one battery.

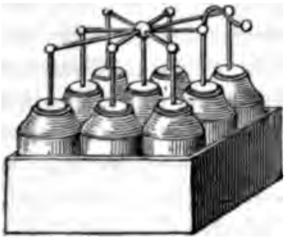

*Fig.* 57.

Whether there be but one battery or several batteries under experiment, it is always a long and tedious operation to charge them; for this purpose, we must have a good electrical machine, and must have it in action for some minutes at least. For accelerating this operation, it has been suggested, for charging each jar of a battery, to make use of the positive electricity developed by induction in the outer coating of the others, and which is generally lost in the ground.

With this view, each jar of the battery is placed upon an insulating and independent support, and they are so arranged that the knob of each is in metallic communication by means of a chain, or simply by immediate contact with the exterior coating of the preceding one (*Fig.* 58.). The knob of the first is in communication with the conductor of the machine, and the outer coating of the last with the ground. It follows, from this arrangement, that the positive electricity from the outer coating of the first jar, instead of being driven away into the ground, serves to charge the second by penetrating into its

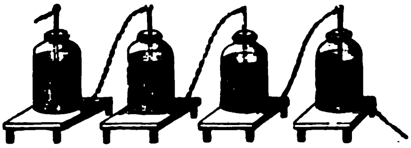

*Fig.* 58.

inner coating; that the positive electricity of the outer coating of the second charges the third; and so on to the last, the outer coating of which, being in communication with the ground, parts with the positive electricity, that is developed in it by induction. We see that, by this means, which is called *charging by cascade,* we are able to charge any number of Leyden jars with the quantity only of electricity that is necessary to charge but one. But, when the jars are charged, if we would accumulate the effect of the discharge upon the same point, we must suppress the communications that are established between the outer and inner coating of each jar: this is done by removing with an insulated handle the conductors by which this commuication is established, or by withdrawing the jars from each other. We must, furthermore, make all the interior coatings communicate together, which is also done by properly arranging conducting rods or wires by means of an insulated handle. A similar communication is to be established between the outer coatings; —a result which may also be obtained without the employment of conductors, by putting the jars tolerably close to each other, so that the outer coatings may come into contact. We have then a battery charged and ready for operation; but we must use care and skill in making these various arrangements, so as to avoid discharging the jar, and especially receiving the discharge oneself.

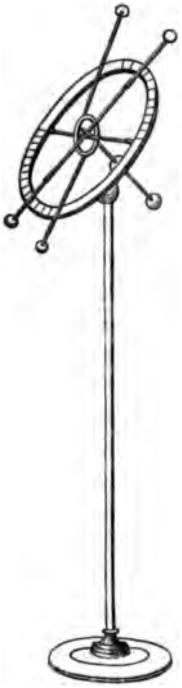

*Fig.* 59.

In order to know the moment at which either a Leyden jar or a battery is sufficiently charged, the inner coating is put into communication with a quadrant electroscope, the movable stem of which describes a greater or less arc of a circle by the effect of the free electricity possessed by this coating. In general, we cease giving electricity to the inner coating, when its free electricity is capable of making the movable stem of the electroscope describe an angle of 45° or 50°; or, better still, when we see that this angle ceases to increase,—a proof that the charge has attained its limit. In this kind of experiment, we use with advantage Harris's circular electrometer, which depends upon the same principle as that of the quadrant, but which is more sensitive and more accurate (*Fig.* 59.).

As the divergence of the electroscope depends only upon the quantity of free electricity that is found upon the interior coating, it furnishes no datum as to the intensity of the total charge of the jar or the battery: this charge may be measured by means of the greater or less distance to which the spark darts between the knob of the inner coating and a similar knob communicating with the outer coating. The apparatus that is used for estimating these distances is called *Lane's Discharging Electrometer* (*Fig.* 60.). A bent glass arm comes from the rod that penetrates into the interior of the jar, and itself carries an horizontal stem, terminated at one of its extremities by a knob, which is facing and at a short distance from the knob of the inner coating, and communicating by its other extremity with the outer coating. This horizontal stem is made to advance gradually, until the two knobs are sufficiently near for the electric spark to pass between them. The distance at which the discharge takes place is thus measured very accurately; but we should not lose sight of the fact, that it must depend not simply on the intensity of the accumulated electricities, but also on the degree of humidity and of the rarefaction of the air; and it is only as the latter element is constant, that the former may be estimated with any accuracy. When, therefore, we employ this means for comparing relative power of different Leyden jars or electrical batteries, we must operate, as much as possible, under the same atmospheric circumstances.


*Fig.* 60.

*Cuthbertson's Discharging Electrometer* is an apparatus, which of itself brings about the discharge when the jar or battery have attained the limits of their charge. An insulating support carries a metal stem, formed like the two arms of the beam of a balance, of two equal branches, movable about a central axis. These two branches, which communicate with the inner coating and with a quadrant electrometer, are each terminated by a knob. Beneath the knob of one of the branches, but at a sufficient distance to prevent the discharge taking place, is another similar knob, placed at the extremity of a metal rod, which communicates with the outer coating. In like manner, beneath but very near to the knob of the other branch, there is also another knob placed at the extremity of a metal rod, which is fixed to the same support as the movable rod in metallic communication with it, and consequently also with the inner coating. When the electric charge of the jar or the battery has attained its limit, the repulsive force which the free electricity of the inner coating impresses upon the two approximated knobs that are both in communication with it, drives the movable one from the fixed one, and consequently brings, at the same time, the knob of the opposite branch nearer to the fixed knob that communicates with the outer coating. This approximation determines the discharge at the moment when it has reduced the distance by which the two knobs are separated to the *explosive distance* of the apparatus. A slightly different form is sometimes given to the apparatus,

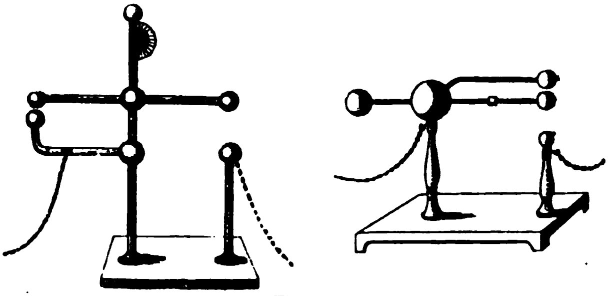

*Fig.* 61.

but the principle of its construction is the same. *Fig.* 61. represents them both.

Finally, another apparatus that is indispensable for experiments made with electric batteries, is *Henley's Universal Discharger* (*Fig.* 62.). It consists of two insulating supports of the same height, and placed on the same stand at a distance of 10 or 12 inches apart. Each of them carries at its upper extremity a universal joint, to which is fixed a small metal tube, within which a metal rod slides very tightly. The two rods may thus be placed in all directions; and their extremities, when they are placed opposite to each other, may be withdrawn to any distance. Between the opposite extremities of these two rods are placed the bodies that are to be traversed by the discharge, as a piece of wood, a pane of glass, metal leaf, &c., by laying them upon a small support which may be raised at pleasure; one of the ends is then made to communicate with the outer coating of the battery, and a communication is established between the other and the inner coating by means of a discharging rod with glass handles, or by Cuthbertson's discharging electrometer.

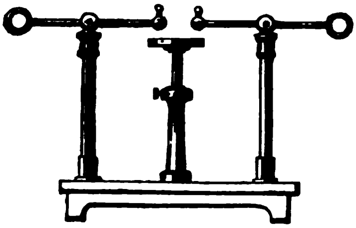
*Fig.* 62.

### *Some Effects of Leyden Jars and Electric Batteries.*

Before terminating this Chapter, we will describe some of the most remarkable effects, that may be produced with the Leyden jar and electric batteries, although the phenomena that result from the transmission of electric discharges through different media can only be studied thoroughly in the Fourth Part of this work.

The shock which so powerfully affected the philosophers of Leyden was, immediately after the discovery of the Leyden jar, the phenomenon that was mostly studied. It was remarked that it could be transmitted through a file of men forming a chain, namely, holding hands, the first of whom took hold of the jar by its outer coating, while the last touched it by the knobs; an entire regiment, ranged in array, were subjected to this trial; and, it is said, they were all struck down by a single blow. In this experiment, it was observed that the men who were in the middle experienced a less violent shock than those who touched the jar. In experiments of this nature we must employ the charge of a single jar only; a battery would be dangerous, and might occasion serious accident. In fact, it has been observed that it does not require very strong batteries to kill birds, rabbits, and even animals of larger size.

The calorific effects of the jar and batteries are numerous, and of very various kinds. Thus, with the discharge of a single jar, ether, alcohol, or cotton powdered with a mixture of rosin and lycopodium, is easily inflamed. For this purpose, it is necessary that the inflammable substance be placed in a metal capsule, communicating with the outer coating by means of a wire or a metal chain, whilst the knob is brought near to the substance itself. At a certain distance the spark passes and inflames this substance by traversing it, provided it does not form too thick a layer. Gunpowder may in like manner be inflamed by placing it in a cartridge about a fifth of an inch in diameter and a couple of inches long, and by introducing through its two ends two iron wires, which approach its centre at a short distance from each other, and between which the discharge passes. It frequently happens that the powder, if it is fine, is dispersed by the effect of the discharge, instead of being inflamed. To avoid this inconvenience, we should place in the route of the discharge a tube full of water, or cotton or paper impregnated with moisture. The presence of this moist conductor, by diminishing, as it seems, the velocity or instantaneity of the discharge, gives it time to inflame the powder.

With the discharge of a battery we are also able to ignite, to melt, and even to inflame very fine wires placed between the two opposite extremities of the rods of the universal discharger. The length that may be given to the same wire depends upon the power of the battery. If it is an iron wire, it is seen to dart into small metal globules, which are thrown afar. Tin wires also give rise to a similar phenomenon, in which, if the discharge is still more powerful, they disappear under the form of a fine white powder, similar to a vapour. It is the result of the oxidation of the tin. Gold reduced into wire or thin leaves is also, as it were, volatilised by a powerful discharge; at least, it rises in the air in the form of a reddish vapour. This property is made use of to produce electrical prints; a pattern is cut in a card, to the two extremities of which is cemented a band of tin. The pattern is covered on the one side by a sheet of gold leaf which touches each of the tin bands by one of its edges; and, on the other side, by a silk ribbon itself resting by its other side upon a sheet of pasteboard; the gold leaf is also covered with pasteboard. The whole system is placed in a press to ensure contact. The discharge of the battery is then made to pass through the gold leaf by means of the two tin bands; the gold is heated and oxidised; and, as it cannot escape into the air, it passes through the holes of the pattern, and forms upon the ribbon a print of a reddish-brown colour, which is very regular, and which produces the image of the pattern (*Fig.* 63.).

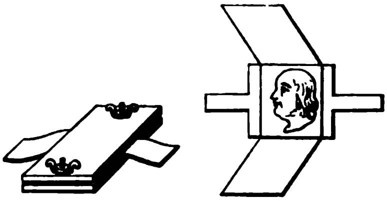

*Fig.* 63.

Strong discharges produce upon masses of metal two kinds of coloured rings, which appear to arise from the high temperature to which the surface of these metals is exposed, at the place where the electricity traverses them. Priestley made a particular study of these circles of fusion, which he attributed to a partial liquefaction brought about by the heat.

What characterises more particularly the discharging of electrical batteries, is their mechanical or molecular effects.

A glass plate, if placed between the two ends of the arms of the discharging rod, is pierced by the discharge: to prevent the electricities uniting by making the tour of the plate, the surface of which is always more or less moist, and by this means slightly conductible, it is necessary that the portion through which we would make the discharge pass, should be surrounded on its two faces by a belt of wax in the form of a ring: a drop of oil, placed in the centre of the ring, facilitates also the success of the experiment. A piece of dry wood, or a stone, may in like manner be split into fragments by a discharge traversing them. A card is also pierced; but if the extremity of the two rods that lead the discharge are not exactly opposite to each other, the hole is made opposite to the point that brings the negative electricity. It is also to be remarked, that the hole presents burrs equally on either side, as if the electric fluid had come from the middle of the card to escape by its two faces at the same time. This very extraordinary effect has greatly engaged the attention of philosophers; it appears to arise, as we shall see, from the electric discharge not actually occurring by a finite movement of translation, but rather by a series of small molecular vibratory movements.

When the air is traversed by an electric discharge, it undergoes a very marked agitation; and an instantaneous expansion, if the phenomenon occurs in a closed vessel. This may be proved by means of *Kinnersley's Thermometer* (*Fig.* 64.), which consists of a glass tube, closed at its two ends, and of a lateral tube, in which a liquid rises that gives the measure of the expansion. The discharge is made between two metal balls, that penetrate into the tube.

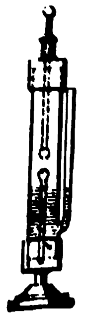
*Fig.* 64.

With regard to the luminous effects, properly so called, and which are not due to a simple incandescence of wires, they are generally manifested under the form of a spark, nearly similar in intensity, but greater than that which is drawn from an electrical machine, and susceptible, like the latter, of presenting the very varied appearances, that we shall study hereafter. We shall confine ourselves to quoting here a beautiful experiment, which consists in passing the discharge of a battery through a metal chain of several yards in length, suspended by silk cords from the ceiling of a room: at the moment of the discharge, this chain is illuminated in its whole length by the effect of the sparks passing from one link to the other.

## CHAP. V.

### THEORY OF STATIC ELECTRICITY, AND DIVERS FACTS CONNECTED WITH IT: DI-ELECTRIC BODIES.

### *Properties of the two Electric Fluids.*

We have thus far explained all the phenomena of static electricity, setting out on the supposition that electricity is composed of two extremely subtile and imponderable fluids; that the particles of each of these fluids mutually repel each other, whilst those of one of the fluids attract those of the other. The experimental laws that we have established enable us now to enter with more precision than we have done into the properties of the two fluids. Thus, by attributing to the fluids themselves the property that we have recognised in the bodies that contain them, we are able to admit that the force with which the particles attract and repel each other is in inverse ratio to the square of the distance by which they are separated. We must in like manner lay down as a principle, that bodies, in the natural state, contain an equal quantity of both fluids in each of their particles; and that if they cannot exercise any action on surrounding bodies, it is that *at the same distance the attractive power of one of the fluids is equal to the repulsive power of the other.* We can demonstrate this principle experimentally by rubbing together two glass plates, the one polished, the other roughened. We bring an electroscope near to them, after having rubbed them, but without separating them, and we observe no effect; we separate them, and then find on the roughened face of one of the plates a strong charge of negative electricity, and on the polished surface of the other a strong dose of positive electricity. These two surfaces had been electrised by their mutual friction; the one had acquired a certain quantity of positive electricity, and the other an equal quantity of negative; but the insulating property prevented the two electricities neutralising each other, notwithstanding the contact of the two faces: the nullity of the exterior action, so long as the contact remains, is therefore the proof that the two electric strata situated at a same distance from any body, if they are equal and of the contrary nature, exercise upon this body two effects that neutralise each other.

### *Theoretic Explanation of the Distribution of the Electric Fluids on the Surface of Insulated conducting Bodies.*

The general fact, established by experiment, that electricity distributes itself entirely on the surface of an electrised conducting body, is a natural consequence of the mutual repulsion of all the particles of the same fluid, and of the facility they possess of moving in the body. When arrived at the surface, they accumulate; and, if they do not quit it, it is because they are retained there by the air or by the insulating supports, which oppose themselves to the tendency they would have to escape by virtue of their mutual repulsion. They therefore form there an excessively thin stratum, which does not sensibly penetrate within the surface of the body; for, however thin the metal envelope of a hollow sphere may be, electricity is never found there on touching it interiorly. With regard to the stratum, its exterior surface is evidently the same as that of the body, but its interior surface varies with the form of the conducting body. In a sphere it is similar to the exterior, because all points have the same electric charge; whilst in non-spherical conductors, upon which, as we have seen, the distribution of the electricity is never uniform, we may suppose, that to the most highly charged elements of the surface corresponds a stratum either of greater thickness or of greater density. As considerations of another kind seem to prove that the electric fluids are incompressible, we prefer to admit the former of these two hypotheses; thus the electric stratum would be terminated in the interior by a surface, whose form would be slightly different from that of the exterior surface, at least when non-spherical bodies are in question. This form may be established *à priori*, setting out, as we have done, from certain principles of mechanism, and from the definite and precise properties of the electric fluids. As thus:

The stratum is in equilibrio; for its state does not change as long as the body preserves its electricity, and remains protected from all exterior influence. The figure of the stratum, therefore, is that which results from the equilibrium of the repulsive forces of all the molecules of which it is composed, by supposing them subject to the law of the inverse of the square. This is not all: it must be such that the stratum exercises neither attraction nor repulsion; or, in other terms, no action upon any point placed in the interior of the body. In fact, if it exercised an action, it would decompose the natural electricity of the point upon which it acted; this electricity, developed by induction, would react in its turn upon that of the body, and there would be a change in its electric state, which does not take place, since the introduction of a new body into the interior of an electrised body in no degree changes its electric state. Thus the equilibrium can subsist only as long as the resultant of all the repulsive forces upon an interior point is equal to zero. By means of these conditions we are enabled to determine the relations which ought to exist between the intensities of the repulsive forces in different points of the surface of an electrised conducting body; or, which comes to the same thing, the thicknesses of the electric stratum; and we obtain results perfectly in accordance with those, to which Coulomb arrived by experiment. In this manner we find, for a sphere, that the stratum is terminated interiorly by a spherical surface; for an ellipsoïd, that it is by an ellipsoïd surface, whose greater axis is to its smaller in exactly the same relation as those of the exterior surface; so that the stratum goes on increasing in thickness from the extremities of the small axis, where it is at its minimum, to the extremities of the large axis, where it is at its maximum.

By applying mathematical analysis to the principles of mechanics and physics that we have just laid down, M. Poisson has succeeded in determining, *à priori*, the thickness of the electric stratum for the different points of the surface of a conducting body of any form; he has done the same for two, or for several bodies in contact, as well as for the case when the bodies are simply subject to their mutual influence. However, this determination has been made, in a rigorous and complete manner, only in the cases of an insulated sphere and an ellipsoïd, and in that of two spheres in contact; for the other cases, Poisson has merely indicated the general method, without having given its application. We must then take account of the electricity, developed by induction, which modifies the electric state of each body; but this modification, which occurs at the very instant when the bodies are placed in presence, does not prevent the electric state becoming permanent, so long as the latter do not change their place. It is further necessary, in order that this permanent state of equilibrium should remain, that the resultant of the actions exercised, upon any point taken in the interior, by the fluid strata which covers them, should be equal to 0. This condition furnishes, in each case, as many equations as there are conducting bodies under consideration; and these equations serve to determine the variable thickness of the electric stratum on the different points of these bodies.

It follows, from this mode of looking at the phenomena of static electricity, that the office of a conducting body consists simply in determining in the air, for the electric fluid, a vessel of which it is, so to speak, itself the mould; and the boundaries of which are the stratum of air that envelopes it. Free to travel in this vessel, the electric fluid distributes itself entirely towards the insulating sides, against which it is retained, exercising, however, a pressure from within outwards, against which the atmospheric pressure resists. This pressure depends at once on the number of particles included in the stratum; consequently, on its thickness, and on the repulsive force exercised by the particles of the exterior surface,—a force which is itself proportional to this thickness. The pressure is therefore in a ratio composed of the thickness of the stratum and of the repulsive force of the surface, or proportional to the square of the thickness. It necessarily follows from this, that the pressure of the electric fluid against the air may be very different in certain points to what it is in others, according to the form of the body on which the thickness of the stratum depends; and may even become infinite in one point in respect to that experienced by other points. It may hence happen that this pressure may surpass, in some parts of the body, the resistance opposed to it by the air; the air then gives way, and the fluid passes away, as it were, through an opening. This takes place at the extremity of points, and on the sharp edges of angular bodies; for it has been demonstrated that, at the summit of a cone, the pressure of the electric fluid would become infinite if the electricity could be accumulated there.

It is impossible for us to give here a more complete idea of M. Poisson's labours, which are entirely within the domain of pure mathematics. We shall confine ourselves to adding that Mr. Plana took up a portion of the subject treated of by M. Poisson, in a memoir on the distribution of electricity on the surface of two insulated conducting spheres, published at Turin in 1845. He examined the different cases that may be presented by the problem: that in which the spheres are in contact; that in which they are separated by any interval; that in which this interval by which they are separated is very small in comparison with the distance of their two centres. Mr. Plana has, in like manner, demonstrated in a more rigorous way certain admitted principles on the relations between the thickness of the electric curve, and the forces which emanate from it; as well as the theory of the proof-plane, against which objections had been made. In this great work, which is the fruit of a very deep mathematical analysis, the mass of the electric matter, and the form that it assumes, are the only elements taken into consideration. The calculation is completely independent of the cause, whatever it may be, which retains free electricity on the surface of conducting bodies. Mr. Plana, in a note which terminates his researches, shows that we may demonstrate *à priori*, by the simple general fact that free electricity distributes itself on the surface of conducting bodies, that the law of its repulsive force must be that of *the inverse ratio of the square of the distance.* This very elegant demonstration, which is based solely on a result of observation, replies victoriously to Sir Wm. Snow Harris's objections against the law discovered by Coulomb; at least when it is circumscribed, as we have said, to the case of simple physical points.

### *Theoretic Explanation of the Movement of electrised Bodies; and the Electric Mill.*

The repulsion and attraction of electrised bodies is a consequence of the repulsion and attraction exercised upon each other by the two electric fluids. In fact, if the electrised bodies are of an insulating nature, the fluids, not being able to separate themselves from the ponderable particles to which they are united, draw them with them in their attractive or repulsive movements; at least, when the electricity is not too feeble, or the bodies are not too heavy to obey these actions. But if the two bodies are conductors,—if, for example, they are pith-balls, we must refer to atmospheric pressure in order to explain their movements. Since the two balls have the same electricity, immediately they are brought near to each other their electricities repel each the other; and being able to travel freely, they arrange themselves into the most remote portions of the balls. There they each form a stratum which, acting exteriorly in a contrary direction to the atmospheric pressure, diminishes its effect; whilst this pressure experiences no resistance on the interior portions of the surface of each ball, from which the fluid has been driven. Being more pressed upon by the atmosphere from within outwards, than inwards from without, the two balls separate. When they have a contrary electricity, the two electricities convey themselves, by virtue of their mutual attraction, into the portions of the surface of each ball that are nearer to each other; and these diminish the effect of the atmospheric pressure, which, not being counterbalanced on the exterior part of the surfaces, drives the balls one towards the other. We can imagine that the same explanation is applicable to the case in which there is only one movable ball opposite to a fixed electrised body; it is equally applicable to the case in which the movable ball is not electrised; for, as we have already seen, it is first electrised by induction, and the action takes place between two bodies both electrised.

Finally, there is another case of movement in electrised bodies that we have not yet described, and which merits especial mention, on account of the interest it presents in a theoretical point of view. It is that which is realised by a small apparatus, known under the name of the *electric mill.*

The electric mill consists of a thin stem of metal, whose two ends are pointed, and bent in an opposite direction, and which is itself balanced upon a pivot by means of a cap fixed to its centre of gravity. The pivot is put into communication with the conductor of an electrical machine, and, as soon as the latter is in action, the stem acquires a rapid rotatory movement, as if the extremities of the points were powerfully repelled. In this experiment the electric fluid that is spread over the surface of the stems of the mill, exercises everywhere a pressure on the surrounding air; if it found no escape, the opposite pressures being always equal, the apparatus would remain at rest. But it escapes by the points, where it overcomes the atmospheric pressure; and, as it no longer exercises any pressure on the orifice of escape, the pressure, which continues to be exercised on the opposite point, causes the movement by a true *recoil*, analogous to that produced by liquids or gases upon reacting machines during their escape. We shall return to this explanation, for it is not altogether free from certain objections; and we shall see that the experiment of the electric mill is probably connected with a more general phenomenon of dynamic electricity. Four or five branches, instead of two, are given commonly to the electric mill (*Fig.* 65.); the form of the experiment may also be varied by making, for example, a stem that is terminated by two points turned in opposite directions, ascend along two wires by the effect of the escape of electricity (*Fig.* 66.).

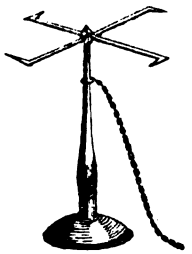
*Fig.* 65.

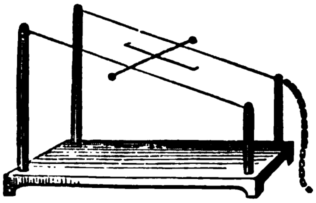
*Fig.* 66.

### *Examination of the Part attributed to atmospheric Pressure, in the Phenomena of static Electricity.*

The part attributed by theory to atmospheric pressure in the phenomena of static electricity, is not free from all objection. Some facts that we are about to relate are but little favourable to it. M. Becquérel succeeded in developing by friction, and in maintaining under vacuum, a notable quantity of electricity in a gold-leaf electroscope. Although the air had been rarefied to $\frac{1}{23}$th of an inch, the gold leaves remained diverging, and consequently retained free electricity, for more than two days. It is very difficult to admit that the small quantity of air remaining in the receiver had been able to exercise a sufficient pressure to produce this effect.

Hawksbee and Gray had also observed that electrised bodies attract light bodies, as well in vacuo as in air; but, as they were insulating bodies, we can prove from this nothing very positive against the action of atmospheric pressure, when conducting bodies are concerned. It is not the same with the experiments recently made by Sir W. Snow Harris. This philosopher had fixed a copper ball, of two inches in diameter, at the extremity of an insulated metal rod; and, after having placed it in the centre of a receiver, had put it in communication with an electroscope by another rod; he then gave to the ball a quantity of electricity such that the deviation of the electroscope was 40°. This divergence was maintained even when $\frac{59}{60}$ths of the air had been removed from the receiver. The result was the same when the electroscope itself was placed under the receiver, and when it was electrised directly by means of an insulated metal rod communicating with the exterior. The divergence did not vary even when the air was reduced by $\frac{69}{70}$ths of its original density. In both cases the gold leaves of the electroscopes gradually approached, when an insulated metal ball was brought near to the electrised body; but they separated again when the ball was withdrawn: this was evidently a simple effect of induction. In all these experiments the interior of the bell-glass must be well dried by chloride of calcium, or any other substance of the same kind.

The facts that we have just related show, that if the air retains electricity on the surface of bodies, it is not by virtue of the pressure it exercises, but rather by virtue of the insulating power which depends on its very nature. The air and gases act, therefore, as an insulating stratum of resin or gum-lac; and, as in the most perfect vacuum, bodies still retain at their surface a film of air that remains adhering to them: this circumstance would explain how it happens that electric phenomena are manifested even in vacuo. It is true they are never so intense as in air; and the electricity cannot be maintained beyond a certain intensity upon the surface of bodies so circumstanced; but this would simply be a proof that the insulating power of air is less when the gaseous stratum by which the body is covered is reduced to a great degree of thinness, and the density of the air that remains in the receiver is diminished. Sir W. Snow Harris has observed that the attractions and repulsions between electrised bodies take place in vacuo as they do in air; a further proof of the error we should commit by admitting atmospheric pressure to play a part in these phenomena. This fact, on the other hand, is very well explained by admitting that the electricities are retained, in the portions of the surfaces where they are distributed, by the insulating effect of the film of air that remains adjacent, and in no degree by atmospheric pressure: once retained at the surface by this cause, as they would have been by a coating of varnish, they are no longer able to obey their mutual attraction or repulsion, except by drawing with them the bodies themselves, if their mass is not too great. This explanation, even though it should not be based upon observations made in vacuo, would seem to us in every case preferable to that in which atmospheric pcessure is made to intervene; this intervention being implicitly founded on a purely hypothetic idea, namely, that electricity is a fluid of the same kind, and about the same tenuity as air and gases.

Further, while still believing that the electric effects observed in vacuo, as well as others no less curious, of which we shall speak hereafter, are due to the film of air that remains adhering to the surface of bodies, we by no means wish to pretend that conducting bodies have not for themselves the property of preserving, or rather of *coercing*, on their surface a certain dose of electricity, feeble, it is true, but nevertheless sensible. This is a delicate point, to which we shall have occasion to return hereafter.

### *Inductive Power of di-electric Bodies.*

If the theories that we have unfolded seem to be defective, as far as concerns the part which they attribute to atmospheric pressure, they are now attacked by another class of facts, which tend to nothing less than to overthrow them entirely by leading to the denial of actions at a distance, and replacing them by molecular or contact actions. Before unfolding the theory to which Mr. Faraday has been led by these facts, let us study the facts themselves, as discovered by this philosopher; we shall then be in a better condition to appreciate the degree in which they must modify, if, as we think, they do not entirely overthrow, the theories founded upon the labours of Coulomb and Poisson. When an electrised body acts by induction upon a conducting body, there always exists between the two bodies an insulating medium, generally a stratum of air, sometimes a plate of glass or a plate of resin. To this medium there had never been attributed any other than a passive part; that is to say, it was only regarded in the relation of the obstacle it opposed to the reunion of the contrary electricities of the two bodies; the only difference that was established between the different media was, that some, being endowed with a greater insulating property than others, permitted the two electrised bodies to be brought nearer to each other without there being an electric discharge between them. With regard to the effect of induction itself, it was admitted that it depended only on the distance by which the two bodies were separated, and in no degree on the nature of the interposed medium. Mr. Faraday has shown that things do not take place in this manner. The following is the fundamental fact, which serves as the basis of his researches.

An insulated disc A is electrised positively. Near to this disc, and at the same distance, are placed two other insulated discs, which are similar to it, one on one side, which we will call B, the other on the other side, which we will call C. A acts by induction upon B and upon C; and, if the two latter discs are made to communicate with the ground, they preserve only their negative electricity, which is disguised by the positive of A. If B is brought towards A, so that it becomes nearer than C is, the electroscope of B is immediately seen to indicate the presence of a little positive electricity; and that of C to show the presence of a small quantity of negative electricity, which has become free. This double effect arises from the inductive power of A upon B becoming greater than it was by diminishing the distance, whence there resulted the decomposition of a new quantity of electricity in B: now, since the communication of B with the ground has been interrupted, this disc preserves the positive electricity produced by this new decomposition, but the negative being attracted by the positive of A is disguised by it; it hence follows that a stronger proportion of the electricity of A being employed to disguise that of B, the proportion acting upon C becomes less, and consequently a part of the negative electricity that was disguised before becomes free. Hitherto the phenomena have occurred exactly as theory would have them. But if, after having restored things to their primitive state, namely, the two discs B and C *to the same distance* from A, we interpose a disc of gum-lac between A and B, we produce the same effect as if B had been brought nearer to A; that is to say, we increase the induction of A upon B. The distance, however, as well as all the other conditions of the experiment, have remained the same; there is no other change than the substitution of a disc of gum-lac for the stratum of air, whose place it occupies. If a disc of sulphur is interposed, the same effect is produced, but in a still greater degree. Thus insulating bodies have a proper inductive capacity; and, as we see, that of gum-lac is greater than that of air, and that of sulphur is greater than that of gum-lac. In order to characterise this property, Mr. Faraday names the bodies, which possess it, *di-electrics*, in opposition to conducting bodies. In fact, the interposition of a conducting body produces an entirely opposite effect: if a metal plate, either insulated, or, which is still better, communicating with the ground, be interposed between A and B, B immediately gives very strong signs of negative electricity, which arises from the induction ceasing to act upon it; its negative electricity, which was formerly disguised, becomes free. C also gives signs of negative electricity, because all its electricity can no longer be disguised by A, on account of the presence of the new metal plate; and, consequently, a portion becomes free. Thus, to put a metal disc between A and B, corresponds to replacing B by another disc nearer to A than it was, and consequently withdrawing it from the induction of A. We see, therefore, that the effect which follows from the interposition of a conducting plate has no relation with the effect produced with the interposition of a di-electric body.

We have now to determine the inductive capacities or the relative inductive power of different di-electric bodies. With this view Mr. Faraday made use of Coulomb's electric balance, having for a torsion thread a filament of glass, twenty inches in length, and of great elasticity; at the extremity of the movable lever is a gilt pith ball, three-tenths of an inch in diameter. The proof-plane is a similar ball. The substance submitted to proof is placed between two concentric metal spherical surfaces, the interior of which is provided with a metal handle, insulated so as not to communicate with the outer one: this forms a true Leyden jar, the insulating stratum of which is the di-electric substance, and the two coatings are the spherical surfaces (*Fig.* 67.). There is a second apparatus, perfectly similar to the former, in which air alone serves as the insulating stratum between the two spherical surfaces. We begin by removing the di-electric body from the former apparatus, so that they both have air as the insulating body. A certain charge

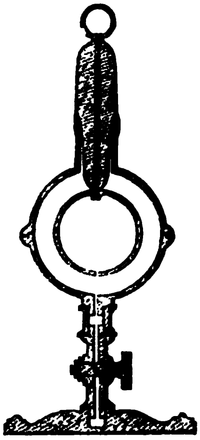

*Fig.* 67.

of electricity is given to the interior spherical envelope, the exterior being put in communication with the ground; we then determine the reaction of the electricity that remains free on the interior surface, by touching with the proof-plane a knob, placed at the end of the rod, that communicates with it. We find 250° for the angle of torsion: this is what Mr. Faraday found in his experiment, which is the one we take as our example. The two apparatus are then made to communicate by their inner coatings, and are then separated: after their separation, 120° is found upon one, and 124° upon the other; so that we may say that the electricity is equally divided between them; and this is what we should expect, because they are perfectly similar in every respect. The same experiment is repeated, after having substituted in one of the apparatus a stratum of gum-lac in place of the stratum of air. We begin by charging the air apparatus as before; and find 290° as the angle of torsion, obtained after the contact of the proof-plane; communication is established between the interior surface of the air apparatus, and that of the gum-lac apparatus. Had this latter contained the stratum of air, as in the former experiment, we should have found, after the separation, 145°, or the half of 290°, on the interior coating of each apparatus; but the substitution of gum-lac for air changes all the results. We find only 114° for the charge remaining on the interior surface of the air apparatus, and 113° for the charge of the interior surface of the other. Now it is evident that the air apparatus, having a charge of only 114° instead of 145°, which it ought to have had, arises from a charge of 176°, being the difference between the total quantity 290° and 114°, having passed into the gum-lac apparatus: we ought, therefore, to have found 176° instead of 113° in this latter; and, as we find only 113°, it is because, induction being stronger through gum-lac than through air, a more considerable portion of the free electricity has been disguised; in fact, the quantity of electricity, measured by the angle of torsion, which is the free quantity, ought to be less, in proportion as the inductive power is greater, or, which comes to the same thing, this power is the inverse of the quantity that remains free. Thus, if we call 1 the inductive power of a stratum of air, and $x$ that of a stratum of equal thickness of gum-lac, and remembering that the 113° of charge, in the experiments which were given with the insulating stratum of gum-lac, would have given 176° with an insulating stratum of air, we shall have:—$1 : x :: 113° : 176°$; whence, $x = \frac{176}{113} = 1{\cdot}55$.

In order to verify these results, Faraday then made the inverse experiment: he began by charging the gum-lac apparatus; he then made it communicate by the inner coatings with the air apparatus. He found, in this case, that the free electricity, with which each of the two apparatus were charged after their separation, was stronger than the half of the initial charge of the former. This result proves that the total quantity of electricity, with which the interior surface of the gum-lac apparatus is charged, is, under the same circumstances, much more considerable than that with which the air apparatus is charged, because the former, in giving to the latter a stronger charge than the half of the charge, which this latter would have acquired had it been charged directly, does not itself lose the half, but merely a more feeble proportion of its proper charge. The experiment made in this manner shows also that gum-lac has a stronger inductive power than air, and it gives the same numerical result for the relation of these two powers. Different di-electric bodies have been submitted to the same proof, always comparing them with air; the experiment upon each of them has been repeated several times, and the following results have been obtained.

*Specific inductive powers, that of air being* 1.

| | |
|---|---|
| Glass - - - - - | 1·76 |
| Gum-lac - - - - - | 2·00 |
| Sulphur - - - - - | 2·24 |

The result of 2·0 obtained for gum-lac is a little different from that which we found above; this is due to the stratum of gum-lac, in the experiment we have described being not so thick as that of the air, with which it was compared. Faraday has found that, by supposing the thickness the same, the inductive power of gum-lac ought to be 2, and not 1·50.

Sir W. Harris has completed Faraday's experiments: he gave to each substance the form of a disc of the same thickness, and he covered it on each face with a disc of tin-foil, one-half less in diameter. These were true magic pictures, with insulating substances of different natures. By operating in this manner he has drawn out the following table of the inductive power of these substances:—

| | | | |
|---|---|---|---|
| Air | 1·00 | Glass | 1·90 |
| Resin | 1·77 | Brimstone | 1·93 |
| Pitch | 1·80 | Gum-lac | 1·95 |
| Bees-wax | 1·86 | | |

Faraday has found that, among liquids, those which are the best insulators, such as turpentine and rectified naphtha, when submitted to experiment, have an inductive capacity superior also to that of air; but, in the experiment with liquids, we must operate on those alone which do not possess of themselves any conducting power, a property that would interfere with the results.

The different gases have all been similarly subjected to experiments; they have been compared two and two, by placing one in one apparatus, and the other in the other. In like manner, the effect of air more or less rarefied has been compared with that of air maintained at the normal pressure; also that of air maintained at 0°, with that of air heated from 50° to 200°. As a result of these multiplied experiments, we have succeeded in detecting that all gases have the same power and possess the same inductive capacity, and that the variations in pressure or in temperature, and consequently in density, do not produce any further effect. When the rarefaction of the gas arrives at a certain point, however, the discharge occurs between the two coatings; but, up to this moment, there is no change in its di-electric property. We may even give the apparatus so feeble a charge that the discharge does not occur, and we thus prove that, whatever be the degree of the rarefactions of the air, its inductive capacity remains the same.

### *Polarisation of Di-electrics, and molecular Theory of Induction.*

It follows, therefore, from the experiments we have related, that the nature of the insulating or *coercing** medium through which the induction operates, exercises a marked influence on the phenomenon, and that this new element must be added to those which we have already recognised as having an influence on its intensity, such as the greatness of the electric charge, the distance of the induced body and that of the inducing body. It is an effect that is due to an action proper to bodies; but what is this action? Faraday admits that it consists in the generation of molecular strata, alternately negative and positive, which succeed each other in the dielectric, and which constitute what is called its *polarisation.* However, some facts that had already been observed by Beccaria and other philosophers, and studied more closely by Faraday himself, by showing that electric charges may penetrate to a certain depth into coercing bodies, seem but little favourable to this hypothesis. Thus, two discs of spermaceti, after having been placed upon each other, were armed with metal plates so as to form a magic picture. The system was electrised and then discharged, and the two discs of spermaceti having been separated, it was found that the one upon which the positive coating was placed, possessed positive electricity, and that the other was negative, like the coating which covered it. This experiment proved, in an evident manner, the fact of penetration. It is true to say that spermaceti is not a perfect insulator, and that this circumstance may explain to a certain point how the two electricities, being strongly attracted towards each other, have penetrated it in part.

We have already seen, in the fact of the possibility or

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* We shall frequently employ this word, which expresses the idea of a body acting in a certain manner upon electricity better than the word "insulating," which indicates only a passive or negative state.

removing the two coatings of a Leyden jar without discharging it, the proof of the adherence or of the penetration into glass of the electricities possessed by bodies in contact with it: we may draw the same conclusion, as far as resin is concerned, from the experiment of the Lichtenburg figures. However, these facts, while demonstrating that electricity accumulated upon the surface of an insulating body may penetrate it to a certain depth, greater or less according to the nature of this body, are not conclusive against the possibility of its polarisation.

The following experiment of M. Matteucci seems, on the other hand, to prove in a positive manner the polarisation of coercing bodies. Many very thin plates of mica are superposed and strongly compressed; upon the two opposite faces of this kind of pile are applied two tin-foil coatings, so as to constitute a magic picture. After having charged it, the coatings are taken away with an insulating handle, and the different plates of mica are then successively detached one from the other. It is found that each of them has one of its faces positive, and the other negative; the face in contact with the positive coating being positive, and that which had been in contact with the negative coating being negative. The intensity of the electric charges goes on diminishing from the extreme plates, where they are at their maximum, to the middle plates, where they are at their mininum: this difference is probably due to the surfaces of the plates being found greater at the extremities than at the centre of the system. Care, however, must be taken, in separating the plates from each other, to avoid all friction; we discover, by direct means, that the simple fact of detaching them does not constitute them in an electric state. The polarisation of insulating or coercing bodies seems to be proved by the experiment we have just related; and it may equally occur, even though their insulating power is not sufficiently good to prevent their being penetrated to a certain depth by the electricity of a coating applied upon their surface. Setting out from the principle, that all insulating bodies are susceptible of being polarised, Mr. Faraday deduced the consequence, that it is by their intervention that all the phenomena of induction are brought about, and that there is no action at a distance, or at least at a distance greater than that which separates two molecules that immediately follow each other. Most commonly it is the air whose polarised particles, like the plates of mica in the preceding experiment, transmit from one electrised body to another, which is not so, the inductive effect of the former. It may, in like manner, be any other gas or insulating body; but then the effect is transmitted in a better or worse degree, according to the inductive power of the body. This manner of regarding the phenomena differs essentially from that which we had hitherto adopted: in this latter, the insulating or coercing bodies only play a passive part, consisting simply in preventing the reunion of the opposite electricities, without themselves experiencing any modification in the electric state of their mass.

To render the molecular polarisation of the contiguous particles of a di-electric body visible, which cannot be the case when we are acting upon air, we employ essence of turpentine, in which are placed filaments of silk about a tenth of an inch in length. The bottom of the vessel, in which the essence is placed, is of metal, and communicates with the charged conductor of an electrical machine: no effect is manifested until we bring near to the surface of the liquid a conductor held in the hand; but at the moment when this approach takes place, we see the filaments of silk arrange themselves in every direction, and unite end to end, so as to form an uninterrupted chain between the metal body and the exterior conductor, towards which they tend without touching it.

These particles adhere strongly to each other, as we may discover by touching them with a glass tube; but immediately the conductor of the machine is discharged, they fall and go to the bottom of the vessel. The filaments of silk represent the particles of the essence in which they float; and the polar state that they assume is similar to that of conductors insulated from each other, and placed under the same circumstances. In place of the filaments of silk we may put powdered sugar into the vessel, the particles of which in a similar manner form a chain, which indicates their polar state. Small particles of gold leaf have also been placed in it, which arrange themselves in a similar manner, but which, on account of their conducting nature, discharge themselves upon each other, as is indicated by the small sparks that are seen to glisten between them.

If we regard the whole mass of a di-electric placed near an electrised body, we shall remark that each of its particles, according to the preceding theory, must be in active relation not only with the particles which precede it, but with all those that surround it in all directions; from this there results a diffusion of forces in every direction, and the inductive lines of action along which polarisation is brought about, when they encounter no obstacle, tend to propagate from each particle as from a centre; they may even take a curvilinear direction, when any obstacle is opposed to their free propagation.

Faraday has endeavoured to verify the accuracy of this latter conclusion, by proving directly from experiment that induction may be exercised in a curved line. With this view he took a cylinder of gum-lac 6 or 8 inches long, and about an inch in diameter. He fixed it vertically on a wooden foot, and placed a metal sphere of a diameter at least equal to that of the cylinder upon its upper extremity, which was rendered concave for this purpose. Then, having rubbed the gum-lac with warm flannel, in order to electrise it without touching the conductor, he touched with the proof-plane the different points of the metal sphere, electrised as it was by the induction of the negative electricity of the gum-lac. The proof-plane was always charged with positive electricity, at whatever point of the surface of the conductor it was placed, —a proof that no part of this conductor takes from the gum-lac by communication its negative electricity, and that it is only by induction that it is electrised throughout. We must always take care to touch the proof-plane whilst it is in contact with the spherical surface; but, according to the points of this surface with which it is in contact, it acquires a stronger or a more feeble charge. Thus, if we touch the spherical portion very near the cylinder upon which it is placed, there is a charge of 512°; by touching it on the summit, the charge is not more than 130°; and it is 270° if the contact takes place at a point equally distant from the summit and from the very point where the sphere rests upon the cylinder of gum-lac. These differences in the intensity of the electricity induced upon the different points of the sphere, not being able, according to Mr. Faraday, to be explained but by admitting that, since induction takes place by the intervention of the particles of air, it is necessarily more feeble at the points upon which it can exercise itself only along curved lines, such as the summit and surrounding parts, than it is at the nearer points upon which it exercises itself along straight lines, or along a very feeble curvature.

Analogous and still more striking results are obtained by placing upon the cylinder, instead of a sphere, a hemisphere or metal disc, the diameter of which is greater than that of the cylinder (at least double). If we touch the different points of the hemisphere with the proof-plane, we find that the charge which it acquires is less upon the points of the flat circular surface which terminates it above, than it is upon the lateral parts of the curved surface; and that it is at its minimum in the centre of this flat surface. But if we elevate the proof-plane itself vertically over the centre, the induced charge that it acquires becomes more considerable up to a certain height, beyond which it decreases. When it is a disc that is placed upon the gum-lac cylinder, we obtain no signs of induced electricity by touching it at its centre; while the proof-plane is electrised by induction, if we raise it above this centre.

From these various experiments, and especially from the latter, it follows that the induction does not take place through the metal; that it is, therefore, brought about by the intervention of the molecules of air, and along lines which, setting out from the different points of the gum-lac cylinder, curve themselves more or less around the sphere, the hemisphere, or the disc, in order to arrive at the point where, the plane being at the very centre of the disc, the curvature of the lines of induction is too strong for induction to be propagated to it.

The effects remain the same when the metal body that rests upon the gum-lac cylinder communicates with the ground by means of a wire passing through the axis of the cylinder. On the other hand, if the gum-lac is entirely surrounded with a metal envelope communicating with the ground, the whole of the effects cease to take place.

Without concealing from ourselves the importance of the preceding experiments, we cannot, however, regard them as leading necessarily to the conclusion which their author has drawn from them, namely, that induction is brought about by the intervention of particles of air, arranged according to curved or straight lines. In fact, it would not be impossible, as we think, to explain, by the received theories of induction, and by resting upon the principles that we have established in the former chapters of this Second Part, the electric state of metal surfaces, placed upon the gum-lac cylinder, as detected by the proof-plane. We recognise, however, that there is a new point acquired to science, namely, that of the polarisation of the insulating body; in this respect, the former experiments of Faraday, and those of Matteucci that we have related above, establish it in a positive manner; if not for air and gases, at least for solids and liquids. With regard to air and gases, we shall find in phenomena of another order, namely, those that relate to discharges, a demonstration, if not direct, at least sufficiently proving the existence among them of this polarisation. Considerations of this kind also follow from Mossotti's labours, with which we shall be occupied further on.

### *Faraday's general Theory of Static Electricity.*

Setting out from the preceding facts, Mr. Faraday lays down as a principle, that an absolute electric state, whether positive or negative, cannot exist in a body; but that every electrised body always finds near to it, either in the insulating or conducting bodies with which it is surrounded, a contrary electrical state to its own, which makes induction a general phenomenon. This general condition, to which all electrical phenomena are subjected, possesses a great analogy with the fact of the action and reaction of mechanical bodies. Thus, a steel spring presents to us the example of a body susceptible of exciting a force as soon as an exterior agent renders it evident. The condition which the action of the spring must obey, is to exercise itself to the same degree in two opposite directions. If we compress or extend the spring, we perceive its action and its reaction; not only do we thus establish the existence of two opposite forces at its two extremities, of which one must be regarded as positive, the other as negative; but we shall perceive that each intermediate section of the spiral is in a similar state of action and reaction, or, which comes to the same thing, in a kind of polar state. In estimating the sum of the forces we measure it in a certain direction; and we are compelled to admit that the sum of these forces, in the opposite direction, is equal to the former. It must be the same with electricity. All the phenomena of positive and negative electricity may probably be explained by the action and reaction of a force capable of being manifested in different degrees in different substances, more simply than by the hypothesis of imponderable fluids. The two opposite forces of electricity resemble in fact action and reaction, in that they always accompany each other.

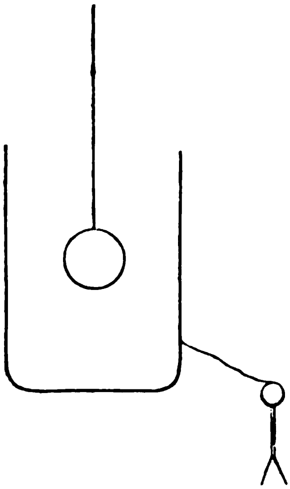

*Fig.* 68.

The following is an experiment which, in fact, shows that the electricity developed by induction is contrary, and perfectly equal in intensity, to that which developes it. An insulated and electrised ball is placed in the interior of a cylindrical jar, the dimensions of which are very great, in relation to those of the ball (*Fig.* 68.). The jar communicates with a gold-leaf electroscope, which diverges immediately that the electrised ball is introduced within; the ball is then made to touch the jar, and it loses its electricity, and the electroscope diverges neither more nor less than before. This experiment proves that the electricity which is induced by the ball and that which it possesses are exactly equivalent in quantity and in power, whatever be the position of the ball in the interior of the jar; whether it be nearer or farther from the bottom or the sides, the divergence of the electroscope is the same. Instead of a single jar, three or four may be placed concentric and insulated from each other by plates of gum-lac, which separate the bottom of each of them from the bottom of the succeeding jar (*Fig.* 69.), the electroscope still communicating with the outer surface of the outer jar: the effect is exactly the same as if there were only one jar; it is also the same if the four jars are in metallic communication with each other. When a gum-lac or a sulphur jar is introduced in place of the inner jar, leaving still a metal jar outside and the electrised ball in the centre, not the slightest change occurs in the divergence of the gold leaves of the electroscope of the outer jar. We see, therefore, by this experiment, that the principle laid down above, of the equality of the two forces that constitute the two electricities, is general; for it is verified in very different cases, and notably in di-electrics, such as gum-lac and sulphur, of an inductive power very different from that of air. Another manner of demonstrating the same principle is to introduce a small electrised sphere into the centre of a hollow unelectrised and insulated sphere. The electricity which the latter acquires by induction is, as the indications of an electroscope show, exactly equal to that which it acquires by communication on being placed in contact with the small interior globe, which has remained electrised.

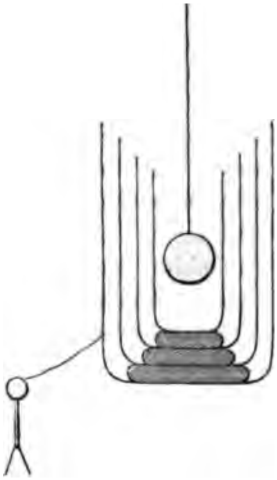

*Fig.* 69.

By applying his theoretical ideas to other and different phenomena of static electricity, Faraday is led to admit that the tendency of electricity to distribute itself on the surface of conducting bodies is more apparent than real; and that the experiments which prove that there is not in fact any free electricity, except at their surface, are easily explained in another manner. No electric charge, according to his theory, can be manifested in the interior of a body, on account of the opposite directions of the electricities in each of the interior particles; whence the resulting effect is null: whilst the induction exercised by exterior bodies renders the electricity sensible on the surface. From this manner of regarding it, electricity must show itself only on the surface of a conducting envelope, whatever be its conductibility or the insulating property of the substance placed within. Faraday, in fact, demonstrated this by strongly electrising oil of turpentine, placed in a metal vessel. There was no apparent electricity except on the exterior surface of the vessel. He also constructed a cubical chamber twelve feet square, the wooden sides of which were covered outside with tin-foil: he insulated it; then, after having introduced into it electroscopes and other objects, he electrised the interior air with a strong machine. No trace of electricity was manifested within, whilst considerable sparks and luminous brushes darted off in all directions from the exterior surface. While these experiments complete those of Coulomb, in which he operated only upon conducting bodies, they render the explanation that was given rather improbable, since it was based upon the free propagation of electricity in the conducting mass; whence it followed that this electricity distributed itself entirely on the surface. When once the phenomenon has occurred in the same manner with insulating bodies placed interiorly, this explanation is not tenable.

With regard to the influence of form upon the quantity of electricity accumulated at the surface of bodies not spherical, it would always depend, according to Faraday's theory, upon some points of the surface being exposed to a greater amount of inductive forces than others. Thus the extremities of a cylinder, or of an elongated ellipsoïde, would be more strongly electrised than the rest of the surface, because there go from them a greater number of filaments of polarised particles, establishing with surrounding conductors the communication necessary for induction. A point is far superior in this respect; for it is the centre whence emanate, in all directions, the lines of inductive force, which, for example, when a ball is in question, are found distributed over a greater extent, and do not set out from a single point only, but equally from all points of its surface.

In the theory that we have been explaining, the mutual repulsion of bodies charged with the same electricity is only apparent; it is called into existence because there is no electricity on the nearer surfaces, and because each of the bodies is attracted in opposite directions by the surrounding bodies, upon which induction determines an electrical state dissimilar to their own. We may even prove, by means of the proof-plane, that the two gold leaves of an electroscope, when they are diverging, have no electricity on their interior surface, whilst they are strongly electrised exteriorly, however thin they may be in other respects. Repulsion is also explained by attributing it to the attraction exercised upon each of the two gold leaves by the contrary electricity, developed by induction, in the strata of air in contact with their exterior surface. This mode of action of the air is much more natural and more probable than that in which it is regarded as determining repulsion by the greater pressure from within outwards, than inwards from without, which it exercises upon electrised bodies. However, the experiments which show that repulsion takes place in vacuo as well as in air, would seem to be equally contrary to these two explanations, except that, in the former, we admit the effect by induction of the ambient bodies, even when they are placed at a great distance.

Faraday was not contented to follow out the consequences of his theory, as far as the phenomena of static electricity alone are concerned. He followed them out equally in the effects of dynamic electricity, of which indeed he made the happiest applications. He studied and classified the different modes in which electrical discharges take place between bodies charged with a different electricity. He particularly showed that the return, as far as electricity is concerned, to a state of equilibrium, of the polarised particles of di-electric or coercing bodies constitutes discharge, and is the origin of the greater part of the phenomena that accompany it, such, especially, as the rupture of these bodies. He has farther shown that, although the inductive capacity is in no degree modified in gases, by a difference in their nature or their density, the distance at which the discharge with a spark can occur is extremely influenced by the physical state of the medium, as also by its chemical nature. Density, in particular, has this influence, that the limit of the charge that an insulated conducting body may acquire depends on the number of the particles of the ambient di-electric, to which this charge may be communicated by induction; the fewer there are, the more quickly we attain to the limit. It would also appear that, for an equal number of particles, they experience the effects of induction more or less rapidly, according to their nature. But this subject, and all the details connected with it, will be treated upon in the Fourth Part; we shall not detain ourselves with it any longer at present.

We have thus laid down Mr. Faraday's theory of the phenomena of static electricity. Although it still has need of being more precise, it deserves, however, even in its present state, to draw the serious attention of philosophers. It has in its favour, as we shall see, the establishing a more intimate connection between the phenomena of static and those of dynamic electricity; it seems to be based upon a sound principle, namely, that electric actions are never manifested, except by the intervention of material particles; finally, it tends to bring about a remarkable approximation between electric forces and the other forces of nature. M. Mossotti, a learned mathematician, by the application of calculation and of the laws of mechanics, has already succeeded in explaining by this theory, in a satisfactory manner, the laws discovered by Coulomb, and which Poisson had connected with the theory of two imponderable fluids. However much we may recognise the application of this latter theory, we cannot yet completely admit the new; in other words, we cannot, in the incontestible fact that the insulating medium that separates two bodies, between which electric induction is exercised, modifies this action and is itself influenced by it,—we cannot see in this the demonstrative proof that induction is exercised by means of it. Could it not happen that, induction having determined at a distance an electric state in a body different from that existing in the inducing body, these two contrary electricities would modify the electric state of the particles interposed upon the line that separates them, as in their turn they may be modified by these particles? What would make us incline to an explanation of this kind, is the difficulty of conceiving a power of induction emanating indifferently in all directions from an electrised body, like a species of radiation; whilst we know by experience the very great influence that the presence of a conducting body, placed in a certain position, exercises over the direction of this emanation. It is true that Faraday and the partisans of his theory reply to this objection by the experiment that we have quoted above, of the small electrised sphere, placed in the centre of the large one, and by certain considerations, drawn from the reaction that the conducting body, when exposed to the influence of an electrised body, must in its turn exercise over this body. But we do not believe, notwithstanding these replies, that the principle of radiation of the inductive power in every direction indifferently is demonstrated. The effects that occur in vacuo, as we have already said, equally appear to us as a very strong objection against the theory that denies all action at a distance; unless we suppose that the particles which remain even in the most perfect vacuum are sufficient to explain the phenomena that occur, which appears scarcely probable. Furthermore, the very obscure and curious part that vacuum plays in electrical phenomena will also in the Fourth Part form the subject of a close examination; for it is intimately connected with the effects of electric discharges.

The objections that we have been offering against Faraday's theory are confirmed by some recent researches that Matteucci has made on the propagation of electricity in solid insulating bodies; and as the result of which he arrived at conclusions different from those of Faraday, upon the part played by these bodies in the phenomena of induction. He has satisfactorily proved that, in insulating bodies, there is developed in presence of an electric body a molecular electric state, according to which each molecule of the insulating body has the two contrary electric states developed on its opposite faces. This molecular electrisation is manifested in a different degree by the different insulating bodies: it is this which is the cause, for example, of sulphur and resin exercising an unequal attractive power upon the same electrised pendulum: moreover, it is developed or ceases at the very moment when the presence of the electrised body commences or ceases. The molecular electric states may destroy each other; and the electricity may propagate itself either on the surface or in the interior of insulating bodies; the insulating power consists precisely in the greater or less resistance opposed by bodies that are endowed with it, to the destruction of the molecular electric states by the entry or the escape of the electric fluid from the molecules themselves; in no case can electricity penetrate into the molecules of an insulating body without having overcome the repulsive force of the electricity of the same kind that is found upon the molecules themselves.

All the experiments by means of which M. Matteucci arrived at the results that we have been enumerating were made by means of apparatus similar to Coulomb's balance; but the details of the construction of which corresponded with the particular object he had in view. It is easy, in particular, to prove the propagation of electricity in the interior of an insulating body. A cylinder of stearine or one of sulphur having been placed in contact with the conductor of the electrical machine in action, and then rubbed on its surface, gives signs of negative electricity; being then placed upon a conductor, it ceases to give them; and, in a little time afterward, it gives signs of positive electricity. Moreover, Faraday, by making use of discs of spermaceti, had already proved this penetration of electricity into insulating bodies.

The first and the most important of Matteucci's experiments is that which he made with insulating plates fixed by sealing-wax to glass rods 4¾ in. long, and which he introduced successively, holding them by this stem, into the interior of the cage of a Coulomb's balance, having its two electrised balls divergent. The insulating plate was introduced so that its centre was in contact with the fixed ball, the electric reaction of which it diminished at the end of a few seconds. And the ball in contact with the plate having lost a certain quantity of electricity, which has diffused itself upon the plate, the repulsive force that remains after the contact, when compared with that formerly existing, must in each case give the measure of the electricity that has passed into the insulating plate. Many experiments, made with plates of sulphur, showed that the greatest loss occurs with the thinnest plate, and the one that has the least surface; whereas, while the contact lasts, the electric force is the less, as the mass of the insulating plate is the more considerable. So that we must not confound this latter force with that which remains after contact has occurred; which may, according to circumstances, be greater or less than the former.

In comparing the effects obtained with plates of different natures, we find very variable results with glass, which is always more or less hygrometric; and, on the other hand, very constant results with gum-lac and sulphur, which produce the same loss of electricity upon an electrised metal ball, when touched by them. A glass plate, covered with a coat of gum-lac varnish, produces the same effect, providing the coating be at least $\frac{1}{100}$ in. thick. Other experiments were made by putting the plate between two contrary electric charges, or, in other words, by using plates of different natures as the insulating stratum between the two coatings of a magic pane. It was by operating in a very similar manner that Faraday, and after him Harris, found differences between different bodies, with regard to their influence upon the charge of the two coatings, and determined their specific inductive power. M. Matteucci, thinking that these differences are due only to differences in the propagation of the electricity, either upon the surface or at a very small depth in the interior of the bodies, formed, with this in view, an insulating plate, hollow within, formed of plates of mica, secured together with gum-lac. The surface of this plate was about 4 sq. inches, and it was a kind of box; its interior surface was covered with a layer of gum-lac $\frac{1}{10}$ in. thick: it consisted then, in fact, of a stratum of air $\frac{2}{3}$ in. thick, interposed between two plates of mica covered with gum-lac. After having operated with this plate, M. Matteucci introduced into it melted sulphur, which thus formed a stratum of sulphur $\frac{1}{10}$ in. thick, substituted for the stratum of air: the results were exactly the same in both cases. They were also the same with a plate of sulphur and one of flint-glass, covered with a layer of sulphur $\frac{1}{12}$ in. thick, —with a plate of gum-lac and one of sulphur, covered with a layer of sulphur $\frac{1}{30}$ in. thick.

All these results would seem to prove that the differences found by some philosophers with insulating plates of different natures, employed for forming magic panes, are not due to a specific inductive power. In fact, we see that a certain insulating plate produces the same effects as another different one, provided that the surface of the former plate is formed of a layer of the same insulating material as that of which the whole of the second is composed; but it is necessary that the layer which is added should possess a certain degree of thickness, in order that its effects shall be similar to that of a plate formed entirely of the same substance as this layer. It is therefore to differences in the propagation of electricity, either at the surface or in the interior of different insulating bodies, that we must have recourse, according to Matteucci, in order to explain the phenomena observed by Faraday and by Harris.

The observations that we have just reported are unquestionably of a nature to cast some doubt upon the part played, according to Faraday, by insulating bodies in the phenomena of induction of static electricity. But, although we may recognise with Matteucci that electricity penetrates into insulating bodies, it is difficult for us to admit with him that the electricity diffused over their surface, and propagated into their interior, returns on the instant to the surface of this body, when it is covered with a metal plate in communication with the ground. The subject deserves, therefore, being further studied; in any case one point is gained, for it is to be deduced from all the experiments:—it is that of molecular polarisation, which has been demonstrated in insulating bodies, and which is probably the mode of the propagation of electricity equally in conducting bodies. In this respect Faraday's theory, although presenting in its details many objections, appears to us to rest in the main upon a perfectly just principle.

We shall return to this subject in the Fourth Part, when we are engaged upon electric discharges and their effects. There exists, in fact, between the molecular induction, that belongs to static electricity, and the discharges, that are one of the phenomena of dynamic electricity, an intimate connection, which establishes an important relation between the two forms under which electricity is presented.

### *Franklin's Theory of a single Fluid.*

We have not spoken in this Chapter of a theory which, by its apparent simplicity, and from the name of its author, enjoyed great favour for some years. It is Franklin's theory of a single fluid. This fluid possesses precisely all the properties that, in the theory of two fluids, are attributed to each of them considered separately. It is composed of particles infinitely attenuated, which all repel each other with a force the inverse of the square of the distance. In the theory of a single fluid each body in its natural state contains a certain portion of this fluid; if, in a given body, we accumulate a larger proportion, we electrise it *plus*, or *positively*; if, on the other hand, we diminish the proportion that it ought to contain, we electrise it *minus*, or *negatively*. So long as the natural state remains, no manifestation occurs; but, as soon as the state becomes positive or negative, there is then an electric action. We have further to admit, that there is an attraction between ponderable matter and the imponderable electric fluid; so that, when two bodies are in presence of each other, several forces are in conflict, which, according to their relative intensities, must determine the attraction or repulsion. These are, the repulsive force of the electric fluids which the two bodies possess; the attraction between the electric fluid of the one and the matter of the other; finally, the mutual action of the imponderable particles of one of the bodies upon those of the other. Æpinus, when subjecting this theory to calculation, was led to the singular consequence that, in order to explain the repulsion of two bodies negatively electrised, it would be necessary to admit that the mutual action of the particles of matter is repulsive, instead of being attractive. This result, which is so contrary to the ideas that have been admitted since Newton's time, has necessarily caused the theory that led to it to be renounced. On the other hand, the very pronounced and constant antagonism that is always found between the two opposite principles in electrical phenomena, can only be explained by the existence of two different fluids; or, which comes to the same thing, of two different modifications of the same fluid. What are these modifications? What is this fluid, which is susceptible of undergoing them? Here, we must confess, are questions that are not resolved; and we are far from presenting the theory of the two fluids, such as we have explained it, as the limit to our knowledge. It is to us only a convenient means of connecting together facts, and of permitting us to group them under certain more general laws. Further on we shall be able to study this theory in itself and to discuss the fundamental objections which it presents. We shall see that electrical phenomena very probably depend upon the combined action of the particles of matter and of the ethereal fluid which fills the universe; and, by thus approaching to Faraday's molecular theory, we shall be nearer to the truth than with the hypothesis of two imponderable fluids, existing of themselves, and in a manner independent of bodies.

# PART III.

## MAGNETISM AND ELECTRO-DYNAMICS.

## CHAPTER I.

### ON THE MAGNET AND MAGNETIC PHENOMENA.

### *General Notions on Magnetism.*

THERE exists in nature a mineral named *Loadstone*, known from all antiquity, which possesses the property of attracting particles of iron that are placed near to it, in certain points of its surface which are called *poles*. This mineral is a compound of iron and oxygen, or a *deutoxide of iron*. The ancients called it *μάγνης*, from the city of Magnesia in Lydia, where it was found in abundance; hence arose the name of "magnetism" for that part of physics which treats of the phenomena of which it is the origin, and the name of "magnetic" for the phenomena themselves.

One of the most remarkable properties of the loadstone is that by virtue of which it communicates the property that it possesses, of attracting iron, to a needle or a steel bar that is rubbed several times consecutively in the same direction against one of its poles. This needle or bar thus becomes capable of attracting towards its extremities, a considerable quantity of filings or pieces of iron. The needle or bar is then said to have been magnetised, and its magnetic poles are at its extremities. If the steel bar exceeds six or eight inches in length, we sometimes find two or even four other poles beside those that are at its ends. These poles, which are recognised by the accumulation of iron filings that occurs around them, are always in even numbers, and placed two and two on either side, and at the same distance from the centre: these are termed secondary or consecutive poles (*Fig.* 70.).

A magnetised steel bar possesses also, like the loadstone, the property of communicating its magnetic virtue to another steel bar or needle. To obtain this result we have merely to rub the bar or needle that we wish to *magnetise,*—the name that is given to this operation,—against one of the poles of the magnet along its whole length, and always in the same direction. Magnetic needles may be cylindrical; they have generally, however, the form of a prism or thin elongated lozenge. With regard to bars, they are generally prismatic; they have sometimes also the form of a horse-shoe, and, to increase their strength, several are superposed upon each other. They are thus capable of attracting large masses of iron, and of supporting even 50 or 100lbs., without a weight of this amount being able to detach from their poles the iron that is adhering to them (*Fig.* 71.).

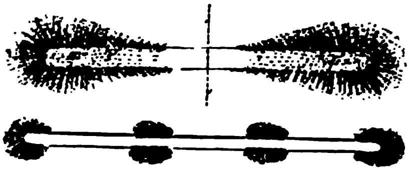

*Fig.* 70.

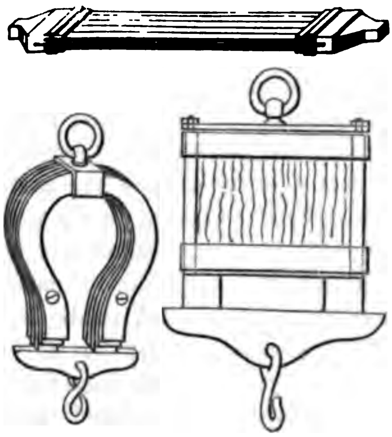

*Fig.* 71.

## *Directive Properties of the Magnetic Needle—Inclination and Declination Compasses.*

If, after having magnetised a steel needle, it is suspended by its centre of gravity to a thread, or is placed on a point by means of a cap (*Fig.* 72.), it is found to take a determinate direction towards a point of the horizon, which is very nearly north and south. This direction is so constant that, even when the needle is displaced, it always returns to it, after a greater or less number of oscillations, with perfect precision. More than this, it is always the same extremity of the needle that is turned towards the north, and the same that is turned towards the south; so that if the needle is turned aside 180°, it is no longer in equilibrio in the new position, but makes a pirouette and describes a semi-circumference on one side or the other, to return to its original position. The point of the needle that is directed towards the north has been termed the *north pole*, and that which is directed towards the south, the *south pole*. In order to recognise them immediately, and consequently to know on which side the north is, the precaution is taken of slightly blueing, by heating it, the half of the needle that is directed on the north side, and leaving that which tends towards the south of the natural colour.

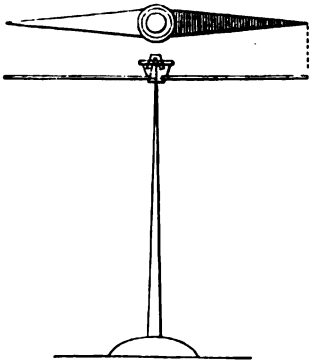

*Fig.* 72.

The direction of the magnetised needle is constant in the same place and at a given epoch; but it varies from one place to another, and changes with years: it is also subject, on the same point of the globe, to small periodic variations during the day; variations which on this account have been termed *diurnal variations*.

We have seen that this direction is not exactly north and south; hence the plane that passes through the centre of the earth in the direction of the magnetic needle in any place under consideration is termed the *magnetic meridian*, to distinguish it from the *terrestrial meridian*, which is the plane passing through this same place and the axis of the earth. The angle made by these two planes, or, what amounts to the same thing, the two *tracks* they leave on the surface of the globe, is termed the *declination* of the magnetised needle. It is determined by measuring the angle which the direction of the horizontal needle makes with the meridian line. The declination is *east* or *west*, according as the north pole of the needle is on the east or west of the meridian line. At Paris, it was 11° 30′ *to the east* in 1580; nothing, or 0°, in 1663; 8° *to the west* in 1700; 22° in 1785; 22° 14′ in 1814; and from that time it has commenced to diminish; in 1849, it was 20° 34′ 18″.

In London, it was 11° 15′ *to the east* in 1576; 0° from 1657 to 1662; 2° 6′ *to the west* in 1670; 24° 2′ 18″ in 1815, an epoch at which it attained its maximum: it was 22° 35′ in 1849. At Geneva, it was 19° in 1818, and 18° 18′ in 1849.

There are places on the earth where the needle is directed exactly according to the meridian line, and for which the declination is nothing; the series of these places or points *without declination* does not form a regular curve: we shall have occasion to return to this, and investigate their distribution.

Every apparatus suitable for observing and measuring the declination, or reciprocally for determining the direction of north and south, namely, the meridian line, the magnetic declination of the place being given, is called the *declination compass* (*Fig.* 73.).

This apparatus consists of a magnetised needle, delicately suspended, either by means of silk thread without torsion, or by means of an agate or steel cap resting upon a pivot. A carefully divided circle, upon which is read the division corresponding with the extremities of the needle, is fixed against the sides of a circular box of copper or wood covered with a glass, in which is placed the needle and the point upon which it rests. The instruments may be furnished with a telescope carried on an axis of rotation, parallel to the plane of the circular division, and the middle of which is upon the vertical that passes through the centre of the suspension of the needle.

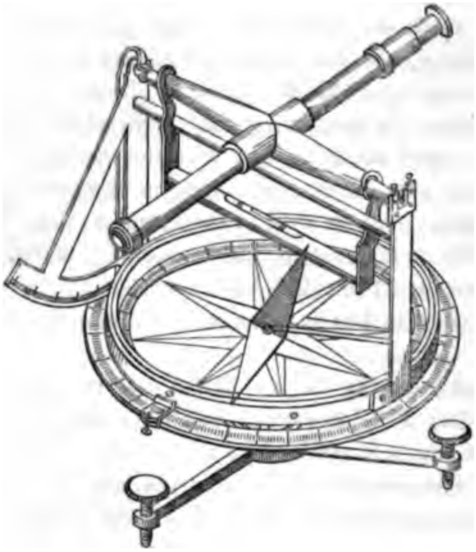

*Fig.* 73.

This axis carries an air-level, and a vertical quadrant divided to measure the angles described by the telescope. The box can be turned round upon a vertical axis, by which it is fixed upon its stand, until the telescope is found to be placed in the direction of the meridian. The angle made by the direction of the telescope with the direction of the magnetic needle, is then determined, and we obtain the declination. Or rather, knowing this declination, we turn the box until the angle made by the axis of the telescope and the direction of the needle are equal to it, and then we have the position of the meridian. The *marine compass*, or *variation compass*, differs from the ordinary compass, only in that it has a double suspension, which allows of its maintaining itself in a sensibly horizontal situation, notwithstanding the agitation of the sea.

We have supposed that the magnetised needle was suspended by its centre of gravity; but we should add that this centre of gravity has been determined after the needle was magnetised. In fact, if we determine it before, namely, if we suspend to a silk thread, without torsion, an unmagnetised steel needle, so that it is perfectly horizontal, we find that, after having been magnetised, it does not preserve this horizontality, although it is suspended in the same manner. It begins by taking the ordinary direction of S. E. and N. W.; we then see its north pole incline, as if the half that is on the north side were heavier than that which is on the south side. We may, however, in a direct manner, satisfy ourselves that the magnetism has in no degree modified the weight of the needle or that of any of its parts. The effect that is made manifest is the result of the same action that determines the constant direction of the declination needle; it is called the inclination (or *dip*) of the needle; it is measured by the angle that is made with the horizon by a needle which can move freely around its centre of gravity, in the plane of the magnetic meridian.

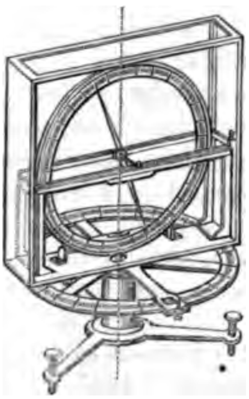
*Fig.* 74.

An inclination compass (*Fig.* 74.) consists of a needle traversed at its centre of gravity by a cylindrical axis of polished steel, resting by its two extremities upon two very sharp agate knife edges. These two edges are supported by two horizontal metal cross-pieces, parallel to each other, and which are the diameters of a vertical circle, upon which is traced a circular division. Care is taken, by means of a very simple contrivance, to place the needle upon the knife edges, so that its axis of rotation exactly passes through the centre of the divided circle, and is perpendicular to its plane. More frequently, instead of employing knife-edges of agate, steel pivots are introduced into cylindrical holes, pierced in the two horizontal cross-bars, and situated in the line perpendicular to the plane of the circle and passing through its centre; but the friction, which is much more considerable in this mode of suspension than in the other, creates a risk of

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interfering with the free movements of the needle. On this account, the former is employed in preference in very perfect apparatus. This circle or vertical limb rests upon a foot which is movable round a vertical axis, the prolonged direction of which passes through its centre, and consequently through the axis of suspension of the needle. An azimuth or horizontal circle enables us to determine at each instant the angles described by the vertical limb, and consequently of placing the latter in all azimuths, and particularly in the direction of the magnetic meridian. The magnetised needle then of itself takes a position according to the line of inclination. The angle is measured by means of the division of the vertical limb, which is generally furnished with a magnifier. Several observations must be made, and their mean must be taken in order to arrive at an accurate result; because, whatever precautions may be taken, the suspension is always imperfect, and because we are never very sure that the axis passes exactly through the centre of gravity of the needle. To be secure against this cause of error, we should make four kinds of observations, and take the mean of the results of each of them. After the first observations fresh ones are taken, after having turned the faces of the bar round, without changing the poles; then two other similar series of observations are made, after having changed the poles of the needle by magnetising it in the contrary direction, namely, by rubbing it against the same pole of a magnet, in a contrary direction to that in which it was formerly rubbed, so that the extremity that directed itself towards the south is found to be directed towards the north, and that which was directed to the north is directed to the south.

The inclination (or *dip*) which was 75° at Paris in 1671, has from that time been continually diminishing; in 1835, it was 67° 14′, and in 1849, 66° 44′. It varies like the declination, not only with the epochs of observation, but still more with the places; at London, it was 70° 27′ in 1720; 69° 2′ in 1833; and 68° 51′ in 1849. At Geneva, it was 65° 48′ 30″ in 1825, and 64° in 1849. It increases the more we approach the north pole: thus there exists a place in 80° of north latitude discovered by Captain Parry, when the inclination is 90°. On the other hand, the inclination decreases as we approach the equator: there is also on the surface of our globe a series of points where it is absolutely nothing, and which form a curve around the earth, called the *magnetic equator.* This curve is very regular in one part of its course, and may be regarded as a great circle inclined 12° or 13° to that of the terrestrial equator. Beyond the equator the inclination begins again, and increases in proportion as we approach the south pole; but it is then the south pole and not the north pole of the needle that inclines below the horizon.

When we do not know the declination, and have to make an observation of inclination, we may, without a declination compass, easily determine the plane of the magnetic meridian by looking for the plane in which the dipping needle holds itself perfectly vertical: this plane is perpendicular to that of the meridian. When, therefore, we have determined the former, we know the latter, and place the needle in it by making the vertical circle describe an angle of 90° on the azimuthal circle. This very simple connection between the two planes arises from the magnetised needle placing itself naturally, when it is free, in the plane of the magnetic meridian; and, not being solicited to go out of it, it must evidently, in order to obey this law, take the vertical position when the plane in which it is obliged to move is perpendicular to that of the magnetic meridian; for in this manner it is found to be at once in both planes.

The force which determines the direction of the magnetised needle is in fact neither attractive nor repulsive, but simply a directive force, incapable of impressing upon the magnet any movement of translation. This may be proved by different experiments: thus a magnetised needle floating upon water by means of a piece of cork to which it has been fixed, does not experience any onward movement; it simply takes the direction of the magnetic meridian like the needles which, resting on their point, are retained at their centre. A magnetised needle, fixed crosswise, and at the extremity of a horizontal slip of wood, with a counterpoise at the other extremity to maintain equilibrium (*Fig.* 75.), also takes a direction exactly in the plane of the magnetic meridian, when the slip of wood is suspended by its centre of gravity to a silk thread without torsion, although its centre is not that of the needle. Finally, if we ballast a magnetised needle by means of a piece of platinum, so as to make it remain in equilibrio in the interior of a mass of mercury, and thus to withdraw it from the action of gravity, we see it place itself in the magnetic meridian, and take a direction inclined to the north, perfectly similar to the direction of the dipping needle. This direction is therefore that which results naturally, abstraction being made of every mode of suspension, from the action exercised upon the magnetised needle by the forces or the force termed *terrestrial magnetism.*

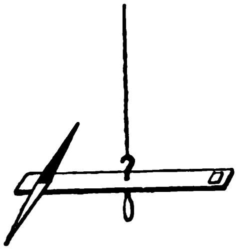

*Fig.* 75.

It was not seen at first that the force, which impresses upon the magnetised needle the direction that we have just determined, emanates from the earth. Some placed the seat of this force in a small star, forming the tail of the Great Bear; others placed it further on still. Gilbert, at the end of the sixteenth century, in a very remarkable work, entitled *Physiology of the Magnet**, was the first to show that it must be sought for in the terrestrial globe, a result that evidently arose from observations made in various places on the surface of the earth. We shall, in fact, see further on that by means of these numerous and varied observations, it becomes easy to determine the directions of the forces by which the needle is attracted; and that these directions are such, that it is evident these forces themselves emanate from the earth. We have, in like manner, become aware that the intensity of terrestrial magnetism varies, as well as the declination and inclination, with time and with places; and that it increases from the equator to the poles.

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* Physiologia nova de Magnete, magneticisque Corporibus: London, 1600.

With regard to the nature of the magnetic forces that emanate from the earth, the conjectures that have been formed in this respect are connected with the properties of magnets: we shall take care to point them out when studying these properties, but we shall not be able to examine their value until in the Third Chapter of Part the Fifth, when we shall be occupied upon natural electricity and terrestrial magnetism.

The discovery of the compass is much less ancient than that of the magnet. It appears that the first European navigator who made use of it was Vasco de Gama, in his first expedition into India. However, express mention is made in a Chinese dictionary that was completed in the year 121 of the Christian era; and in another dictionary, completed under the reign of Kang-hi, of the fact that, under the dynasty of Tsin (419 before Christ), vessels were directed towards the South by means of the magnet. The discovery of the declination appears to go back to Christopher Columbus; he was the first to perceive, in 1492, when he was traversing the Ocean to go and discover the New World, that the needle did not turn directly to the north in all places of the earth, as had hitherto been supposed. With regard to the change of declination in the same place, it was discovered in 1622, by Gunter, a professor in Gresham College. The dip was discovered in 1576 by Normann.

### *Different Properties of Magnets and magnetic Bodies.*

Hitherto we have only been considering a magnetised needle or bar as insulated; we have recognised in it the property of attracting iron to its poles; that of being directed, when it is movable, by the action of the earth; that, finally, of communicating the virtue it possesses to other steel bars or needles. But magnets possess other properties, which are especially manifested when they are brought near to each other; such, for example, as a mutual attraction or repulsion. If we bring near to the north pole of a magnetised needle, freely suspended, the north pole of another needle or bar held in the hand, we immediately perceive a very decided repulsion established between the two poles: it is the same if we present the two south poles to each other; these repulsions occur at a distance, and are very energetic. But if to the north pole of the movable needle is presented the south pole of the fixed needle, or to its south pole the north pole of the other, there is no longer a repulsion, but a very strong attraction takes place; the pole of the movable needle rushes to the pole of the fixed needle, and an adherence is made manifest between them, which lasts so long as we do not detach them from each other by a violent effort; and this establishes a very characteristic difference between these attractions and electric attractions, which latter cease at the very moment of contact. The repulsion of the two poles of the same needle upon the two poles of the same name of another needle is manifested in a very sensible manner when we approach parallel to each other two needles, having the north and south direction that is given them by terrestrial magnetism.

Magnetic attractions and repulsions are in no degree influenced by the medium interposed between the two magnets, or between the magnet and the magnetic body, when it is acted upon by the simple attraction exercised by a magnetised body upon one that is not so. These actions occur with the same force, whether the interposed medium be air, vacuum, or any substance whatever. It is only necessary that the medium itself be not magnetic. Thus, a plate of wood, glass, non-magnetic metal, a sheet of paper or cotton, a stratum of liquid or of any gas, the interposition of a flame, in no degree modify this kind of action; distance alone exercises an influence upon its intensity, into the investigation of which we shall very shortly enter.

The experiments that we have been relating, joined to observations relative to the needle, magnetised by the influence of the terrestrial globe, establish the important fact that, even while the two poles, situated at the opposite extremities of a magnetised bar, equally attract iron, they present essential differences in their properties, and a kind of antagonism analogous to that which exists between the two electricities. Thus, when a piece of steel or iron is magnetised, by continually rubbing it in the same direction along one of the poles of a magnet, the pole acquired by the extremity of the steel bar that is last in contact with the magnet depends upon which of the two poles of this magnet it is where the friction occurs, and it is always of a name the contrary to this. If the north pole is employed for magnetisation, the steel acquires a south pole at the extremity that remains last in contact with the north pole, and consequently acquires a north pole at its other extremity.

Steel is not the only body that is susceptible of being magnetised; iron itself, cobalt, and nickel, possess the same property. Not only do these bodies attract a magnetised needle, when they are presented to one of its poles, or are attracted by it, but they may be magnetised, and consequently may acquire all the properties possessed by a magnet, that of having two poles and being influenced by terrestrial magnetism, &c. However, differences exist in this relation between these different metals. Thus, when iron is very soft, that is to say, well annealed, and as much as possible deprived of carbon, it acquires only temporary magnetism.

If the extremity of a soft iron cylinder or wire be touched with the pole of a magnet, we immediately see the other extremity of this cylinder attract iron filings, and act upon a magnetised needle; in a word, we discover therein the existence of a magnetic pole of the same name as that of the magnet with which the cylinder is in contact by its other extremity. But as soon as the contact ceases, the iron filings fall, and the pole disappears; in a word, the soft iron loses all its magnetic properties; or, if at least it preserves them for a few moments, they are singularly feeble. Thus soft iron may therefore instantly acquire magnetism; but it also immediately loses it, after the cessation of the cause by which it had been produced. We should observe, however, that whilst it is under the influence of the magnet, the soft iron acquires a stronger magnetism than a similar piece of steel does when magnetised by the same power. A steel needle does not acquire magnetism so easily: a simple contact with the pole in the hand, we immediately perceive a very decided repulsion established between the two poles: it is the same if we present the two south poles to each other; these repulsions occur at a distance, and are very energetic. But if to the north pole of the movable needle is presented the south pole of the fixed needle, or to its south pole the north pole of the other, there is no longer a repulsion, but a very strong attraction takes place; the pole of the movable needle rushes to the pole of the fixed needle, and an adherence is made manifest between them, which lasts so long as we do not detach them from each other by a violent effort; and this establishes a very characteristic difference between these attractions and electric attractions, which latter cease at the very moment of contact. The repulsion of the two poles of the same needle upon the two poles of the same name of another needle is manifested in a very sensible manner when we approach parallel to each other two needles, having the north and south direction that is given them by terrestrial magnetism.

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Magnetisation may take place at a distance as well as by contact; it is sufficient, for example, for a soft iron cylinder to become magnetic, to bring the pole of a magnet near to it, without contact being necessary. This action may be made manifest in a very simple manner by suspending two pieces of iron wire to two silk threads, like the two pith balls of electroscopes; we bring near to it the pole of a magnetised bar, and they are immediately seen to separate from each other by the repulsive effect exercised by the poles of the same name, which they acquire at their lower and upper extremities. But immediately the magnet is withdrawn the two pieces of iron wire approach by recovering their vertical position; a proof that their magnetisation has ceased. Steel, nickel, and cobalt present the same phenomenon; but it is less decided as the magnetic body possesses less facilities of being promptly magnetised.

The attraction exercised by magnets upon iron filings, and generally upon magnetic or magnetised bodies, arises from their magnetising them by their influence at a distance, by which they determine in the part of the body that is nearest to them a contrary pole to that which is acting; and it is between these opposite poles that the attraction is manifested, just as if the two bodies were magnetised. It is, however, always easy to distinguish a magnetised substance from a body simply susceptible of being magnetised, and on this account termed magnetic. It is sufficient for this to present all the points of a substance to the same pole of a magnetised needle; if the action is every where attractive, the body is only magnetic; but if it is attractive in some points and repulsive in others, it is a sign that the body has two contrary poles, and that consequently it is magnetised. It is not necessary that the needle which serves for this test should be too strongly magnetised; for if the substance submitted to experiment had but a feeble magnetism, there would be a risk of not indicating any difference between its poles by acting upon it as upon soft iron, and attracting it equally in all its points.

### *Influence of Terrestrial Magnetism on Iron, and the Effect that results from it upon the Direction of the Compasses in Vessels.*

The terrestrial globe may, like a magnet, exercise at a distance its magnetising powers. If we hold vertically, or, which is still better, in the direction of the dipping needle, a bar of soft iron about a yard in length, we find that it acquires two poles, a north pole at its lower, and a south pole at its upper extremity. The existence of these two poles is manifested by the attractive and repulsive action exercised by the two extremities of the bar upon the same pole of a magnetised needle, delicately suspended and brought near to them. The terrestrial globe, therefore, acts as a great magnet would act whose axis, passing through the centre of the earth, should be situated in the magnetic meridian, and which should have at the north a pole contrary to the pole of a needle that is directed to the north; and at the south another pole, in like manner contrary to the pole of the needle that is directed to the south. This hypothesis upon the cause of terrestrial magnetism would also explain the direction of the magnetised needle; which would also be the result of the attractions exercised by the magnetic poles of the globe upon the contrary poles of the magnetised needle. It would be sufficient, therefore, in order to know the position of the magnetic pole of the earth, situated at the north, to determine carefully the direction of the dipping needle in several different places; and the intersection of these lines would be the point where the pole in question would be found. It would be necessary to go through the same process on the other side of the magnetic equator, in order to determine the position of the terrestrial magnetic pole situated on the south. But it is found that the directions of the dipping needle, when produced, whether in the boreal or austral hemisphere, do not all intersect exactly in the same point; which would seem to prove that there is not, therefore, in each hemisphere, a single pole or a single centre of magnetic action. We shall return in detail to this interesting subject of terrestrial physics, when we shall be treating upon the numerous observations that have been collected upon the different phenomena of terrestrial magnetism; and upon the hypotheses that have been made of its origin and its nature.

It may not be useless to mention here a denomination still employed in French works, and which owes its origin to the terrestrial theory of the magnet. Setting out from the hypothesis that the earth possesses two magnetic poles, and from the principle established by experiment, that poles of the contrary name attract each other, they have called that pole of the magnetised needle that is directed towards the north, the *austral* pole; because, say they, it is attracted by the magnetic pole of the earth situated at the north, and which is naturally the boreal pole: for the same reason they have given the name of *boreal* pole to that end of the needle that is directed towards the south; because, say they, it is attracted by the austral pole of the globe. With regard to ourselves, as we prefer a denomination founded upon a fact to that which rests upon a theory more or less contestable, we shall continue to call the *north* pole of the needle that which is directed towards the north, and the *south* pole that which is directed towards the south.

The magnetisation produced by terrestrial magnetism is facilitated by all actions, whether mechanical or physical, which derange the molecules of iron from their natural position of equilibrium. Thus percussion, torsion, every kind of vibration, impressed upon a bar of iron determines in it the presence of the two magnetic poles; simple oxidation in the air produces the same effect. To prove that this magnetisation is entirely due to the influence of terrestrial magnetism, and not to these actions themselves, we have merely to examine the position of the poles in the bars submitted to experiment, and we find that this position is always that which would result from the immediate action of the globe; thus the north pole is always the one found at the extremity of the bar that is inclined below the horizon, or at that which is turned towards the side of the north, if the bar is horizontal. We may even, if the bar is of very soft iron, immediately change the poles by suddenly turning it so that the extremity which was directed towards the north shall be to the south, and that which was directed towards the south shall be to the north. Furthermore, it is easy to prove that, whatever be the action by which the body is constrained, the magnetism that it acquires is the more intense as its position approaches more the direction of the dipping needle; and that it becomes altogether null if the bar is placed in a position perfectly perpendicular to this direction. We have thus the evident proof that the effect does not arise in an immediate manner from the action to which the bar is subjected, but simply from terrestrial magnetism, the influence of which is favoured by this action.

To the influence of this magnetism must be attributed the magnetisation possessed by all magnetic bodies left for any length of time in the same place: thus the rods of lightning conductors, the points of steeples*, bars, or other iron objects placed in buildings, always present traces of magnetism: it is the same with iron or steel tools, such as those of a locksmith; or punches or cutting instruments that are liable to undergo vibratory movements by the use to which they are applied. We can even obtain powerful magnets, from the magnetism produced by means of the terrestrial globe, by taking a certain number of iron wires, twelve or fifteen inches in length, and

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* It is probable that, in respect to elevated iron points, such in particular as those of lightning-conductors, atmospheric electricity, or more especially that from lightning, contributes its part to their magnetisation as much, and more so, than terrestrial magnetism.

twisting them strongly while held in a vertical position, or, which is better still, in the direction of the dipping needle. This operation, which renders them stiffer, facilitates at the same time the developement within them of a very powerful magnetism; and, when once they have been magnetised, they are united to form a bundle, care being taken that their similar poles are all at the same extremity of the bundle.

The magnetising action exercised by terrestrial magnetism upon iron may determine upon the needles of compasses very serious deviations when they are placed upon vessels in motion. In fact, these structures, which always contain in their fabric a very considerable quantity of bars and plates and rods of iron, are found from this circumstance to contain magnets, the poles of which must change with the position of the vessel in respect to the magnetic meridian. There is produced, therefore, upon the magnetic needle, a variable action, the effect of which it is impossible to determine beforehand; whilst, if the vessel always remained at the same place, it would be an easy matter to appreciate the influence of this cause of deviation, and to take account of it. Navigators also are exposed to making great errors, which might be attended with serious consequences. Suppose, for example, that the axis of the vessel, that is to say, the line going from stem to stern, was at first perpendicular to the plane of the magnetic meridian and directed to the west; that, in this position, the deviation of the needle was 20° to the west of the direction that it ought to have: a change in the course of the vessel causes the axis to turn 180°, namely, from west to east; by the effect of this change of direction, the deviation has also passed from west to east, and is consequently 20° to the east. It is evident that the observer, who should not be acquainted with the action of the iron contained in the vessel, to which these two deviations of 20°, first to the west and then to the east, are due, would believe that the needle has remained parallel to itself, and would judge that the rotation of the vessel had only been $180° - 20° \times 2$, or $180° - 40°$, namely 140°, whilst it had really been 180°. He would have been deceived, therefore, to the amount of 40° on the second direction of the vessel, supposing that he had carefully determined the first direction by the ordinary processes.

Mr. Barlow proposed various means of avoiding the dangerous errors to navigation that we have just pointed out. One of these means consisted in placing in the neighbourhood of the compass a plate of soft iron which becomes magnetised, like the other masses of iron in the vessel, by the influence of the globes. This plate is put into such a position in front of the compass, that its action upon the needle shall be exactly equal to the total action of all the iron distributed throughout the vessel; so that, by removing the plate, one half of the local deviation is removed, whence the amount of local deviation due to the ship's iron is readily obtained. The position that should be given to this plate has been previously determined by trials.

Another means has also been employed by Mr. Barlow from numerous experiments made by placing the vessel in every azimuthal position, and comparing by means of two telescopes the direction of its compass in every position with that of a magnetised needle remaining on the shore: he succeeded in determining empirically the correction that should be made in the observed deviation in order to obtain the true magnetic declination of the place where the observation was made. But this process, like the former, requires a series of distinct operations for each vessel in particular, those made for one not being able to be used for another: it is, moreover, not without some practical difficulties.

M. Poisson, impressed with the importance to navigation of the question upon which we have just been treating, and convinced that it had been only imperfectly resolved by the empirical means that we have pointed out, endeavoured to submit it to analysis, and so to arrive at a general formula of correction. He proposed to determine directly the true inclination and declination in any given place on the globe from observations of the compass made on board a vessel, and under the influence of the iron that it contains. The iron being magnetised by the magnetic force of the earth, it is evident that its action upon the needle will be proportional to this force. Further, since the components of this action correspond to three rectangular axes passing constantly through the same points of the ship, they have, for their expressions, linear functions bearing relation to the components of the action of the globe in the direction of these same axes. The magnetic force of the globe, then, is common to all the terms of the equation of the equilibrium of the compass, and consequently disappears from it. The formula contains different terms that must be determined; and, in particular, the quantities dependent upon the total amount and the distribution of the iron contained by the vessel. But, for various reasons, connected with the distribution of the masses of iron in vessels, which is in general symmetric, and with their position, which is for the most part below the horizontal plane drawn through the point of suspension of the compass, M. Poisson succeeded in simplifying the problem. The two unknown terms to be determined are the true inclination and declination; and, for this determination, two data from observation are sufficient: those required by M. Poisson's simplified formula are, the angles of the principal section or of the axis of the vessel, with the apparent direction of the compass before and after this section or axis has been made to turn to a known angle. Other formulæ enable us even to avoid this operation, and to be content with merely observing the direction of the compass before and after the addition of a mass of iron, always placed in the same manner, and so as easily to be brought near to the compass to change its direction.

### *Influence of Temperature upon Magnetism.*

Among the actions that facilitate magnetisation by terrestrial magnetism, one of the most efficacious consists in heating the magnetic body to redness, and allowing it to cool under the influence of this magnetism. The cooling that follows a much lower elevation of temperature is even sufficient. MM. Moser and Riess have proved that to this kind of effect we must refer the phenomena of magnetisation that have been supposed to be produced by rays of light, and especially by the violet rays. They have proved that, as these effects only take place when the needles which experience them are in a position perpendicular to the magnetic meridian, they can be attributed to terrestrial magnetism alone, the action of which is facilitated by the elevation of temperature brought about by the solar rays, or rather by the cooling that follows it. Heat, in fact, far from increasing, notably diminishes, on the contrary, the intensity of the magnetic virtue. A magnetised steel bar, when brought to a red-white heat, totally loses its magnetism; should it have become magnetic during cooling, it is due to the action of the earth. A soft iron bar is no longer magnetic, that is to say, is no longer attracted by the magnet, when it is simply brought to a red heat. Nickel ceases to be magnetic at the temperature of boiling oil. With regard to cobalt, its magnetic force does not seem gradually to diminish, as is the case with other substances, in proportion as its temperature increases; but it suddenly ceases at an extremely high temperature, and it then appears again just as rapidly when the metal is made to descend from this high temperature.

The remarkable influence that is exercised upon magnetism by elevation of temperature had led several philosophers to believe that the property possessed by certain bodies of being magnetic was due to the small distance existing between the atoms of which they are formed.

In fact, iron, cobalt, and nickel are among those bodies which, under the same volume, contain the greatest number of atoms, and consequently are those whose atoms are the nearest together. To heat these bodies is to remove their particles from each other; now, since this increase of distance makes them lose their magnetic properties, when it is carried to a certain point, it follows that the substances among which the atoms are naturally more apart cannot possess these properties. What must be done, then, to make them acquire these properties? We must bring the particles nearer, and, for this purpose, must cool these bodies. Guided by this ingenious idea, Faraday had exposed to an exceedingly low temperature the greater part of the metals, and several of their compounds, and also carbon; and, notwithstanding he acted upon them with a very powerful magnet, he was unable to discover any trace of magnetism: he had the precaution to take all these bodies in a state of great purity, and deprived of all traces of iron. By means of a mixture of ether and carbonic acid placed in a vacuum, he succeeded in reducing their temperature to 105° cent. below 0°. Manganese itself presented no trace of magnetism. Mr. Faraday has shown that it is to the presence of a few particles of iron, of which it is a difficult matter to deprive it, that this metal had hitherto been erroneously classed among those which are magnetic. Thus, iron, nickel, cobalt, and steel would seem to be the only bodies in nature that are magnetic, that is to say, that present magnetic properties, such as we have just studied and defined them. However, we shall see, in the last chapter of this Third Part, that Faraday has arrived by other means to discovering equally in all bodies evident magnetic properties, but variable, in the form under which they are manifested, with the nature of the bodies themselves.

### *Means of measuring magnetic Forces.*

After having studied magnetic phenomena in a general manner, we now come to the investigation of the laws by which they are governed. But, in order to deliver ourselves up to this kind of research, we must first study the means of measuring with accuracy the forces to which magnetic actions are due.

Two methods are presented to us here, as in the measuring of electric forces. The first method is based upon the employment of the torsion balance, in which a magnetised needle is substituted for the glass stem that carries the small electric body, and is fixed to the lower extremity of the torsion thread. We must only take care that this needle is sufficiently long without being too heavy. Coulomb made use of a cylindrical steel needle ·1574 in. in diameter, and 25·59 inches long: before making use of it he assured himself that it had no intermediate poles, and that consequently it possessed but two poles, placed each at one of its extremities. The second method is that of oscillations; it consists in making a magnetised needle oscillate, and in deducing the intensity of the action to which it has been subjected from the comparison between the number of oscillations executed by the needle under the influence of this action, and the number it makes when withdrawn from it.

In both methods there is one element which must be taken into the account, and which does not exist in the measuring of electric forces; it is the directive force of the earth. Thus while, in reference to electricity, the torsion of the wire alone exerts an influence upon the resistance which the movable electrised body opposes to the action of another electrised body; it is not the same when a magnetised needle is in question, for then the force, with which this needle tends to obey the directive action of the earth, is added to the torsion, to oppose the action of an exterior attractive or repulsive force. Thus again, whilst the oscillations of the electrised body are made as if it were not electrised when there is no other body present, those of a steel needle are entirely different, according as this needle is magnetised or not; because, in the former case, the oscillations are influenced by terrestrial magnetism, and, in the latter, this influence does not exist. Let us see how, in each of the two methods, the influence may be appreciated.

In order to obtain the value when the torsion balance is made use of, we must begin by suspending an unmagnetised needle to the thread of the balance, and then turn the piece by which this thread is suspended until the 0° of torsion is in the plane of the magnetic meridian. The needle which had been suspended to the wire is then to be magnetised and to be replaced exactly in the same manner. It follows from this that when, in obedience to the directive action of the earth, the magnetised needle places itself in the magnetic meridian, the torsion of the thread of the balance is found to be null. The thread is now to be twisted by turning the upper piece, either in one direction or the other, so as to bring the north pole of the needle to the west or to the east: the result is the same in both cases. We may be sure that so long as the angle of deviation which the needle is made to describe does not exceed 20°, it is proportional to the angle of torsion; that is to say, we may be sure that, after having twisted the wire to a certain angle, 35° for example, to make the needle deviate 1° to the east or the west, we must twist it to a double angle, viz., 70°, to produce a deviation of 2° in the same direction; to a triple angle, viz. 105°, for a deviation of 3°, and so on. The directive force of the earth, which tends to bring the needle back into the magnetic meridian, is therefore represented in each case by the angles of torsion, which maintain it at greater or less distances from this meridian; and, as the angles of torsion are proportional to the angular distances, the force itself is proportional to them. It is not rigorously to the angles, but to the sines of the angles of deviation, that the angle of torsion, and consequently the directive force is proportional, as is proved both by the observation made with more considerable deviations, and a simple calculation based upon the consideration of the forces by which the needle is solicited. But this same observation shows, as well as experience does, that when the angle does not exceed 20°, we may, without sensible error, take the angle instead of its sine; for the relation of the angle to the sine, up to 20°, does not exceed that of 1 to 1·02.

It only remains now, when we wish to measure magnetic forces with the torsion balance, to determine for the magnetised needle which is suspended to the thread, and which is termed the proof-needle, the angle of torsion necessary to make it deviate one degree from its natural position. This angle may vary with the torsion thread employed, with the needle that is suspended to it, and with the intensity of the terrestrial magnetism at the place of experiment. Coulomb found that at Paris, and with the needle he made use of, the angle was 35°. When, therefore, any force causes the needle to deviate from the 0° of torsion, and from the magnetic meridian with which it was made to coincide, as we have said, there are two forces that tend to bring it back, and the sum of which is equal, when equilibrium is established, to that which tends to remove it: these two forces are, the one the torsion represented by the angle of torsion, the other the directive force of the earth. But, in order to add this to the other, we must estimate its value in torsion. Now this is an easy matter when once we know that each degree of deviation corresponds to 35° of torsion. Thus, the force that will maintain the needle at 10° of distance from 0°, will be first the torsion of 10° plus ten times 35°, namely, in all, a force equivalent to 360° of torsion.

In order to appreciate the influence of the directive force in the second method, we must employ the formula of the pendulum; the magnetised needle oscillates, in fact, like a pendulum, only gravity is here replaced by the equally attractive action exercised upon one of the poles of the needle by terrestrial magnetism. It follows that the intensity of the force is in the ratio of the square of the number of oscillations which take place in the same time. This conclusion supposes that the oscillations are made by a dipping needle placed in the direction of the force by which it is actuated, that is to say, in the magnetic meridian, and oscillating in this plane, exactly as the pendulum is placed in the direction of the force of gravity, and oscillates in a vertical plane. However, it is demonstrated that the same formula or law may be applied, without sensible error, to the case in which the needle is a declination needle oscillating in a horizontal plane. When, therefore, we wish to employ the method of oscillations, we must commence by carefully determining for the needle that we employ, and which is still the proof-needle, the number of oscillations it makes in a given time, by taking the precaution of removing from it every magnetised body, or body susceptible of being magnetised, such as iron, so that it may not be actuated by any other force than by that of terrestrial magnetism. It is also understood that experiments, in order to be comparable, should be made, not only with the same magnetised needle, but in the same place*, so that the intensity of the terrestrial magnetism may be constant.

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* For the mathematic developments relating to the two methods, see note C.

### *Law of magnetic Attractions and Repulsions.*

We shall begin by applying the methods that we have now unfolded to the determination of the law that magnetic attractions and repulsions obey according to distance.

For employing the former method, that which depends upon the use of the torsion balance, Coulomb had suspended to the torsion thread the same long steel needle in which the directive force of the terrestrial globe was represented by 35° of torsion for 1° of deviation from the magnetic meridian. A second magnetised needle, similar to the first, was placed vertically in the magnetic meridian, so as to act by its north pole upon the north pole of the proof-needle. The disposition of the needle was such, that the two points acting immediately upon each other, or which would have been the line of intersection of the two needles had they been in contact, were an inch from the extremities of each. These points were those of the maximum of the repulsive forces. The movable needle was driven immediately to a distance of 24° from the magnetic meridian, which gave, in order to produce equilibrium to the repulsive force at this distance of 24°, a force of torsion of 24° plus the directive force of the earth, equivalent to 24° × 35° of torsion; in all, 864°. The movable needle was then brought up by turning the upper piece, and it was found that, to bring it back to a distance of 17°, it would have been necessary to make the piece describe three circumferences, or to twist the thread 1080° at the upper part. The total force was therefore composed, 1st, of the 17° of torsion that the needle was distant from the 0° of torsion, its starting point; 2ndly, of the 1080° of torsion necessary to maintain it at the distance of 17°; 3rdly, of the 17° multiplied by 35, namely, 595° of torsion, which would represent the effect of the directive force of the earth. This makes in all 1692° of torsion to make equilibrium to the repulsive force at the distance of 17°. In order to make the needle attain to a distance of 12°, it would be necessary to turn the upper piece 5 circumferences, namely 2880°, which gives a total torsion of $12^\circ + 2880^\circ + \overline{12^\circ \times 35} = 3312^\circ$.

Thus the forces of torsion that respectively produce equilibrium with the repulsive forces are, at the distance of—

| | |
|---|---|
| 24° - - - - | 864° of torsion. |
| 17° - - - - | 1692° „ |
| 12° - - - - | 3312° „ |

The results are closely approximated to those which would be given by the law of—Inversely to the square of the distances for the intensity of the repulsive force. In fact, setting out from the force 3312°, the other, according to this law, would be

$$3312^\circ \frac{12^2}{17^2} \text{ and } 3312^\circ \frac{12^2}{24^2}; \text{ or}$$

1650 and 828, instead of 1692 and 864, which are given by experiment. These differences are very slight if we consider that an error of a single degree on the observed position of the movable needle makes one of 35° for the force, since the directive force is 35° for each degree of deviation from the magnetic meridian. Besides, we shall remark that the mutual action of the two magnetised needles, not being all concentrated in two single points situated upon each of them, the variation in the distance establishes a variation in the relative position of the acting points, and that, in proportion as the distance increases, there are more points that may act mutually upon each other. Thus we find the force a little greater when the distance increases, which it ought not to be according to the law. We should operate in a similar manner, in order to demonstrate that the law exists equally for attractions; it would merely be necessary to place, opposed to each other, the poles of the two needles having contrary names, first having taken the precaution to place the movable needle, by means of torsion, at a considerable distance from the fixed needle.

We must now see how Coulomb employed the second method.

The proof-needle was a steel wire weighing 57·89 grs. Troy, strongly magnetised, and suspended to a silk thread without torsion. This needle made fifteen oscillations per minute under the influence of the terrestrial magnetism. Coulomb then placed vertically in the plane of the magnetic meridian a magnetised steel wire, about 23½ inches long, taking care that the north pole was turned downwards, the south pole of the wire being opposite to the north pole of the proof-needle, but at variable distances. The centre of the attractive action of this pole should be situated in the horizontal plane of the proof-needle, a necessary condition, in order that the needle should not run the risk of dipping, either below or above this plane. For this reason it would be necessary to place the south extremity of the magnetised steel wire at about an inch above the same plane. Things being thus arranged, at 4 inches from the wire, the needle made forty-one oscillations per minute instead of fifteen; at 8 inches it made twenty-four; at 16 it made seventeen.

From the law of the pendulum that we have just mentioned as being applicable to the present case, we have, calling $m$ the force of terrestrial magnetism, $m'$ that which acts upon the needle at the distance of 4 inches, and $m''$ that which acts at the distance of 8 inches,

$$\frac{m'}{m}=\frac{41^2}{15^2}, \quad \frac{m''}{m}=\frac{24^2}{15^2}.$$

But, in order to obtain the law of the simple action of the magnet upon the movable needle, we must deduct from $m'$ and $m''$ the total force acting upon this needle, $m$, the force of terrestrial magnetism; the differences $m'-m$, $m''-m$ express correctly the simple action of the magnet at the respective distances of 4 and 8 inches. Now we deduce from the two preceding propositions $\frac{m'-m}{m''-m}=\frac{41^2-15^2}{24^2-15^2}=\frac{1456}{351}=4{\cdot}1$. Thus the force that acts at 4 inches, namely, at a certain distance, is *quadruple* that which acts at a *double* distance. We should find for the distance of 16 inches, $17^2-15^2=64$, a number a little too small; for $\frac{1456}{64}=22\frac{3}{4}$, and it ought to be found to be 16. This variation occurs because that, at the distance of 16 inches, the lower north pole of the fixed magnet acts upon the north pole of the movable needle, and diminishes, by its repulsive effect, the attractive action of the south pole which is above. It was with a view of avoiding this inconvenience that we gave a considerable length to the vertical magnet; but this precaution, which fulfils the object in view, as we may easily conceive, when the movable needle is not too far off, is no longer sufficient as soon as the distance exceeds a certain limit.

In fine, we may conclude equally from both methods *that magnetic attractions and repulsions are inversely as the square of the distance.*

### *Distribution of Magnetism in a magnetised Bar.*

The same two methods that we have just employed to find the law of the inverse of the square, come to our aid also in determining the distribution of magnetism in a magnetised bar.

We may too, by a very simple method, prove the inequality of this distribution: it is sufficient for this to hold a magnetised bar in a horizontal position, and to move under its lower surface and along its whole length a small piece of soft iron, sustaining a small scale-pan by three or four threads. We very quickly discover that the weight, which must be put in the pan to detach the soft iron, varies much with the position of the point of the magnet that acts upon the iron; hence we conclude that the magnetic force, which may be regarded as proportional to the weight, is very unequally distributed. Thus it is at its maximum at two points, distant a tenth of an inch or so from the two extremities of the bar. Setting out from these points, it goes on diminishing very rapidly, either in the interval by which they are separated, or from each of them to the same extremity of the bar. The manner in which iron filings are distributed around the bar, when they are attracted by it, confirms this result. We see them, in fact, accumulated in a large proportion about the poles, around which they seem to converge from all parts, as towards centres of action (*Fig.* 76.). The central portion of the bar attracts only a very small number of the particles of iron; it even sometimes happens that it does not attract any. However, if the bar is not very long, the filings are distributed around the central point, describing a species of curves which go from one pole to the other, and forming as it were an ellipse, having for its axis that of the bar, and for its foci its two poles. To make these figures evident, we should project the iron filings, after the manner of rain, upon a sheet of white paper or upon a pane of glass, covering the magnetised bar; by means of small taps given to the paper, the arrangement of the filings and the formation of the figures is facilitated. M. de Haldat succeeded in fixing these figures, which he termed *magnetic phantoms*; with this view, he applied to a pane of glass upon which the figure is formed, a sheet of stiff paper impregnated with starch glue prepared from gelatine; the powder of iron filings is thus obtained fixed, as it was distributed upon the glass. We are, by this means, enabled the more easily to study the distribution in all its details. M. de Haldat thus proved that the centres, whence the radiating lines arise, are in truth the poles of the magnet, which are themselves deprived of the iron filings. The disposition of the curves formed by the iron filings is such that, divergent at their origin, they are never distinct and separate from each other throughout their extent. On the contrary, they unite again after their

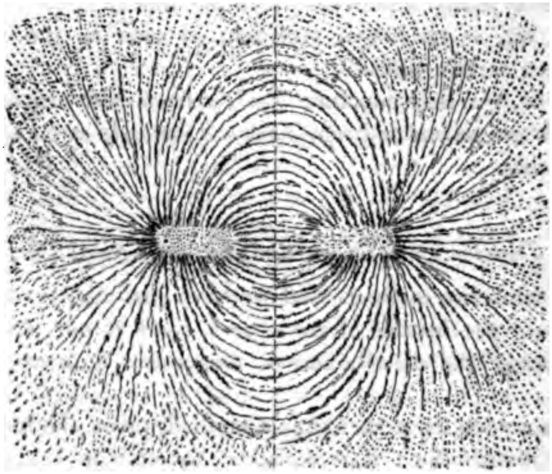

*Fig. 76.*

origin, and form species of meshes. M. de Haldat has also studied the magnetic phantoms produced by two magnets placed in relation to each other in various ways; and he estimates that this study may lead to important results on the state of magnetism in all bodies, on its power and its distribution.

Long before M. de Haldat, the magnetic curves had fixed the attention of many philosophers, independently of the description given of them by Lucretius.* Thus Mushenboeck, Lambert (who had succeeded in giving the equation of their curves), Playfair, and Leslie, have also been successively occupied with them. Dr. Roget simplified the methods described by his predecessors, and pointed out some easy processes for obtaining these curves graphically. The following are the principal properties of these curves, engendered by the simultaneous and contrary or similar action of the two polarities of magnets upon parcels of soft iron, or upon infinitely small magnets.

1st. The difference of the co-sines of the angles formed with the axis of the magnetised bar by the lines which join any given point of the curve with the two poles, is a constant quantity, these angles being taken on the same side.

2nd. A tangent, drawn to any point of the curve, cuts the axis produced of the magnet producing it in such a point, that its distance from the nearest pole is to the absolute length of the magnet as the cube of the distance from the point of the tangent to the same pole is to the difference of the cubes of its distances from the two poles.

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* "Fit quoque, ut a lapide hoc ferri natura recedat
Interdum; fugere, atque sequi consueta vicissim,
Exsultare etiam Samothracia ferrea vidi;
Ac ramenta simul ferri furere intus ahenis
In scaphiis, lapis hic magnes quum subditus esset;
Usque adeo fugere a saxo gestire videtur
Ære interposito; discordia tanta creatur:
Propterea, quia nimirum prius æstus ubi æris
Præcepit ferrique vias possedit opertas;
Posterior lapidis venit æstus et omnia plena
Invenit in ferro; neque trabat quâ tranet, ut ante;
Cogitur obsensare igitur pulsareque fluctu
Ferrea textu suo, quo pacto respuit ab se,
Atque per æs agitat sine eo quod sæpe resorbet."
*De Rerum Naturâ*, vi. 1041–54. Wakefield's edition.

3rd. The sines of the angles, formed by this tangent with the right lines which measure these distances to the two poles, are to each other as the squares of their distances.

Dr. Roget described an instrument suitable for tracing these curves by a continuous movement, and founded upon the first of the principles announced above. He also acquainted us with the following process, by the aid of which they are described by points: —

From each pole as a centre, and with radii of an arbitrary length, two circumferences are traced. After having produced the axis until it meets them, it is divided into any number of equal parts; each of the points of the division is projected perpendicularly upon the circumference. Through the centre of each circumference, and the points that have been determined upon it, are drawn radii, indefinitely prolonged. These radii cut each other mutually in points which belong to the curves in question. If the two generating poles are heterogeneous, the curves are called *convergent*, and are curvilinear diagonals, in the direction of the magnetised axis, of quadrilateral intervals formed by the intersection of the radii. If the two poles are homogeneous, these curves are called *divergent*, and their direction is determined by that of the curvilinear diagonals perpendicular to the former, and consequently to the axis that joins the poles.*

But to return to the employment of the two methods, which will give us more accurate results. With the torsion balance, Coulomb used two similar magnetised needles, one fixed, the other movable; by means of which he determined the law of the inverse of the square. He made the fixed one slide behind a thin wooden rule, which separated it from the movable one, care being taken that it remained vertical. He then noted the torsion which it was necessary to give to the suspending thread, to constrain the extremity of the movable needle to remain in the plane of the magnetic meridian, and almost in contact with the fixed one, from which it was separated only by the thickness of the wooden rule. By operating in this manner, Coulomb avoided the effect upon the

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* For the mathematical developments, see the note D, at the end of the volume.

movable needle of any other points than that which was in the same horizontal plane with it; he no longer had occasion to take account of the directive force of the earth, since the needle remained in the magnetic meridian. The angles of torsion necessary for maintaining them exactly represented, therefore, in each case, the magnetic force of the point acting upon the fixed needle.

In the second method, Coulomb caused the proof-needle to oscillate before the different parts of a long magnetised bar, which he made to glide along vertically, so that all its points were to be found successively in the horizontal plane of the needle, and at the same distance. Calling $m'$, $m''$, and $m'''$, the total action exercised upon the needle, when it is successively before each of the points of the bar, $m$ being still that of the terrestrial magnetism, and $n'$, $n''$, $n'''$ the number of oscillations made by the proof-needle before each of these points, $n$ being the number of oscillations when terrestrial magnetism alone acts upon the needle, we have $\frac{m'}{m} = \frac{n'^2}{n^2}$;

$$\frac{m''}{m} = \frac{n''^2}{n^2}; \quad \frac{m'''}{m} = \frac{n'''^2}{n^2}; \quad \text{whence } \frac{m'-m}{m''-m} = \frac{n'^2-n^2}{n''^2-n^2};$$

$$\frac{m'-m}{m'''-m} = \frac{n'^2-n^2}{n'''^2-n^2}.$$

Now $m'-m$, $m''-m$, $m'''-m$, represent the magnetic forces emanating respectively from each point of the magnet; because these quantities are the total action diminished by that of the terrestrial magnetism, and we may compare these together when once we have by experiment determined $n$, $n'$, $n''$, $n'''$, &c.

The following is a table of the results obtained by Coulomb with a steel wire 28¾ in. long, and ·176 in. in diameter.

The proof-needle, before the steel wire was presented to it, made one oscillation in a minute, or $60''$.

| | | | | | |
|---|---|---|---|---|---|
| Before the extremity of the wire it made | | | 64 | oscil. | in $60''$ |
| Before the same extremity | lowered | ·53 in. | 58 | „ | „ |
| „ | „ | 1·06 „ | 44 | „ | „ |
| „ | „ | 2·12 „ | 18 | „ | „ |
| „ | „ | 3·18 „ | 12 | „ | „ |
| „ | „ | 4·80 „ | 1 to 2 | „ | „ |

Thus, setting out from the point situated from 4¼ in. to 4¾ in. below its extremity, the steel needle presented no sensible magnetic force. By continuing to lower the needle, it was found that the almost complete absence of action continued to about a distance of 4¼ in. to 4¾ in. from the other extremity. But, setting out from this distance, the same were again produced in an inverse order; and the proof-needle made a complete rotation to present its other pole to the action of the steel wire, the second pole of which, in like manner, commenced acting upon it.

By the employment of this method, we may easily prove the presence of consecutive points or intermediate poles, in the portion of a magnetised wire or steel bar comprised between its extreme points: we can also determine the intensity of the magnetic forces with which they are endowed. With regard to the intensity of the forces that emanate from the very extremities of the magnetised wire, it is necessary, in order to obtain the true expression, to double the result obtained; for the effect would evidently be, for these extreme points, the double of what it is really if the magnet were prolonged beyond and presented points on the outside as efficacious as those that are within; which takes place for the other parts of the bar.

Coulomb also succeeded in representing geometrically all the results that he obtained, by erecting upon each of the points of a horizontal line, representing a magnetised wire, perpendiculars of lengths proportional to the intensities obtained by experiment. The extremities of these perpendiculars, in the experiment that we have related above, form a curve, which is confounded with the axis of the wire, which was 28¾ in. long, for a length of about 19¼ in., and goes on receding rapidly from this axis from the 4¾ in. and the 24th in. to the extremities, where it attains its maximum (*Fig.* 77.).

It is very remarkable that this curve, or, which comes to the same thing, the distribution of the magnetism of which it is the representation, is exactly the same for wires or plates of different lengths, provided that the length exceeds eight inches; there is no other difference, except that the space left in the middle, where the magnetism is sensibly null, varies in length. It follows also from this, that all magnets of the

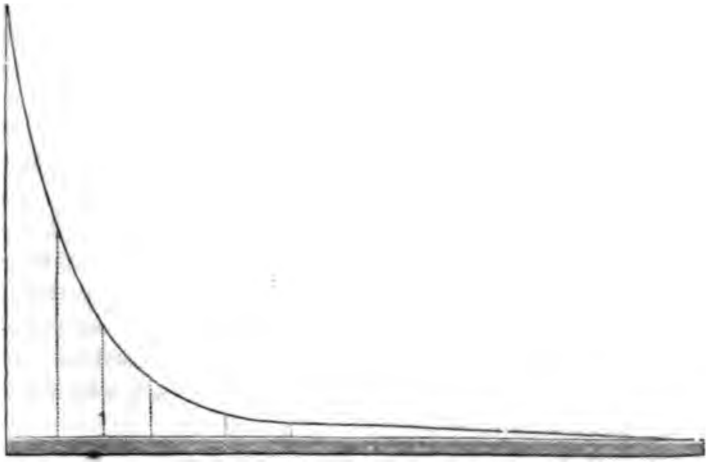

*Fig.* 77.

same force, and of greater length than eight inches, have their poles at the same distance from their extremities: this distance is about $1\frac{1}{2}$ in., according to Coulomb's calculations. The same philosopher found that, when magnets are too short, their poles are very nearly one-third of their half-length from their extremities: thus, for a needle of $3\frac{1}{2}$ inches, the poles will be at a distance of $\frac{7}{12}$ in. at least from its extremities.

All these results are only true for magnets whose length is very great in respect to their transverse dimensions, whose form is perfectly regular, such as the cylindrical or rectangular, and which are magnetised in a normal manner. With needles in the form of a lozenge the poles are much more distant from the extremities: in this case, as in others, the proof-needle must be employed, in order to determine their position; calculation cannot lead to it *à priori*.

M. Becquerel endeavoured, by means of the torsion balance, to determine the distribution of magnetism in excessively fine steel wires: he obtained these wires by drawing through the draw-plate a steel cylinder, of small diameter, which he had placed in the axis of a cylinder of silver ten times larger. Then, after having obtained a very fine silver wire, having for its axis an almost capillary steel wire, he dissolved the silver in mercury, which did not attack the steel, and obtained an almost microscopic steel wire.

These wires are not susceptible of acquiring strong magnetism: however, they become sufficiently magnetised to enable us to prove that the distribution of their magnetism follows very nearly the law deduced from Coulomb's observations. M. Becquerel found that, in a wire ·00052 in. in diameter, and 5 in. in length, the poles were ·334 in. from its extremities. One might have thought that they would have been at the extremities themselves, which would probably have happened, had the wire been composed of only one range of consecutive particles; an ideal case, which it is not possible to realise.

M. Kupffer has remarked, by means of very delicate experiments, made by the method of oscillations, that there exists in a magnetised bar a point, which exercises absolutely no action upon the needle, and which he has termed *point of indifference.* The position of this point is influenced in a very pronounced manner by terrestrial magnetism, when the bar is not strongly magnetised. If this bar is arranged in a vertical position, its north pole being below, the point of indifference is found to be nearer to the north than to the other pole. If the bar is inverted, the point of indifference approaches the middle. In the former case, the north pole of the bar was stronger than the south pole. In the latter case, the two poles approached gradually towards having the same power. It would follow from this, that the point of indifference would be always nearer to the stronger pole; and that the kind of influence of terrestrial magnetism that has just been pointed out, would consist simply in determining a greater intensity in one of the poles than in the other. The same effect may be remarked upon a horizontal magnet; its north pole is stronger than its south, when it is in its natural direction.

Elevation of temperature, as we have seen, diminishes the magnetic intensity of a bar. M. Kupffer has shown that it also modifies the distribution of magnetism in the same bar. The displacement of the point of indifference is especially sensible, when only one of the poles is heated. The point of indifference recedes from the heated pole, which also becomes more feeble.

It would seem to result from these observations of M. Kupffer, that the relative intensity of the two poles is the only cause exercising an influence over the distribution of the magnetism; and it is only because they modify this intensity, that different circumstances, such as terrestrial magnetism and variation of temperature, cause this point of indifference to undergo a change of place. Finally, we should be led to believe that, if the point of indifference does not remain in the middle of a bar, but is carried from the stronger side when the two extremities have not the same magnetic power, it is because the sum of all the opposed forces being necessarily always equal to each other, this condition can be fulfilled only so long as the points from which the more feeble emanate are more numerous than the points from which the more intense emanate; and, consequently, that the portion of the needle whose extremity has the greatest amount of magnetism is shorter than the portion whose extremity has the least.

### *Theory of Magnetic Fluids and of the Coercitive Force.*

The sort of considerations that we have been discussing lead us to entering upon the theory of magnetism, a subject which the labours of Coulomb, followed by the mathematical researches of Poisson, would seem to have exhausted, when the discoveries of which we shall speak in the following Chapter, if they did not totally overthrow, at least modified considerably, the theoretical ideas of these two philosophers. However, their theory is too important, and at this time too widely extended, to permit of our passing over it in silence. The importance and the utility of being acquainted with it, in order to comprehend that which has been substituted for it, and which includes a great number of points common with it, render its exposition still more indispensable, even although we should be obliged to abandon it hereafter.

As soon as we enter upon the study of magnetic phenomena, we are struck by the analogy they present with electric phenomena: we are then very quickly tempted to attribute them to two magnetic fluids, possessing properties of the same kind as those possessed by the two electric fluids; one, the *north magnetic fluid*, would be the cause of the effects produced by the north pole of a magnet; the other, the *south fluid*, of the phenomena presented by the south pole of the magnet. The fluids of the same name repel each other; those of the contrary name attract. Analogy, however, would not go further; for experiment has shown that the magnetic and electric fluids exercise mutually no influence upon each other: moreover, the electric fluids may be manifested upon all bodies in nature, whilst the magnetic fluids are sensible only upon a very small number of bodies.

An important experiment shows, moreover, that the two magnetic fluids are not distributed in a magnetic bar in the same manner as the two electric fluids are in an insulated conductor; on the contrary, their distribution would seem to have much more analogy with that assumed by the two electricities in an insulating body whose successive particles are polarised, as the recent researches of Faraday have demonstrated.

The following is this experiment. We take a magnetised cylindrical needle, of good and well-tempered steel, and presenting no consecutive points; we satisfy ourselves that each of its halves possesses a contrary magnetism. We break it in the middle; it would seem that each half ought to possess only one of the two magnetisms after its rupture, as it had before: it is not so, however; each of its halves has become a perfect magnet, having its two poles and its point of indifference in the middle. The half that is terminated by a north pole has acquired a south pole, and that which is terminated by a south pole has also acquired a north pole at its new extremity; so that, at the point of rupture, two contrary poles make their appearance. We may also break through the middle of each of the former fragments that had become magnets, and so produce four new magnets, perfectly similar, except in dimensions, to the preceding. These latter may be again broken in like manner; and if this operation is pursued to the last possible limits of mechanical division, however small the fragment obtained may be, it always gives a magnet having contrary poles, and endowed with all the properties of a more considerable magnet.

We should necessarily conclude, from this curious experiment, that the two magnetisms are equally to be found in all the particles. We are therefore led to admit, that each particle of a magnetic body contains the two magnetisms in equal proportions; that, in the natural state, these two magnetisms neutralise each other, and there is no action from them: but that the magnetism separates them without their leaving, on that account, the particles which contain them; only all the magnetisms of one kind are led toward one side of the particle, and all the magnetisms of the other kind are led toward the other side. Let us suppose a filament, or a series of particles ranged one after the other, in a right line. We move along this series the north pole of a magnet; this pole decomposes successively the natural magnetism of each of the particles over which it passes; it attracts the south magnetism into the extremity of the particle directed to the side toward which it travels, and repels the north magnetism into the opposite extremity. In this way, each particle has a south pole turned in the direction followed by the magnet that is moved along, and a north pole turned on the other side. A south pole is finally found on the outside of the last particle touched by the magnet, and a north pole on the outside of the first. These two poles will be the only active ones, for the contrary magnetisms of all the intermediate particles will be mutually disguised, although they are in different molecules (*Fig.* 78.). If they were in the same, they would neutralise each other. The experiment in which a magnet is broken is the proof that they are only disguised; the two poles that appear are due to the contrary magnetisms

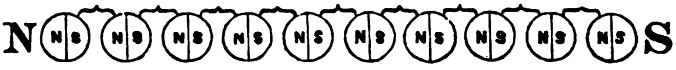

*Fig.* 78.

which occur in the extremities facing the contiguous particles that rupture has just separated. Had they been neutralised, and not simply disguised, these magnetisms would not have been set at liberty by the separation of the two particles. The nature of the two poles that are manifested at the points of rupture of the two fragments is perfectly in accordance with theory, as is rendered evident by the figure. This property, that is attributed to the two magnetisms, of being able to disguise without neutralising each other, may be proved directly by experiment. It is sufficient for this purpose to suspend any object of soft iron, for example a key, to one of the poles of a magnetised bar, and to approach it from above with the opposite pole of a similar bar. At the moment when contact between the two contrary poles occurs, and sometimes even a little before, the suspended iron object falls suddenly; and it is impossible to cause it to be sustained again so long as the opposite poles of the two bars are in contact, a proof that the action of the one is disguised by the other; in fact, as soon as they are separated, they each recover their former energy.

However, one cause which, while it sensibly modifies the distribution of the free magnetism, has an influence also upon the place of the poles, is the mutual action which the two poles of the contrary name may exercise upon each other, and which becomes sensible, on account of their limited distance, in very short magnets. This action recomposes a great part of the magnetism developed by exterior magnets in the act of magnetisation: thus we see that the quantity of free magnetism is much less in short magnetised wires than in long ones. This reaction of the contrary poles upon each other ceases to be sensible, it is true, in magnets whose length is very great; but it is then exercised upon the intermediate portions, and tends to develope their natural magnetisms, as an exterior magnet would. Hence result the consecutive points, which are thus formed of themselves in very long pieces of steel, as soon as they are withdrawn from the influence of the bars by which they are magnetised.

The case of a simple series of particles is only a theoretic case. We may approximate to it by employing very fine steel wire, as Becquerel did; but it is never completely realised. In fact, a magnet is a union of a greater or less number of similar series of particles,—series which would be parallel in a cylindrical or in a perfectly prismatic magnet. The poles of the magnet, which are the points of application of the resultants of all the forces emanating from the poles situated at the extremities of these parallel series, ought in this case to be found at the very extremities of the bars. But this result is never completely realised, because, in consequence of the molecular structure of the metal, the series of particles are not perfectly parallel: because, also, they are never all equally prolonged to the end. This last case is especially presented in needles whose form is not that of a prism or a cylinder; in those of a lozenge form particularly. It is evident that the resultant of the forces emanating from the extremity of each series cannot have its point of application at the extremity of the needle; but it must necessarily be at a point nearer to its centre. We shall see further on that the difference we have been pointing out between the result of theory and that of observation is connected also with other causes of a more important order, relative to the magnetic state of the interior portions of a magnet.

The theory of magnetism that we have been unfolding implicitly supposes the existence of a force, that has been called *coercitive.* It would be analogous to what in electricity is the insulating force that maintains the two separated electricities in a body whose particles are polarised, as occurs in the experiment of Matteucci's that we have quoted, of a pile formed of several superposed plates of mica, which, when separated, are found to be electrised *plus* on one of their surfaces, and *minus* on the other.

The coercive force is that which maintains the two magnetisms separate in each particle, by compelling them to obey their mutual attraction. This same force must equally be opposed to their separation; it is, therefore, that which must contend against magnetisation. Thus, we remark, that the bodies which are the most difficult to become magnetised, such as tempered steel, preserve better the magnetism that has been given to them; whilst those which, like soft iron, are very easily magnetised, in like manner immediately lose their magnetism. The former have a considerable coercitive force; the latter have a very feeble, or hardly any force. This difference may be made manifest by a very simple experiment. A soft iron wire is to be suspended from the pole of a magnet by one of its extremities; we immediately find at the other extremity a pole capable of attracting iron filings; if we then cut the wire, still leaving it suspended by the magnet, at a small distance from this pole, the detached fragment has no longer at either of its ends any trace of magnetism. With steel wire the fragment would be a true magnet, having at each of its two ends a different pole.

Heat destroys the coercitive force; and so it is that magnetised bodies lose their magnetism when they are brought to a high temperature; the two magnetisms then unite in each particle. But, if they are under the influence of terrestrial magnetism, then the feebleness of the coercitive force again permits the separation under this influence of natural magnetism; a separation which is maintained when, after cooling, this force has become more considerable. Æpinus had also found, that a steel needle or bar may be powerfully magnetised by heating them to a red heat, and allowing them to cool between the two contrary poles of strongly magnetised bars, which produce the same effect as the action of terrestrial magnetism.

Mechanical actions have the same influence over the coercitive force that heat has; and therefore it is that they facilitate magnetisation, as we have already seen by numerous examples. The following is a new experiment by M. de Haldat. Unannealed iron wires, about 4 in. in length and

$\frac{1}{25}$th in. in diameter, had been placed horizontally between two bars, the contrary poles of which were turned toward the end of the wire, but at a distance too great to magnetise them by their influence. However, as soon as they are rubbed in the direction of the poles with hard bodies, they acquire a decided magnetic polarity under this influence.

The following, on the other hand, is a case in which mechanical actions bring about demagnetisation. M. de Haldat succeeded, by moving the pole of a magnet over steel plates, and even over plates of sheet iron, in determining in them, by magnetisation, figures that became visible when iron filings are spread over the surface of the plates and sheets, and gentle taps are given. The parcels of iron accumulate at the limits of the tracing, leaving bare the interval which marks its thickness, so that they are found collected together upon the lines by which the magnetised parts are separated from those that are not magnetised. The magnetism that is thus developed by simple friction, or rather by the simple approach of a bar, remains for a very long time. To make it disappear, we have merely to strike the plates strongly for a minute or two on a plank with a small wooden mallet, which excites reiterated and violent vibrations among them. It of course follows, that the same effect is obtained by heating the plates; we have merely to raise their temperature to straw yellow. If a cartridge made of very fine iron filings is magnetised, it will preserve its magnetism for a very long time; but it immediately loses it when the particles of filings are agitated. This last experiment would seem to prove that magnetisation and demagnetisation should be connected with a change in the relative position of the particles of the magnetised body, and would also explain the effect of heat and of mechanical action that would facilitate the return of the particles to their natural position, which magnetisation might have altered. The coercitive force, in this manner of regarding the phenomenon, would only be the greater or less resistance of the particles to a modification in their mutual arrangement, such as constitutes the natural structure of bodies. We shall see, in the Third Chapter, in which we shall be again engaged on magnetisation, that facts of a different order are altogether favourable to this opinion.

Finally, to complete the theory, we ought to add that a magnet may be constructed by following the principles upon which it rests. For this purpose, we have merely to cut a great number of small bits of very soft iron wire, and then to place them end to end one after the other: by presenting the pole of a magnet to one of the extremities of the series, we see all the fragments of which it is composed adhere strongly to each other; and, at the other extremity, there arises a pole of the same name as that of the magnet which has been brought near. In a word, the series possesses all the properties of a true magnet. But as soon as the pole which produced this effect is withdrawn, every trace of magnetism disappears, and the small fragments detach themselves from each other; a result which arises from the absence of the coercitive force in the soft iron, and because, consequently, as soon as the cause which has separated them is no longer there, the contrary magnetisms of each particle mutually neutralise each other. What occurs in each fragment occurs in like manner in each individual particle of a body that is magnetised.

Some philosophers had admitted in magnetism, as in electricity, the hypothesis of a single fluid. Æpinus, in submitting it to calculation, had found, that in order to be in accordance with facts, it would be necessary to fulfil the following conditions:—

1st. That the particles of the one magnetic fluid repel each other with a force the inverse of the square of the distance.

2nd. That the particles of this fluid attract those of iron, and are themselves attracted by them.

3rd. That the magnetic fluid can move in the pores of iron and soft steel without difficulty; and that, on the contrary, this movement surmounts obstacles in hard and tempered steel.

4th. That the particles of iron mutually repel each other, a condition similar to that to which a single fluid in electricity leads in respect to all bodies, and which is irreconcilable with the ideas that are admitted of the constitution of matter.

### *On the different Processes of Magnetisation, and on the Magnetic Power in general.*

The considerations into which we have entered, and the facts that we have studied, enable us now to return, with a better knowledge of the cause, to an important point at which we have only glanced; we would speak of *magnetisation*, and of the influence of different circumstances upon the intensity of the magnetism that bodies are susceptible of acquiring.

The most simple process of magnetisation consists in applying the pole of a magnet to the extremity of the needle or bar that we wish to magnetise. The first particles in contact with this pole have their natural magnetism decomposed; the south magnetism is determined toward the side nearest to the north pole of the magnet, and the north magnetism upon the more distant side; this latter magnetism decomposes in its turn the natural magnetism of the subsequent particles, and so on to the most distant extremity of the bar, the particles of which are thus found to be possessed only of a magnetism similar to that of the magnetising pole.

This is the theory of the process; but the phenomenon does not always occur so simply. Dr. Robison, a Scotch philosopher, has observed that when, instead of soft iron, steel is magnetised by this means, the acquisition of the magnetism is gradual and progressive, and that the gradation is the more sensible as the steel of the bar, upon which we operate, is the more tempered. Thus, when we apply the north pole of a magnet to the extremity of a hard steel bar, the extremity in contact immediately acquires a south pole, and the other is at first not at all affected. We then observe a north pole formed at a little distance from the south pole; and, after the latter, a second very feeble south pole. These poles advance gradually along the bar: at the extremity most distant from the contact a feeble south pole appears, and it is only after a long time (if it ever happens at all) that a simple and vigorous north pole is found there. More frequently this north pole remains diffused and feeble; and, even if the bar is very long, it frequently happens that we find upon it a succession of north and south poles, which never advance sufficiently to attain to its extremity.

By means of a proof-needle, or by placing upon the bar a sheet of paper powdered with iron filings, we very readily perceive this march of the poles, which is brought about more or less rapidly. If the temper of the bar is not higher than that of cutting instruments, and the bar is only six or eight inches long, the progress of the magnetisation is arrested at the end of a few minutes. When the bar is very hard, the progress of the magnetisation may be greatly accelerated by striking it with sufficient force to make it ring, simply with a key, especially if it is suspended vertically. But it is rarely that we thus obtain a uniform magnetisation, that there are formed simply two poles, and that these poles are of equal force: that which is formed at the extremity most distant from the point of contact is in general diffused, and consequently more feeble. In order to magnetise powerfully by simple contact, it is necessary, when the coercitive force is considerable, to place the bar between two contrary poles; the magnetisation being then made in both directions at the same time, which concur in the same final result, the operation is more speedily accomplished, and more perfect.

A second process, more energetic than the preceding one, and which is more commonly employed, consists in moving the piece of steel that we desire to magnetise along the pole of a magnet: we have already given the theory of this. The coercitive force is more easily surmounted in this operation, in which each particle of the rubbed surface is subject, in its turn, to the direct influence of the magnetism of the pole. We have only to repeat the rubbing several times, especially if the coercitive force is great; but we must take care that it is always in the same direction. The effect of this reiteration of rubbing is not easy to comprehend. In fact, if, after having magnetised a needle by a first operation, we bring back the pole of the magnet to the extremity first touched, we begin by destroying the magnetism which has just been given to it before restoring it by a second rubbing. Each molecule, therefore, when rubbed, becomes first magnetised in a direction contrary to that in which it is afterwards. Why, therefore, does a second rubbing increase the effect of the first, a third that of the second, and so on, to a certain limit? It would appear that the movement impressed alternately, in contrary directions, upon the two magnetisms of the particles, favours their separation, and that the coercitive force yields more easily, after having already been several times surmounted, than when it has not yet been. There is in this, as it were, a kind of vibration necessary for magnetisation, and the intensity of which increases with the number of rubbings. We may in this process follow, in like manner as in the former, the march of the magnetisation. By moving along a bar the poles of a magnet, the line of whose poles is perpendicular to the axis of the bar, we perceive that there appear successively at the extremity last touched, a pole of the same name and a pole of the contrary name to that which is moved along, and the reverse takes place at the extremity first touched. The intermediate points pass through very variable magnetic states; those states present many anomalies, arising probably from differences of molecular constitution existing between the different bars submitted to experiment, and of which no two are ever identical.

When we desire to magnetise very powerfully a compass needle or plate, of a thickness not exceeding $\frac{1}{5}$ of an inch, we must arrange, at the two extremities of the needle to be magnetised, two powerful magnets so that they may act by their opposite poles upon the two ends of this needle. The latter is placed upon the magnet, so as to pass about an inch over its extremities. We then take two other magnetised bars, and holding them each in one hand, we touch with their opposite poles the middle of the needle; then, inclining them 25° or 30°, they are made to slide, under this inclination, one towards one of the extremities, and the other towards the other extremity of the needle. They are then brought again to the middle, to go through the same operation again, which is repeated until the magnetisation has become sufficiently powerful. Care must be taken that the pole of each bar that touches the needle is the same as that of the fixed magnet towards which it is made to slide, in order that the two effects may be added together. This process, called Duhamel's, or *separated touch,* is not sufficient when the plates to be magnetised have great thickness; we must then employ Æpinus's method, called *double touch.* It differs from the preceding only in that the two bars that are employed for magnetisation are moved along together and not separately, setting out from the middle of the plate to be magnetised. They are made to slide first upon one of the extremities, and are then returned along the whole length of the bar to the other extremity; these frictions are continued for a longer or shorter time by this backward and forward movement, with the condition of always beginning and ending at the middle, and taking care to stop only after having passed the same number of times over each part of the plate to be magnetised.

The process of double touch, while it produces a stronger magnetisation, and precisely, as we have seen, because this magnetisation is too strong, and thus determines a reaction of the poles upon the parts of the magnet that are near to them, possesses the inconvenience of frequently giving rise to consecutive points when the plates are of great length, and of giving poles of unequal force. It would be better, therefore, to employ Duhamel's process of separated touch, when operating upon compass needles or plates intended for accurate apparatus. This process is superior, even in this respect, to the two first that we have described. In fact, the presence of consecutive points is very hurtful to the sensibility of a compass needle, for its directive force is then only the difference existing between the force with which the two poles that are at its extremities are directed by the earth, and that with which the two poles respectively opposed to these on the same side, but nearer to the centre, are determined in a different direction. If the former have the predominance it is because they are in general the stronger, and also because they act with the longer arm of a lever.

We have explained, in a very summary manner, the different processes of magnetisation, that have been successively put in practice. A very great number of philosophers, besides those we have named, have been engaged on this subject: Canton, Mitchell, Antheaume, Savery, have all, as well as Duhamel, Æpinus, Robison, and Coulomb, that we have already cited, pointed out new methods for perfecting the old ones. As we are here not giving a history of the science, we cannot enter into the details of these methods and improvements: however, we must say one word upon the labours of a philosopher who is particularly celebrated by the attempts which he made to obtain the most powerful artificial magnets that were possible; it is Dr. Knight, who lived in the last century, and whose researches date especially from the year 1766 and the following years. The Royal Society of London possess a magnet, made by Dr. Knight, and which is confided to the care of Mr. Christie, the armature of which requires a weight of 100lbs., in order to detach it from the poles. This powerful magnet is composed of 450 magnetised bars, each 15 inches long, 1 inch wide, and ½ an inch thick; they are fixed in a box so as to present at each of its extremities two poles (*Fig.* 79.), which come out horizontally to a length of six inches, a height of twelve, and a width of three. This magnet, which Dr. Knight had taken great pains to construct and to maintain in a good condition, he called his reservoir of magnetic force: it was formerly much more powerful than it is at present; the needle of a compass that touched it would acquire so great a force of polarity that it would be in a condition to destroy all the polarity of the best compasses in England. A fire that occurred in the house where this magnet had been placed after the death of Dr. Knight, altered its force, and, notwithstanding the efforts that have been made to restore it to a good condition, it has never recovered its primitive vigour. Dr. Knight also succeeded in making small artificial magnets, which could carry as much as a hundred times their own weight. He also endeavoured to compose magnetic pastes, susceptible of acquiring a much stronger magnetism than steel. According

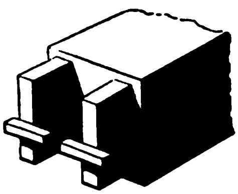

*Fig.* 79.

to Ingenhousz, the composition that gave the most satisfactory results, was a mixture of the powder of a natural magnet, very fine powdered charcoal, and linseed oil, which had been allowed to dry slowly. Experiments made by Ingenhousz himself proved to him that pastes, into the composition of which the powder of the natural magnet entered, were very superior to those prepared with the powder of iron, which is evidently due to the natural magnet having more coercitive force than iron.

It has never been properly known in what Dr. Knight's processes of magnetisation consisted. It is probable that he possessed no processes, properly so called, but that by trials, by persevering cares, and frequently-repeated operations, he succeeded, in course of time, in giving to his magnets the extraordinary powers that have rendered them celebrated.

Whatever be the process of magnetisation that is employed, there exists for each bar or needle a limit of magnetic force, beyond which we cannot pass when once it has been attained. We can very readily develope momentarily a stronger magnetisation; but, when once the magnetisation shall have ceased, the magnetism that the body will preserve will diminish until it has arrived at this limit, which is termed the *point of saturation.* Thus a needle makes 100 oscillations in 60″; we magnetise it more strongly, it makes them in 40″. At the end of a month or two it still makes 100 oscillations in 40″. We are able, by employing more powerful means of magnetising it, to cause it to make 100 oscillations in 30″, but, at the end of a certain time, it returns to making but 100 in 40″. It is evident that this latter number indicates the limit of the intensity that it is susceptible of preserving: it is therefore its point of saturation—a point that essentially depends upon the coercitive force of the body that is magnetised.

Bodies that have been magnetised beyond the point of saturation do not return to it immediately: this return sometimes does not occur until after a very long period; it may be influenced by many exterior causes, the change of temperature, the neighbourhood of other magnets, the action of the earth, &c. Saturation does not itself occur within limits so definite as might have been expected. There frequently occurs in the magnet a reaction of the north and south fluids, which augments or diminishes the magnetic intensity. To discover whether a body is magnetised to saturation, we have merely to magnetise it in the same direction with more powerful bars than those with which it had been at first magnetised. If its magnetism increases but feebly, and if this increase disappears with time, we may be sure of having attained the point of saturation by the first operation.

An important precaution is never to re-magnetise a body with bars more feeble than those which were at first employed to magnetise it. Not only do we add nothing to its force; but we on the contrary diminish it, by bringing back its magnetism to that which would have been imparted to it by the bars last employed, had they alone acted upon it at first. This result is produced because the bars, that are made to slide along, magnetise it only by recomposing at first, and then decomposing the magnetism of each of the particles of the magnetised body upon which they are made to pass.

The action of the earth may in like manner diminish the magnetism of bars magnetised to saturation, when they are struck while placed in certain positions. Dr. Scoresby has made a great number of curious experiments upon this subject, from which it follows that the earth always acts like a powerful magnet, the influence of which may counteract or reinforce the magnetism already acquired, according to the manner in which the body is placed. The same philosopher has also succeeded in magnetising steel bars to saturation, simply by the action of terrestrial magnetism. With this view he took two steel bars, 30 inches long and 1 inch wide, and then six others 8 inches long and ½ an inch wide. A large iron bar was struck in a vertical position, thus being magnetised by this percussion: it was immediately placed, without its direction being changed, upon each of the large steel bars, which were at the same time struck. Each of the small bars was then placed also vertically on the summit of one of the large bars, and successively struck: in a few moments they had acquired a great power of suspension. Finally, the six small bars were then successively united, two and two, by their opposite poles by means of small bars of soft iron, and were rubbed with the others according to the process of double touch, and at the end of these operations it was found that they were magnetised to saturation.

Form is another circumstance that notably influences the intensity of magnetism that a body is susceptible of acquiring. Coulomb having cut from the same plate of steel, needles which he tempered in the same manner and then magnetised to saturation, found that, for the same thickness and the same weight, the form of an arrow is superior to the rectangular form. With regard to the degree of temper, he found that it is not the highest that determines the greatest amount of magnetism; but that this maximum is attained when the steel has been tempered to dull red.

When compass needles are not in question, but magnets which we are endeavouring to procure as powerful as possible, the form of parallelopipedons is given to them, which constitutes magnetic bars, or the form of a horse-shoe. In both cases, but especially the latter, the magnet is not composed of a single piece, but of several similar ones which are superposed upon each other, care being taken that the extremities, which are placed on each other, have the same magnetic poles. Most commonly, slightly different lengths are given to these superposed plates, so that their ends recede from each other, and the magnet terminates in steps.

In order to preserve the magnetism in the bars, care is taken to provide them with keepers or armatures. These are pieces of soft iron placed in contact with the poles of the magnets, to maintain their activity by means of the contrary poles produced in them by the magnetism of the magnets themselves. When it is a horse-shoe magnet, a single prism of soft iron is sufficient for uniting the two poles; when they are bars, two are generally placed in the same box, being arranged parallel and at a slight distance apart, care being taken to place the contrary poles opposite to each other, and upon the two extremities two small prisms of soft iron are placed across (*Fig.* 80.). These pieces of iron, both in this case and the preceding one, become magnets; they react

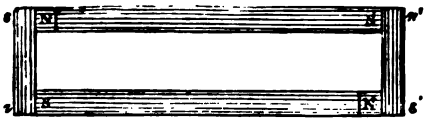

*Fig.* 80.

upon the bars, and maintain in them the separation of the magnetisms which, but for this precaution, would finish gradually by combining in a great degree, and so recomposing the neutral fluid. In compass needles, terrestrial magnetism performs the office of an armature by maintaining by its power the separation of the two magnetisms.

The armatures of horse-shoe magnets generally carry a scale-pan in which weights are placed, care being taken never to exceed the limit of what the armature can carry without being detached. These weights, which may be gradually increased, retain the power of the magnet, and even tend to increase it, providing that the access of weight never becomes such that the armature is detached. In this case, the magnet suddenly loses a great portion of its power, and it cannot recover it except by a fresh, slow, and gradual increase of the weight that its keeper can carry.

An interesting question, which was first studied by Coulomb, and afterwards by Nobili, is to know what the magnetic condition is of each of the plates, or of each of the wires, whose union forms what is termed a magnetic bundle. This determination seems to be able to lead to the knowledge of the magnetic state of the interior strata of a magnetised needle or bar. Coulomb found, by means of the balance, that the plates which formed the two exterior surfaces had a much greater magnetic force than the others. He also found some in the interior that had their poles inverted. M. Nobili, by employing the method of oscillations, succeeded in determining very exactly the magnetic state of each of the very fine needles, of the same length, which, to the number of fifty, formed a bundle that had been powerfully magnetised. He found, after he had undone the parcel, that all the needles were magnetised in the same direction: he then made up the bundle again, maintaining the contact of the needles as perfect as possible.

Having untied the packet two hours afterwards, he found that several of the needles had acquired a contrary magnetism. Having made the same experiment with another packet, and having undone it half an hour after magnetising it, he found that a certain number of the needles had lost all their magnetism. It follows from these facts that the strongest needles demagnetise the more feeble, and even impart to them a contrary magnetism; and that if, in the outset, they had received the same degree of magnetisation, the magnetic force would be very speedily extinguished in the whole system.

These experiments led M. Nobili to conclude that we must not consider, as we have done hitherto, a magnetic bar as formed of a bundle of filaments of the same length, magnetised to the same degree, and all in the same direction; for then the whole system would be very speedily demagnetised. He supposes that the interior of the bar is divided into concentric layers, the magnetism of which diminishes rapidly from without inwards; and that the conservative condition of magnetisation does not depend upon the coercitive force, such as we understand it, but on the mode itself of the distribution of the magnetism in magnets.

In this way of viewing it, tempering acts by determining in the mass such a state, that the exterior molecules, being cooled more rapidly than those of the interior, approach more closely than the latter are able to do. It follows from this, that tempered steel possesses a crust, the density and the other properties of which differ from those of the internal strata. In particular, the magnetism is better preserved in it; and on that account it is that magnetised steel remains more strongly magnetic. It is for the same reason that soft iron, when it has been beaten under the hammer, or has been passed through the draw-plate, acquires the property of preserving a small amount of magnetism. The exterior parts having been rendered more compact than those of the interior, there arises an unequal distribution of the magnetism, which is found in greater quantity on the exterior than on the interior. This also causes small bars to take proportionally more magnetism than large ones, their surface, in proportion to their volume, being more considerable. The following new experiment by Mr. Nobili is entirely in support of his opinion. This philosopher constructed, with the same steel, two cylinders of the same length and the same diameters; the one solid, which weighed 432¼ grs. Troy, the other hollow, which weighed only 247 grs. Troy. These two cylinders were tempered in the same manner, and each magnetised to saturation. Placed at the same distance from a compass needle, the solid one gave a deviation of 9½°, and the hollow one a deviation of 19°. The difference is very great in favour of the hollow cylinder, although its mass was almost one half less than the solid one. This arises from the hollow cylinder being tempered without and within, and then being covered on both sides with this crust that preserves the magnetism: whilst the solid one possesses it only on its exterior surface.

All the facts relating to magnetisation are still enveloped, as we perceive, in very great obscurity. One very evident principle, however, is derived from them all, and which we have already pointed out; it is the connection which they establish between magnetism and the molecular properties of bodies. As we have said, we shall see, in the sequel, when we are considering magnetisation by electric currents, some fresh proofs in favour of this principle; we may possibly then be able to determine, in a more precise manner, what the nature is of the relation in question.

We shall say nothing here upon the experiments of certain philosophers, and especially those of Mr. Barlow, on the magnetisation of bodies of various forms, such as rings and spheres; and of the action that they exercise upon the magnetised needle, when they are of soft iron and not magnetised previously, or merely subjected to the magnetising action of the terrestrial globe. These effects obey laws which are remarkable for their simplicity and their regularity. So also have they been made easily the subjects of calculation, and they have been employed by M. Poisson in his theoretical researches upon magnetism. We shall confine ourselves to pointing out a single fact, which, from its connection with those that have gone before, appears to us very important. It is, that the magnetic power exercised by soft iron spheres resides entirely upon their surface, and is completely independent of their mass; so that the effect exercised by cannon-balls upon the magnetised needle is exactly the same, whether they are solid or hollow. However, this law has limits. Mr. Barlow has recognised that the metal envelope must have at least a thickness of $\frac{1}{20}$ in., in order to act as if the sphere were solid.

The processes of magnetisation have lately been still further improved in a remarkable manner, so that permanent magnets can be obtained of extraordinary power; but the processes that are employed are not known. We shall have occasion, further on, when occupied with the magnetism produced by dynamic electricity, to speak of the principle upon which probably they depend.

# CHAP. II.

## MUTUAL ACTION OF MAGNETISM AND DYNAMIC ELECTRICITY; AND OF ELECTRIC CURRENTS UPON EACH OTHER.

### *Mutual Action of Magnetism and Electric Currents.*

FOR a long time philosophers were struck with the analogy that seemed to exist between electric and magnetic phenomena. Two magnetisms, as there are two electricities; attraction and repulsion exercised between the contrary magnetisms as between the electricities, according to similar laws; these are indeed points of resemblance between the two classes of phenomena. However, it was in vain that attempts were made to establish experimentally a more intimate relation between them. In 1805, MM. Hachette and Desormes had endeavoured, without success, by means of terrestrial magnetism, to give direction to an insulated voltaic pile, having consequently its two poles equally strong, and freely suspended: their attempts were fruitless.

It was not until 1820 that a Danish philosopher, M. Oersted, succeeded in discovering the relation, that had so long been sought after, between magnetism and electricity; but it was not where it had been constantly thought to exist that he discovered it. Electricity acts upon a magnet; and a magnet in its turn acts upon electricity; but only when the electricity is in motion, that is to say, in the condition that we have termed *dynamic:* there is no action when the electricity is in the *static* or *tension* state.

The following is Oersted's fundamental experiment:—

The two poles of a pile are united by a metal wire, called a *conjunctive wire.* This wire is placed either above or below a magnetised needle, freely suspended, and parallel to its direction. The needle is immediately seen to suffer a deviation, which is the more considerable as the voltaic pile is more powerful; and it tends to place itself perpendicularly to the conjunctive wire, a position which it succeeds in attaining when the electricity developed by the pile is very strong. The direction in which the deviation occurs depends upon two circumstances: the first circumstance is the position of the conjunctive wire in relation to the magnetised needle,—it may be above or below; the second is the communication of each of the two extremities of the conjunctive wire with either pole of the pile. Thus if, the conjunctive wire being below the needle, the positive pole of the pile communicates with the extremity of the wire that is on the south side, and the negative pole with that which is on the north side, the north pole of the magnetised needle deviates to the east; it deviates to the west, if we change the place of the poles of the pile. But if the conjunctive wire is above the needle instead of being below, the deviation occurs in the contrary direction, that is to say, the north pole of the needle deviates to the west when the positive pole is at the south extremity of the conjunctive wire and the negative pole at the north extremity, and to the east when the place of the poles of the pile is inverted.

If the conjunctive wire is not placed parallel to the needle, but in such a manner that its direction forms with that of the needle, either above or below it, a greater or less angle, the action is still the same; the needle in like manner manifests its tendency to place itself across or perpendicular to the wire, a tendency which it obeys entirely, when the force of the pile is sufficient to surmount the resistance to deviation, arising from the directive force of the earth. We must only observe that in this case, as in the preceding one, when the needle places itself across, in relation to the conjunctive wire, its north pole is not carried indifferently to the east or the west; but that the direction, according to which the deviation occurs, is subjected to the laws that regulate the primitive case,—that case in which the conjunctive wire is placed parallel to the direction of the magnetic needle.

M. Ampère was not long in taking up this experiment, and deducing from it many theoretical and experimental consequences of the highest interest, which, under the name of *electro-dynamics*, have formed an entirely new part of physics. He first observed that the action discovered by Oersted not only took place in the vicinity of the conjunctive wire, but that it was in like manner exercised by all parts of the conductor by which the two poles of a pile are united, and by the pile itself; but only when its poles communicate together, and not when they are insulated. He further remarked that the direction in which the needle is deviated varies according as it is placed upon the pile or upon the conjunctive wire. This may easily be verified by placing a pile in the direction of the magnetic meridian with a magnetic needle above it, and as near as possible; and a conjunctive wire parallel to the pile, with a second needle, also above the wire. The pile and the wire must be sufficiently distant from each other that the two magnetised needles may not exercise any mutual influence upon each other; it is also necessary that the pile contain no iron in its construction; Wollaston's copper trough pile, or one of Daniell's constant piles, fulfil this condition well. At the moment when the extremities of the conjunctive wire are placed in communication with the conductors coming from the poles of the pile, the two magnetised needles are immediately seen to deviate, but in a contrary direction to each other. It would be the same if the needles were placed upon any two parallel portions of the conductors, by which the poles of the pile are united. If they are placed below, instead of above, the same phenomenon is observed; only the two deviations each occur in a contrary direction to that in which they formerly occurred; and always consequently in a direction the inverse to each other.

Ampère drew some important conclusions from this experiment:—

The first is that the force, whatever it may be, that acts upon the magnetised needle emanates equally from all parts of a *voltaic circuit*, designating by these words the pile and the whole of the conductors, whatever they may be, by which the poles are connected. The deviation occurs in the vicinity of a liquid conductor, as well as in that of a solid one; the only necessary condition is, that the current be transmitted through the conductor, that is to say, that the neutralisation of the two electricities may be brought about in a continuous manner. There results from this a very great difference between the kind of action that dynamic electricity exercises upon a magnetised needle, and the calorific, luminous, or chemical phenomena that it produces. The former are general, that is to say, independent of the nature of the conductor; the latter, on the contrary, depending upon the nature of the conductors by which the poles are united, occur only in certain determinate parts of the circuit, and may even not occur at all.

The second conclusion is, that the force in question is circulating; for how can we otherwise explain why it acts in contrary directions when it emanates from the two opposite or parallel portions of the circuit, this opposition being the only circumstance that establishes a difference in the conditions of the experiment. We may compare its action with that which a current of water would exercise, if circulating in an annular canal: in this case small light bodies, floating on the water, would be drawn onward by two parallel or opposite portions of the current of water. This analogy has led to the name of *electric current* being applied to the force that arises in the whole of the circuit, from the reunion of the two poles of a pile by a conductor. The electric current is the representative of the continued dynamic state of electricity. Ampère supposed by conventional terms that have been admitted, that this current had a *direction,*—that it comes from the positive pole to traverse the conductor and arrive at the negative pole, and returns through the pile to the positive pole, its point of departure. It is easy to see, in fact, by pointing out its direction by means of arrows, that, by regarding it in this way, it is found to have a different direction in the two parallel portions of the same circuit; for example, in the pile itself, and in the part of the conductor that is parallel to it (*Fig.* 81.). However, nothing proves that this direction is the true direction of the current, or even that the movement of the electricity is brought about under the form

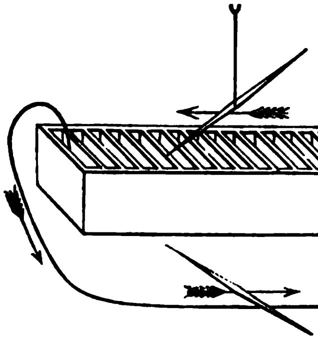

*Fig.* 81.

of a current; it is, we repeat, only a conventional mode, a convenient manner of representing a phenomenon, and which enables us easily to fall back upon the fact itself, abstraction being made of all theoretical ideas. In fact, to say that the current goes from A to B in a conductor, is to say in a few words that the extremity A of a conductor is that by which the positive electricity arrives, and the extremity B that by which the negative electricity arrives.

This conventional form being once admitted, we may with Ampère represent the action of a current upon a magnetised needle under a form very convenient for the memory. We have only to conceive a man lying down in the portion of the circuit under consideration, in such a manner that the current enters by his feet, and goes out consequently by his head: furthermore, we have but to conceive that this man has always his face turned towards the needle, so as to look at it; then the action is always found to be such that the north pole of the needle is deviated to the left of this man. It is easy to see that this kind of formula comprehends all possible cases.

The force that emanates from an electric current acts upon the magnetised needle as well in vacuo as in the air, and through all substances except those that are magnetic, such as iron. We may likewise prove that it diminishes in intensity in proportion as the distance between the current and the needle increases.

MM. Biot and Savart, very shortly after Oersted's discovery, determined also the law which this diminution follows. With this view, they took a very short magnetised needle; they suspended it delicately, by means of a filament from the cocoon, and rendered it indifferent to terrestrial magnetism, by placing a magnetised bar near to it, and at a proper distance. This needle has thus no directive force, and is ready to obey all exterior action. MM. Biot and Savart then acted upon it by a current transmitted through a copper wire six or eight feet in length, stretched vertically, and so arranged that the horizontal plane passing through the needle is divided into two equal parts. The needle, as soon as the current acts upon it, places itself transversely or across, in respect to the conducting-wire, according to the law that we have already enunciated; when removed from this position, it returns to it by isochronous oscillations, of a duration variable with the intensity of the force. Now, the energy of the current remaining constant, this intensity can only depend upon the distance by which it is separated from the needle. The experiments made this distance vary from ½ in. to 4¾ in., taking the necessary precautions that, during the continuance of the experiment, the current should remain very constant; and they found that *the intensity of the electro-magnetic force is in inverse ratio to the simple distance of the magnetised needle from the current.* This law is true only so long as the current is rectilinear, and sufficiently long that it may be regarded as infinite in respect to the needle; or, which comes to the same thing, that the points that would be situated beyond cannot, on account of their distance, exercise any sensible action upon the needle. It is easy to demonstrate, by a simple calculation, that the law we have just discovered, within the limits of the conditions pointed out, is the consequence of another more general law, which may be proved directly, but of which this, that is derived from it, is the proof, namely: *that the elementary action of a simple point, or of a simple section, of the current upon the needle is in inverse* *ratio to the square of the distance.* We may also prove that this action is proportional to the sine of the angle formed by the direction of the current and by the line drawn through the section of the current that is considered to be in the middle of the magnet. In fact, by calculating according to these two principles the sum of all the elementary actions that are exercised upon a small needle by an indefinite electric current, we find that the intensity of this resultant must be, as experiment points out, the inverse of the simple distance. It further follows that, if the indefinite current is angular, that is to say, if it is composed of two directions, forming an angle, the summit of which is upon the horizontal plane passing through the needle, the intensity of this current is also the inverse of the simple distance; but, moreover, it is proportional to the tangent of the half of the angle.*

After having analysed, as we have seen, the nature of the current upon a needle, M. Ampère showed that a fixed magnet acts upon a movable current in the same manner as a fixed current acts upon the magnetised needle. In order to obtain a movable current, he contrived to bend a copper or brass wire into the form of a circle or a rectangle, bringing back its two extremities near to each other, without, however, their being in contact; he terminated them by steel or brass points placed on the same vertical, and one of which, resting on the bottom of a metal capsule filled with mercury, supported the whole of the movable conductor, whilst the other, either above or below, merely plunged into the mercury of a similar capsule, without touching the bottom, so as not to interfere with the mobility. The two capsules are each supported by a solid conductor in the form of a gibbet; one of these conductors enveloping the other, or being very near to it, but without touching it. One of the poles of the battery is made to communicate with the lower extremity of one of the fixed conductors, and the other pole with the corresponding extremity of the other similar conductor.† The

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* For the mathematical developments, see the final note E.

† This communication may be established either by simple contact, or by means of metal pincers; or, which is more convenient, by means of two grooves or cavities filled with mercury, into which the extremities of the conductors and of the poles of the pile are plunged.

current is thus established in the movable part, which, by means of the capsules filled with mercury, serves to complete the circuit (*Fig.* 82.). It is necessary that the fixed conductors be sufficiently distant from the movable conductors, in order that in their different positions, the sides of these latter may not be influenced by the currents that are traversing the former. Moreover, the latter being very close together, and traversed by equal currents determined in contrary directions, their effects upon the movable conductor are mutually neutralised.

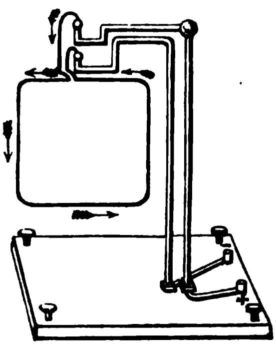

*Fig.* 82.

By placing a magnetised bar below and very near to the lower part of the movable current, and parallel to this current, we see the latter move and place itself transversely to the magnet, but always so as to be directed in the part upon which the magnet is acting, as it would be according to the formula we have established above, in the case of the fixed current and the movable magnet. In other words, it is necessary that the man who is supposed to be lying in the current, his feet turned upon the side by which the latter arrives, and looking at the magnet, which is here below it, should always have the north pole of this magnet on his left hand. If, when the movable conductor has assumed this position, the direction of the current is changed by changing the place of the two poles of the pile, we immediately see the conductor set in motion, and describe 180°, in order to take a position similar to that which it occupied; having then the current determined in the suitable direction. The same movement is effected if, instead of changing the direction of the current, we turn the fixed magnet round, so as to place its north pole where its south pole had been, and reciprocally.

M. Ampère was not long in discovering, by making use of a powerful current, and a movable conductor always rectangular or circular, but of a diameter of 15 or 20 inches at least, that terrestrial magnetism acts upon the current as a magnet would act if placed below it in the direction of the compass needle, but having its south pole turned towards the north, and its north pole turned towards the south. The movable current places itself, in fact, under the influence of the terrestrial globe, transversely or perpendicularly to the magnetic meridian, and so as to be directed from east to west in its lower part, which causes the man who is lying in the current, with his feet to the east, and his head to the west, and his face turned towards the earth, to have the south of the earth on his left. Now, if it were a magnet that was acting, and not the globe, he ought to have the north pole of this magnet on his left, according to the law that we have established: it follows, therefore, that the terrestrial globe acts like a magnet whose north pole would be on the south, and whose south pole would be on the north of the earth. If the direction of the current in the movable conductor were changed, this conductor would move majestically by describing an angle of 180°, in order to place itself so that its plane should be always perpendicular to that of the magnetic meridian; but, at the same time, the current would be directed from east to west in its lower part.

This action of the earth, although much less energetic than that of a powerful magnet very near to the conductor, may, however, complicate the results when this latter action is being studied. Therefore, in order to guard against this, Ampère contrived to bend the movable conducting wire in such a manner as to form two similar rectangles, perfectly equal, and the one below the other, or even one beside the other (*Fig.* 83.). In this latter case the two rectangles

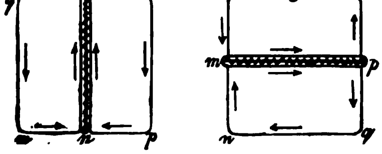

*Fig.* 83.

are situated each on a different side of the axis of rotation, but on the same plane. Small pieces of wood interposed between the contiguous portions of the wire, and connected with them by means of silk thread, maintain the form of the conductor, at the same time preventing metallic contact between its different parts. The wire is so arranged that the current traverses, in different directions, the two associated rectangles; it follows that the action of the earth is neutralised or null upon the movable system, which, on this account, is termed *astatic;* in fact, it tends to give to one of the rectangles a direction exactly the contrary of that which it tends to give to the other; and as the two rectangles are equal, and it is the same current that traverses them both, the two effects destroy each other. In this manner we obtain with the first astatic system a horizontal current, and with the second a vertical current, each movable and perfectly indifferent to terrestrial magnetism. We will call them, for distinction's sake, the former the *horizontal* astatic conductor, and the latter the *vertical* astatic conductor.

The system of suspension employed by M. Ampère for the purpose of obtaining movable currents, presents one inconvenience; it is, as the inspection of the figure makes manifest, that the conductor cannot turn indifferently in all directions, being retained in one point of its circular movement by the branches of the fixed conductors that sustain the capsules intended for establishing communication with the poles of the pile. Endeavours have been made to remedy this inconvenience in various ways; the most ingenious is that which was devised by Professor G. De la Rive. It consists in rendering the whole circuit movable, including the pile: with this view, we fix to a cork, that is made to float upon water slightly acidulated, a pile composed of merely a plate of copper and one of zinc, which are thrust through the piece of cork. The upper extremities of these two plates are connected by a wire upon which we can act with the magnet; the lower extremities, and generally the greater portion of the two plates, are plunged in the acidulated water. As the pile is feeble, the wire, which we take care to envelope carefully in silk, so as to avoid all metallic communication, is made to present several convolutions, and so as to form a circular ring or a rectangle (*Fig.* 84.). The current traverses all the turns successively in the same direction, whence it follows that, instead of acting with the magnet upon a single current, we act upon several similar ones at the same time, and consequently we multiply the intensity of the action to the same extent. The possibility of this multiplication, of which we shall see many other applications, is due to that fundamental property of the magnetic force which we have already recognised, namely, that all the parts of the same circuit act equally upon the magnet. These floats are also directed by the action of the terrestrial globe, in the same manner as movable conductors are when traversed by the current of a powerful pile; it is merely necessary that the diameter of the ring or rectangle be at least three or four inches.

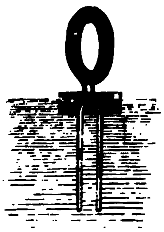

*Fig.* 84.

On the principle that the current may be more energetic which enables us to employ as a conductor a wire making only one turn, we may fix to the cork a small Daniell's pile, contained in an envelope of thin glass, or the copper of which forms the exterior vessel; the whole is made to float in ordinary water. We may also adjust to the cork a helix pile formed of a thin plate of platinum and a thin plate of amalgamated zinc: in this case, the water upon which the cork floats must be acidulated; it is this combination which appears to me to include the most favourable conditions of force and lightness. We then adapt to this apparatus, in order to establish communication between the poles of the pile, conductors of copper wire bent according as they may be required for the experiment; but we must give large dimensions to the figures that are formed by the different conductors, when we do not adopt the system of the multiplier (*Fig.* 85.). Moreover, with one form as with the others, we may easily make all the same experiments that are made with the apparatus that are constructed according to Ampère's mode of suspension, and in particular to obtain direction of a rectangular or circular current by means of the terrestrial

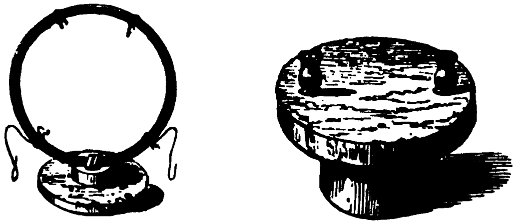

*Fig.* 85.

globe. We must only take great care, when we employ but a single voltaic pair, not to forget, as we have already remarked in the First Part of this work, that the positive electricity sets out from the copper or platinum plate, and the negative from the zinc plate; that, consequently, it is, according to our conventional mode of describing it, from the copper or platinum plate that the current is found to start in order to traverse the conductor, to go thence to the zinc, and to return through the pair to its point of departure. In order that we may be able to put the different conductors successively into the circuit of the pair, the cork disc carries two small cylindrical capsules of wood filled with mercury, which communicate, the one with the platinum, the other with the zinc of the pair, and into which the extremities of the conductor through which the current is to be transmitted are made to plunge.

At the same time that M. Ampère took up Oersted's discovery, in order to generalise and to extend it, M. Arago showed that an electric current not only acts upon a magnetised needle, but that it also acts upon all magnetic bodies, even when they are not magnetised. Having slightly curved a copper wire of about $\frac{1}{25}$th of an inch in diameter, he saw that, when this wire was traversed by a strong current, it acquired the property of attracting and retaining around it, under the form of a cylindrical envelope, a certain quantity of iron filings, and that immediately the current ceased to pass, the filings fell; the wire took them up again as soon as the current passed. This experiment proves that the electric current impresses upon conductors, when it is transmitted by them, properties perfectly analogous to those of magnets, and not simply to those of magnetic bodies; in other words, that it magnetises them, and does not simply render them susceptible of being magnetised. M. Arago went further, by showing that the discharge of a Leyden jar may magnetise a steel needle placed in the interior of a helix made of wire, through which this discharge is made to pass. Davy shortly afterwards discovered that we can in like manner magnetise a sewing needle by merely rubbing it transversely against a rectilinear wire, traversed by the electric current of a pile. We shall return to this subject in the Third Chapter, which is entirely devoted to it.

### *Mutual Action of two electric Currents.*

From the origin of these researches M. Ampère perceived that an electric current not only acts upon a magnet, but that it also exercises an action upon another electric current. He found that this action consisted in that, if two portions of rectilinear currents parallel to each other are both movable, or are the one fixed and the other movable, *they are mutually attractive when they are moving in the same direction, and repulsive when they are moving in a contrary direction.* The attraction in this case does not cease with contact, as occurs when we are referring to the attraction of electric bodies in static electricity; it remains so long as the current continues to traverse the conductors.

In order to demonstrate this principle by experiment, we may employ the floating pile, or Ampère's apparatus, adapting to either of them the vertical astatic conductor. We present to one of its vertical branches a parallel wire traversed by the current of a rather powerful pile. We perceive that this wire, which may simply be held in the hand, attracts the branch of the rectangle, if the two currents are moving in the same direction, namely, both in like manner from above downwards, or upwards from below, and repels it if they are moving in a contrary direction, the one from below upwards, and the other from above downwards * (*Fig.* 86.).

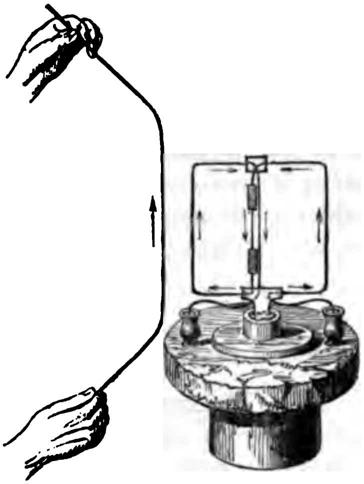

*Fig.* 86.

M. Ampère was not long in generalising the law of parallel currents by extending it to the case of angular currents, that is, to the case in which the two conductors, each being traversed by a current, form an angle by being situated either in the same plane or in different planes; in this latter case, the angle formed by the currents is that which is made by the two planes in which they are situated, and it has for its height the right line that measures their shortest distance.

The following is the law that Ampère discovered in this general case; it is that *the two angular currents attract each other, when their direction is such that they both tend toward the summit of the angle, or that they both set out from it, and that they repel each other when one goes towards the summit and the other sets out from it.* This law comprehends four different cases, for the understanding of which it is necessary to cast the eye upon *Fig.* 87., in which the arrows that are outside the angular lines represent the direction of the currents, and those

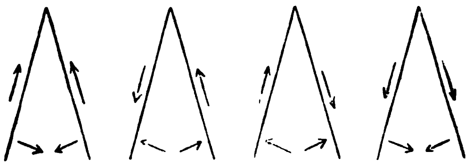

*Fig.* 87.

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* We may hold the wire, by which the two poles of the battery are connected, in the hand, in order to present it to the movable current, without the current ceasing to traverse it, as the metal is a conductor so superior to the human body that the two electricities traverse it exclusively in order to unite with each other.

withinside the lines the direction in which the conductors move in respect to each other. When the suspension of the movable current and the arrangement of the fixed current are such that the angle which they form together remains invariable, this action may give rise to a continuous movement of rotation. But before studying this particular form, under which it is sometimes presented, we must establish it in a more direct manner by entering upon the case in which the arrangement of the experiment permits the two currents to approach or to recede, so that the angle formed between them increases or diminishes.

With this in view, we may employ the floating pile, attaching to it the horizontal astatic conductor. We present to the upper branch a rectilinear current, in like manner horizontal, so that it forms with it an angle, the summit of which is at one of the extremities of each of the two conductors (*Fig.* 88.). Immediately, whatever this angle may be, whether acute, obtuse, or right, we perceive, if the two currents are directed so as to converge to each other towards its summit, or to diverge from it, the movable branch, carrying with it the whole of the circuit of which it forms a part, turns round this summit in order to place itself parallel to the fixed conductor, and as near to it as possible. In this position the two currents have become

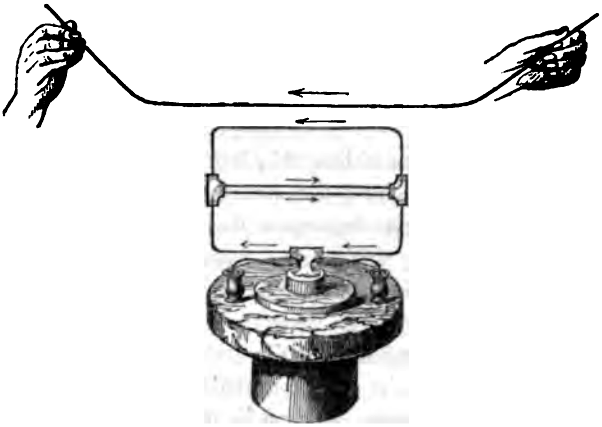

*Fig.* 88.

parallel, and are determined in the same direction with respect to each other. If, on the contrary, one of the currents is at the outset directed towards the summit of the angle, and the other sets out from it, we perceive the movable branch still turning around this summit and avoiding the fixed conductor by increasing the angle which they form between them, and tending to place itself in the extension of this conductor by forming with it an angle of 180°, that is to say, the greatest possible angle.

As the distance between the different parts of the two conductors, which are not very near to the summit of the angle, is necessarily very great, the currents must be very energetic in order that the experiment may succeed well. In order to increase this energy, we may cause the wire of which the astatic conductor is formed to make several turns, having taken the precaution to cover it with silk, in order to prevent metallic contact. But, for experiments of this kind, it is preferable to make use of Ampère's apparatus, which enables us to employ the current produced by a powerful pile. We suspend upon it the horizontal astatic conductor, and, in order to act upon its lower branch, we adapt to it a fixed horizontal conductor, which is placed beneath, but as near to this branch as possible. We may cause the same current to pass through the fixed conductor that traverses the movable conductor if we prefer it, which is the more convenient plan, as we need not employ two different piles. This observation is also applicable to the experiment in which we demonstrate with this same apparatus the action of a fixed vertical conductor upon the vertical branch of the astatic movable conductor. But in order to realise every possible case by employing only a single current which traverses successively the whole system of fixed and movable conductors, we must be able to change the direction of the current, not only in the two conductors at once, which is always easy, since it is sufficient for this to change the place of the two poles of the pile, but also in one of the conductors only, without changing it in the other, which requires a particular contrivance.

The following is consequently the manner in which the apparatus of *Fig.* 82. is arranged so as to serve for all experiments that relate to the mutual attraction and repulsion of electric currents. Upon the table which supports the apparatus (*Fig.* 89.) are placed three steel capsules filled with mercury, and arranged in the arc of a circle, of which the two extremes *a* and *c* each communicate with one of the gibbet-like metal supports which are intended for placing the movable metal conductor in the circuit. The middle one, *b*, is placed in communication with a metal binding screw, or a capsule *m*, intended for receiving one of the extremities of the fixed conductor, whether it be vertical or horizontal, the other extremity of which goes to a second binding screw or capsule, *n*, from which a conductor is led to one of the poles of the pile. The other pole is fixed to a small metal cylinder, *o*, placed in the centre of the circle to which the arc belongs, that is formed by the first three capsules. Along this vertical cylinder a socket slides tightly, and from which proceeds a horizontal metal conductor, that at its curved extremity can be plunged at pleasure into either of the three capsules *a*, *b*, or *c*. From the same socket proceed two glass stems, *o e* and *o g*, each of which carries at its extremity a metal arc, the dimensions and arrangement of which are so calculated that, when the horizontal stem is plunged into one of the extreme capsules *a* or *c*, the two other capsules are connected metallically by one or other of the two arcs. It is easy to

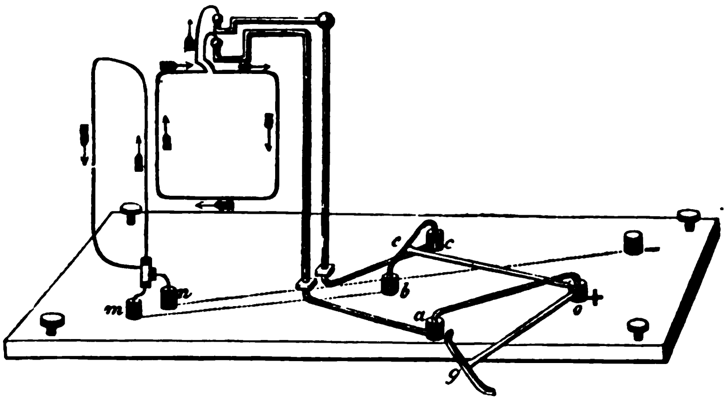

*Fig.* 89.

see that, by this arrangement, the current is established in the whole system of fixed and movable conductors, and that, in order to change its direction in one of the conductors (the movable), without changing it in the other (the fixed), we have merely to plunge the horizontal stem alternately in one or other of the two extreme capsules. In fact, supposing the positive pole of the pile to be in communication with the centre *o* of the circle, the current setting out thence arrives by the metal arc at one of the extreme capsules *a* or *c*; it passes thence to one of the erect supports, traverses the movable conductor, returns by the other support to the second extreme capsule, then passes by means of the metal arc to the middle capsule *b*, whence it is directed to one of the extremities *m* of the fixed conductor, which it traverses in order to arrive by the other extremity *n* of this same conductor to the negative pole of the pile. When we wish to act upon the movable conductor merely by a magnet or by the terrestrial globe, we confine ourselves to removing the system of fixed conductors, and uniting by a wire the two binding screws or capsules *m* and *n*, which were intended for placing it in the circuit. It is easy to see that the movable conductor is then placed in the circuit, and that the direction of the current that traverses it may be changed by the same contrivance that is employed when the fixed conductor is also traversed by the current. We may also do without the apparatus (*Fig.* 82.), that which we have just described being applicable to the same purpose. *Fig.* 89. represents the case in which the fixed conductor is vertical; and it serves for the demonstration of the attraction and repulsion of parallel currents. *Fig.* 90. represents the case in which the fixed conductor is horizontal; it is that which is used in the study of angular currents. This fixed horizontal conductor generally consists, not of a single wire, but of a wire covered with silk and making several revolutions around a frame, and the two extremities of which are put into communication with the binding screws or capsules *m* and *n*: this multiplication renders the action of the fixed current upon the movable current much more energetic.

In order to establish the law of angular currents, we employ,

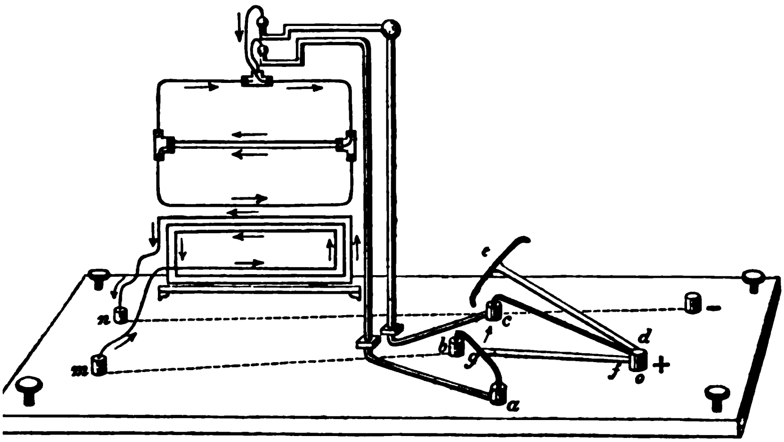

*Fig.* 90.

as we have said, the horizontal astatic conductor; and it is upon its lower branches, which can have only one movement of rotation around the axis of suspension, that the fixed current acts. We may give the movable conductor such a form (*Fig.* 91.), that the movement of rotation takes place around the extremity of the horizontal branch. The experiment is then made in the same manner as with the floating circuit, and it gives the same results, which are merely more decided on account of the possibility of employing more energetic currents. Generally, however, the movement of rotation occurs in the middle of the horizontal branch of the movable astatic conductor (*Fig.* 90.). It is easy, in fact, to see that in this case the effect is double; for the two currents experience, in each of the angles that they form in crossing, attractive and repulsive actions, which, being subjected to the law that we have enunciated, unite in impressing upon the movable branch a motion in two directions that concur. They are in fact repulsive in two of the angles, and attractive in the other two; and it follows that they compel the movable current to place itself parallel to the fixed one,

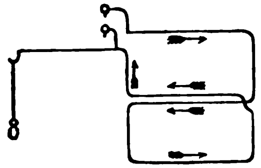

*Fig.* 91.

so that their direction is the same with each other. If we then change the relative direction of the two currents, we see the movable current describe an angle of 180° in order again to place itself parallel to the fixed current, so as to be determined in the same direction with it. This experiment shows that the action of angular currents, according to the mode of suspension and the position of the fixed point about which the movement occurs, may transform the attraction and repulsion into a change of the direction: but the simple and primitive effect is truly attractive and repulsive; the change of direction is only a result of this, which is easy of comprehension, when we regard the mode of suspension.

We have said that the law of angular currents is the same, whatever be the size of the angle: it is easy to prove this by experiment. Regarded in this manner, the law of parallel currents is only a particular case of the general law, that in which the angle is zero. Another particular case, no less interesting, is that in which the angle is 180°, that is to say, in which one of the currents is merely the prolongation of the other. M. Ampère succeeded in giving a direct verification of the law in this case. With this view he divided, by means of a glass partition, an earthen dish into two equal compartments, which he filled with mercury; then, taking a wire covered with silk, the two extremities of which he exposed, he bent it in the form of an arc, taking care that the two ends of the perpendicular wire at the part where the arc is formed were parallel to each other. Thus arranged, he made it float upon the mercury (*Fig.* 92.), so that the two parallel and horizontal branches were one on one side, and the other on the other side of the glass partition, both parallel to this partition, and that the exposed extremities were well in contact with the mercury. Then, by plunging the two poles of the pile, one into the left and the other into the right compartment, he compelled the current to traverse the wire. Immediately the circuit is formed, the float slides along the

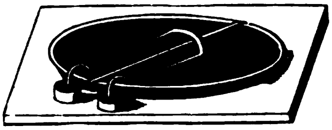

*Fig.* 92.

mercury, rapidly receding backward,—an effect due to there being, in each of the branches separately, a repulsion between the current that traverses it and the current that is transmitted into the mercury before penetrating into the wire or after going out from it. The current of the mercury and that of the wire are only the prolongation of each other, or, which comes to the same thing, those two currents forming an angle of 180°, one of which goes to the summit of the angle and the other sets out from it, there must be a repulsion between them, and this for each of the two branches separately. This important consequence of the general law may be also expressed by saying that *all the portions of the same current repel each other.*

The following is an experiment of Davy's, which demonstrates the same law under another form. It consists in introducing through two small holes, pierced in a disc or capsule at a distance of an inch or so apart, two very short pieces of platinum wire: the capsule is filled with mercury, so that the ends only of each of the two pieces of wire are covered with a very thin stratum. Then these two wires are made to communicate from below with the poles of the battery; the current is thus transmitted through the mercury from one wire to the other. The mercury is immediately seen to rise above each of the ends of the wire in the form of little cones, which, falling back by the effect of gravity, and rising again by the effect of the current, determine in the mercury a series of undulations. The repulsion that occurs between the portions of the same current is here exercised upon the mercury, the wire being fixed; whereas, in Ampère's experiment, it was the movable wire that was set in motion.

By referring the experiment of the electrical mill, that we described in the Fifth Chapter of the Second Part of this work, to the same principle, we may give to it a much better explanation than that which is generally admitted. In fact, in the electrical mill, the electricity that comes out from the points forms a current, which is propagated in the medium into which it penetrates, particularly into the air. Now the continuous rotatory movement that the mill undergoes in the opposite direction to the points, is merely the result of the continuous repulsion that occurs between the current that traverses the movable metal branch, and that which escapes out of it to penetrate into the air.

### *Ampère's Theory on the Constitution of Magnets; and the Law of Electro-dynamics.*

After having studied the mutual action of electric currents upon each other, and having determined their laws, Ampère endeavoured to connect the action of currents and of magnets by means of a very ingenious hypothesis on the nature of magnetism. By carefully analysing the action of the different parts of a magnet upon a movable current, and that of a current upon the different parts of a movable magnet, he saw that these actions were exactly the same as those which might have occurred had the section of the acting magnet, or the magnet submitted to action, been replaced by an electric current circulating around this section and consequently closed, and situated in a plane perpendicular to the axis of the magnet. By observing that in some cases there was attraction and in others there was repulsion between the section of a magnet and an electric current, the direction of which he knew, he further succeeded in determining what the direction ought to be of these hypothetical currents; and for this he rested simply upon the law that there is attraction when the currents move in the same direction, and repulsion when they move in opposite directions. The following is the mode by which we succeed in attaining to this determination. We take a prismatic magnetised bar, using the precaution to hold it horizontally, so as to have the north pole on the left hand; we present it to the vertical branch of the movable astatic conductor, placed alone in the circuit; we find that, if this branch is traversed by the current proceeding upwards from below, it is repelled by all the parts of each of the faces of the bar, and this from one extremity to the other; that, on the contrary, it is attracted if its current is directed from above downwards. When thus passing each of the faces of the bar from one end to the other before the vertical current, we must take care always to hold the magnet horizontally, and the north pole to the left. Now if, by means of a little soft wax, we apply on each of the faces of the magnet small arrows of card, with the point turned in the direction according to which a current ought to travel in order to produce upon the movable conductor the attraction or repulsion that is determined in it by the action of a magnet (*Fig.* 93.), we find that these small arrows represent a current circulating around each of the sections of the magnet, everywhere in the same direction, namely, from top to bottom in the face that is turned toward the movable conductors, and from bottom to top in that which is opposite to it, and moving from the conductor in its lower surface, and approaching it in its upper. The sum of these directions perfectly constitutes a current, circulating around each section of the magnet, as in a closed circuit. When, without changing the position of the arrows, we turn over the magnet, placing the north pole to the right, it is easy to comprehend that, as their direction is then inverted by the mere fact of this turning, it follows that the current which they represent goes from the bottom to the top in the face that is presented to the movable current. Thus, between the different parts of the magnet that are successively presented to the current, and the current itself, there is

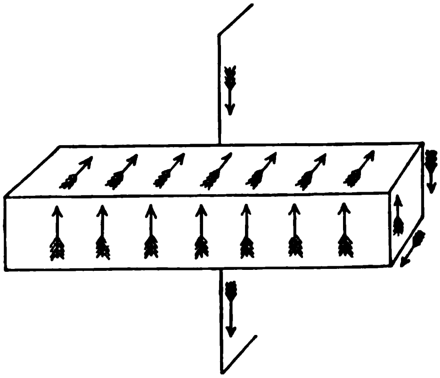

*Fig.* 93.

repulsion when the current is directed from above downwards, and attraction when it is directed from below upwards; actions precisely contrary to those that occurred in the preceding case, namely, before the magnet had been turned over.

We obtain a perfectly similar result by presenting a horizontal current to the different sections of a magnet, suspended vertically to a wire by one of its extremities (*Fig.* 94.), where we indicate, by small arrows fixed upon the different faces of the magnet, and at different heights, the direction that the currents ought to have which are supposed to circulate around its surface, in order to account for the attractive and repulsive effects that are observed.

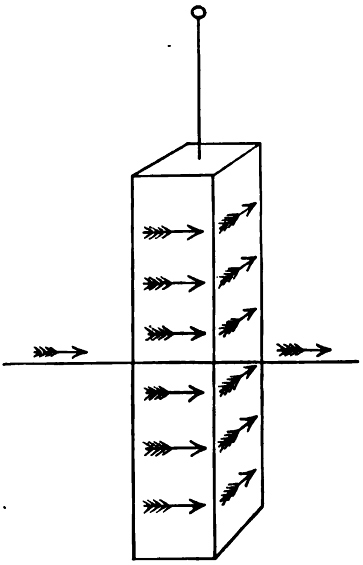
*Fig.* 94.

A magnet may therefore be considered as formed by an association of electric currents, all circulating in the same direction around its surface, and all situated in planes parallel to each other and perpendicular to the axis of the magnet. With regard to the direction of these currents, we have seen, by analysing the mutual action of a magnet and a current whose direction is known, that it is such that, if we hold the magnet horizontally before us, the north pole being to our left hand, the current goes from top to bottom in the exterior face most distant from the observer, and from bottom to top consequently in the face that is nearest or withinside. In order to fix this direction well in the memory, it is more convenient to suppose the magnet in its natural position, that is to say, in that position which is imparted to it, when it is movable, by the directive force of the earth, its north pole consequently turned towards the north; we then find that the direction of the arrows, which we will still leave in their place, is such as to indicate that the current is directed from the east to the west in the lower face of the magnet, and consequently from west to east in its upper face; that it is ascending in the face situated on the west, and descending in that which is on the east.

We may further add, that it is evident that the form of the circuit in which each of these parallel currents circulates, whose association forms the magnet, depends on the exterior form of the magnet itself: that it is circular when the magnet is cylindrical; rectangular when its figure is that of a parallelopipedon; and that it is a series of rectangles, diminishing in size from the middle towards each of the extremities, when the form of the magnet is a lozenge.

It is easy to see that Ampère's hypothesis of the constitution of magnets, as we have just expressed it, explains in the most satisfactory manner Oersted's fundamental experiment; as also all those that relate to the deviation of a magnet or a current, produced by the mutual action they exercise upon each other. All these effects may be traced to those that result from the mutual action of two currents upon each other — an action, by virtue of which they tend to place themselves parallel to each other, so as to be moving in the same direction. In order that this parallelism may occur with currents that circulate around the magnet, it is evidently necessary that the latter should find itself placed transversely to the current that acts upon it, or upon which it acts. Now, it is actually to this that the directive action tends, which is manifested in the experiments in which the movable current or magnet, instead of being able to obey attraction or repulsion, can only turn around a central point.

In order to confirm the hypothesis to which he had been led of the nature of magnetism, Ampère endeavoured to arrange electric currents in the same manner as he had conceived they were naturally arranged in a magnet; and he thus succeeded in obtaining assemblages of currents which possess all the properties of true magnets. With this view he took a copper wire, and twisting it into a helix, taking care that the successive spirals did not touch each other, he brought back the two ends interiorly along the axis of the helix to its middle, and then, making the two extremities come out, without being in contact either with each other or with any part of the helix, he bent them so as to be able to suspend the whole as a movable conductor to an apparatus similar to that of *Fig.* 82. Then, having made the current pass through the wire of the movable conductor, he found that he had a true magnet, the axis of which and the two poles were the axis and the extremities of the helix (*Fig.* 95.). An ordinary magnetised bar exercised upon its extremities the same attractive and repulsive actions that it would have exercised upon those of a compass needle. In order to obtain more marked effects, it would be better to use, in the construction of the helix, a wire covered with silk; we may then bring the spirals of the helix close even to contact, without any fear of the current's passing directly from one to the other, instead of pursuing its course; for there is no metallic communication. In order to give greater firmness to the wire, the helix is wound around a

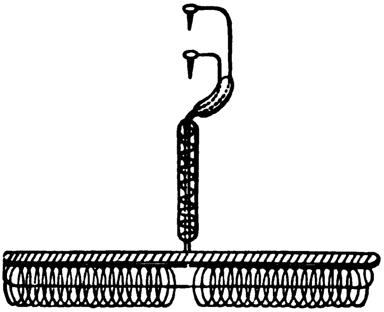

*Fig.* 95.

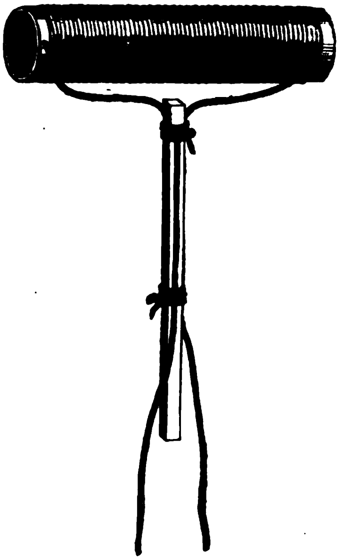

*Fig.* 95. *a.*

glass tube or a simple cylinder of wood, which is left a little longer than the helix itself, when we wish to hold it in the hand and present it, as was done with the magnet, either to a compass needle or to another movable helix (*Fig.* 95. *a.*). In the latter case we obtain with the two helices, each traversed by currents, all the same effects as are produced by the mutual action of two magnets. We may easily procure a current movable in a helix for imitating a magnetised needle, either by adjusting the conductor of the little floating pile into the form of a helix (*Fig.* 96.), or by terminating the two extremities of a helix formed of a silk-covered wire by a plate of zinc and one of copper, each thrust into a cork floating upon acidulated water.

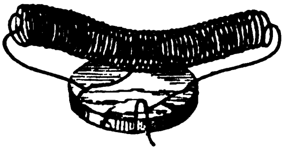

*Fig.* 96.

We are indebted to M. G. de la Rive for an experiment, which evidences in a remarkable manner Ampère's hypothesis of the constitution of magnets. It consists in presenting to the floating electrical ring that we have described (*Fig.* 84.), a magnetised bar held by one of its extremities, whilst the other is placed in the centre of the ring. When the hypothetical current of the magnet and the real currents of the ring are moving in the same direction, we perceive the ring advance parallel to itself, until it has arrived at the middle of the magnet, and when once there it remains there. But if we withdraw the magnet and turn it round, that is to say, if we replace it exactly in the same position, but taking the precaution of merely changing the position of the poles, we immediately perceive the ring recede parallel to itself,—an effect that is due to its currents and those of the magnet being directed in a contrary way. What is curious in this is, that, when once arrived beyond the extremity of the bar, the ring, instead of continuing to be repelled, turns upon itself, describing an angle of 180°, presents itself to the magnet with its currents then moving in the same direction with its own, and returns by a rapid movement to the middle of the bar, where it again remains in equilibrio. We also obtain all these same effects by substituting an electrical helix for the magnetised bar. They may easily be explained by the attraction and repulsion that are exercised, according as they are in a direction which is relatively similar or different, by the currents of the magnet or the helix upon the currents of the movable ring. With regard to the turning round that is executed by the ring when it goes off from the magnet after having been repelled, it is due to its plane never being perfectly perpendicular to the axis of the bar: the repulsive actions upon the different sides are not equal, and are transformed into a change of direction, which is necessarily followed by an attraction, as soon as the currents of the magnet and those of the ring are moving in the same direction. It is also easy to understand why the ring stops at the middle of the magnet; it is that evidently, in Ampère's theory, the middle of the magnet is, like the middle of the helix, the point of application of the resultant of all the parallel currents perpendicular to the axis, and moving in the same direction from one extremity to the other; it is therefore the point where the action exercised upon an exterior current must be at its maximum.

We may here inquire, why it is not the same when a magnet, instead of acting upon one or several currents forming a ring, acts upon iron or upon another magnet: we know, in fact, that in that case the action, on the contrary, is at its minimum at the middle of the magnet, and at its maximum at the poles, namely, at the points situated quite near to its extremities. Further: if we move a vertical electric current along and very near to one of the small vertical faces of a compass needle, we find that when this current is exactly opposite to one or other pole, it exercises no action; and that, if its action is of a certain nature, repulsive for example, upon all the points of the face of the magnet comprised between the two poles, it is of a contrary nature (attractive in this case) upon all the points of this *same face* that are situated beyond the poles, which, as we know, are never at the extremities themselves. The same effect is presented in a contrary direction upon the opposite face.

Thus, if the vertical current is directed upwards from below, it attracts all those points of the west face of the needle that are situated between the two poles, and repels those that are situated beyond; on the contrary, it repels all the points of the east face situated between the poles, and attracts all those that are situated beyond. A convenient and elegant manner of making this kind of action manifest consists in presenting to M. G. de la Rive's floating ring, and parallel to its plane, one of the lateral faces of a magnetised bar, taking the precaution that the centre of the ring be nearer to one of the extremities than to the middle of the bar. We then see the ring slide along the face of the magnet, resting against it on its two vertical sides; and as soon as one of them has passed the end of the bar the ring itself turns, describing an angle of 90°, and returns as before to the middle of the magnet. Thus, although in one of the vertical sides of the ring the currents are moving in a direction contrary to that which they have in the other, yet they are both attracted by points of the same face of the magnet, situated, it is true, on different sides of the pole.

The effects that we have just been describing, which were discovered and described by Faraday and by G. de la Rive, at first appeared very contrary to Ampère's theory of the nature of magnets; in fact, according to this theory, the electrical currents, the association of which forms a magnet, ought all to have had the same direction upon the same face of a magnetised bar, and, consequently, could not have exercised contrary actions, according as they were situated between the two poles, or beyond them. Finally, how are we to explain the nullity of action at the two poles themselves?

The objections that we have been pointing out did not arrest Ampère; he succeeded in overcoming them all, and established his theory upon such a solid basis that it is at the present time generally admitted. He set out from the principle that the electric currents to which, according to his view, magnets owe their properties, are molecular, that is, that they circulate around each particle. These electric currents pre-exist in all magnetic bodies, even although they have not been magnetised, only they are arranged in an irregular manner so that they neutralise each other. Magnetisation is the operation by which a common direction is impressed upon them; whence it follows that the series of the exterior portions of the molecular currents which are all moving in the same direction, constitutes a finished current around the magnet, whilst the interior portions are neutralised by the exterior ones, moving in the contrary direction, of the following molecular stratum. In order to follow out these effects well, we must decompose the magnet into concentric and similar strata: *Fig.* 97. represents the section of a cylindrical magnet, and the magnet itself. The direction impressed upon the currents by magnetisation is maintained in bodies that are endowed with coercitive force, and ceases in others, such as soft iron, as soon as the force that determined it ceases; because then all the molecular currents, being free to obey their mutual action, take the relative position that produces equilibrium, or the neutralisation of every exterior effect.

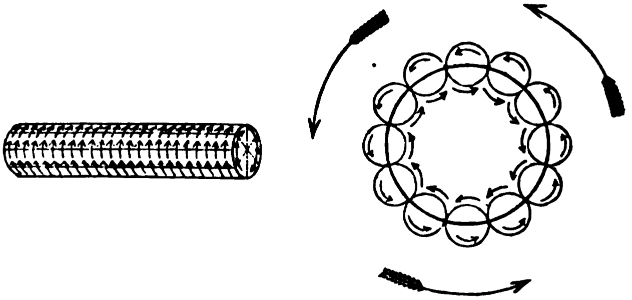

*Fig.* 97.

In order to submit this hypothesis to calculation, and thus to deduce from it all the effects of the mutual action of magnets upon currents, and currents upon each other, it would be necessary to commence by calculating the mutual action of two molecular currents alone, or, which amounts to the same thing, of two infinitely small portions of current. Now, this calculation required for starting points, besides the general law of attraction and repulsion according to the direction of the currents, and which we have already established, certain principles furnished by experiment; and experiment cannot be made upon infinitely small portions of currents. But, by means of a calculation which is as rigorous as it is ingenious, M. Ampère has been able to deduce the principles that are necessary to be established in respect to infinitely small currents, from the cases of equilibrium that are furnished by the mutual action of finite currents. These cases of equilibrium, to the number of four, enable us to determine the laws which the mutual action of infinitely small electric currents must necessarily obey, in order that they may be realised. And when these laws are once obtained, the calculation, on being applied to the consideration of infinitely small currents, leads to consequences perfectly conformable with experiment, in regard to the effects that must be produced by the assemblage of these currents, such as occurs in magnets and electric helices.

Let us now look into the four cases of equilibrium, furnished by experiment, which have served as the basis to the calculations upon infinitely small currents.

### *First Case of Equilibrium.*

Two equal and contrary finite currents exercise upon a third, situated at the same distance from the two former, no action, the attractive action of the one being equal to the repulsive action of the other. In order to demonstrate this principle, we must employ a wire covered with silk, which is bent in the middle upon itself, so that its two halves, which are parallel to each other, may be in contact throughout their whole extent: the two extremities, which are situated one beside the other, are placed in communication one with the positive, the other with the negative pole of the pile, so that the two halves are traversed by the same current in opposite directions. To the vertical or horizontal astatic current of the float we present this double current, composed of two equal and contrary currents situated at the same distance from the movable current, and the action is altogether null. We may also adjust this double current to the apparatus of *Fig.* 89., giving it the form of *Fig.* 98.

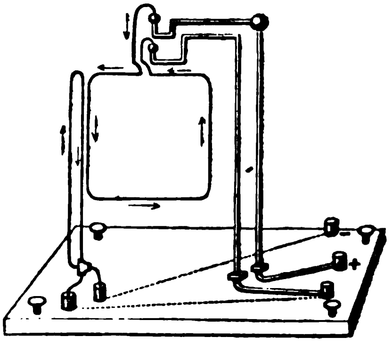

*Fig.* 98.

### *Second Case of Equilibrium.*

The action exercised by a rectilinear conductor upon a movable current is exactly equal to that which is exercised upon the same current by a conductor bent and turned in any manner, but comprised within the same limits, provided that the currents which traverse the two finite conductors are the same, or have the same intensity.

The accuracy of this principle is verified by means of the apparatus of *Fig.* 89., to which the astatic vertical conductor is suspended. For the fixed conductor we place a system of two wires, one of which is rectilinear and the other twisted into the form of a flame, a zigzag, or in any other manner (*Fig.* 99.). They are so arranged that the vertical branch of the movable astatic conductor is situated between them, and the current that traverses it successively has the same direction in each of them; but at the same time that this direction, which is common to them, is contrary to that of the current in the movable branch. We then see that the latter is equally repelled by the two fixed conductors, and is maintained between them exactly in the middle. It is important that the sinuosities of the twisted conductor, designated by Ampère under the name of sinuous, should not be too great comparatively to the distance of the conductors from the movable current. They may, however, providing that this distance be sufficiently great, be situated, one of them in a plane different from that of the other. This case of equilibrium served M. Ampère for showing that we may apply to currents the law of the decomposition and recomposition of ordinary forces, or the law of the parallelogram of forces; which could not be inferred à *priori*, in consequence of the very special nature of the forces which emanate from electric currents, and which are not similar to the ordinary forces of mechanics.

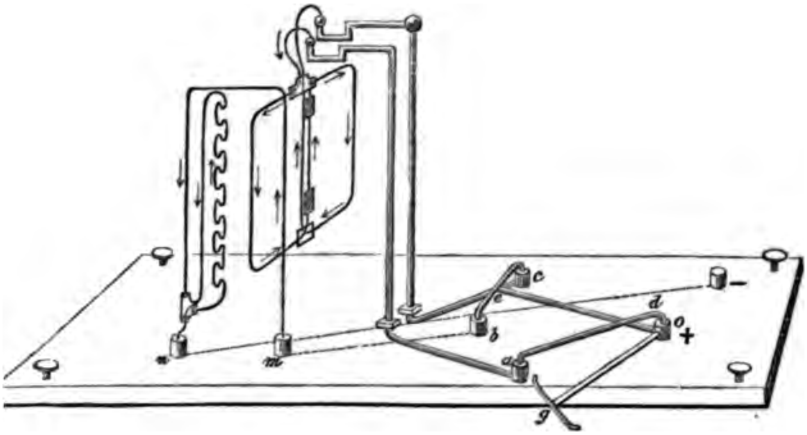

*Fig.* 99.

### *Third Case of Equilibrium.*

A closed circuit of any form whatever cannot set in motion any portion of a current forming an arc of a circle of which the centre is on a fixed axis, around which it may freely turn, — an axis that is perpendicular to the plane of the circle to which the axis belongs. In this delicate experiment, it is necessary that the arc of the circle may move alone, and without the conductors by which it is placed in the circuit. For this purpose we employ two canals filled with a quantity of mercury, so that the level of the liquid rises by capillarity above the sides of the canals. The conductor, in the form of an arc of a circle, fixed by its middle to the extremity of a horizontal stem coming as it were from the axis, situated at the centre of the circle of which the arc forms a part, rests delicately by two of its points upon the surface of the mercury of each canal, so as to be simply in contact with it (*Fig.* 100.).

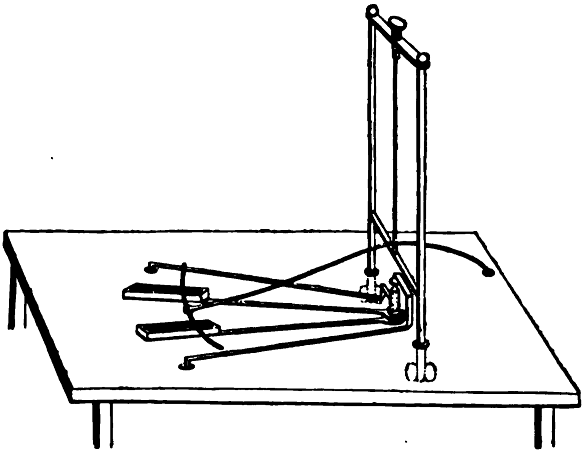

*Fig.* 100.

The positive pole of the pile communicates with the mercury of one of the canals, and the negative with the mercury of the other, so that this conductor of an arc of a circle serves to close the circuit, and is itself the only movable part. A wire is presented to it at a certain distance, which is bent into the form of a circle, an ellipsis, or a rectangle; in a word, forming a polygon or a closed curve, and moreover traversed by a current. In whatever manner this fixed conductor is placed in relation to the movable one, no action is manifested.

### *Fourth Case of Equilibrium.*

We take three circular conductors, situated in the same plane, an horizontal plane for example, each movable around an axis, situated beyond their circumference, and to which each of them is connected by a horizontal branch, soldered to one point of this circumference. If these three circular conductors are situated so that their centres are on the same right line; if, moreover, the distances of these centres are respectively proportional to the radii of the circles; that is to say, if the relation of the radius of the first circle to the radius of the second, and that of the radius of the second to the radius of the third, are to each other as the distance of the first centre from the second, and as the distance of the second centre from the third, the intermediate movable conductor will be in equilibrium between the two extreme fixed conductors, when they are all three traversed by an electric current, moving in the same direction in all, and having the same intensity in each. The mere inspection of the figure (*Fig.* 101.) is sufficient to explain the manner in which the three circular conductors are traversed successively by the same current, the middle conductor being movable between the two extreme ones, which are fixed.

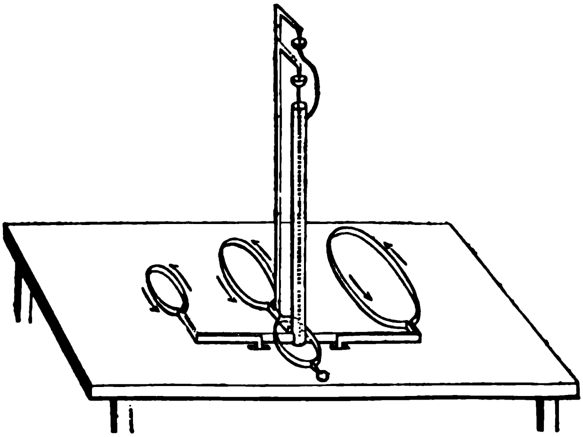

*Fig.* 101.

By means of these four cases of equilibrium, Ampère succeeded not only in determining the form of the mathematical expression of the force that two elements of voltaic currents exercise upon each other, but in finding the value of the constant quantities that enter into this expression, and particularly in deducing from it that the force itself is in inverse ratio to the square of the distance between the two elements. We may remember that the experiment of Biot and Savart had led to the same law for an element of a current upon an element of a magnet, and which establishes a further analogy between an element of a magnet and an element of an electric current.*

Once having arrived at the mathematical expression of the action of two elements of a current, Ampère deduced from it the action of the assemblage of several elementary currents, either upon a similar assemblage, or upon a finite or indefinite current. The results of the calculation were constantly found to agree with those that had been furnished by experiment. But the most important case is that which includes the mutual action of two *solenoïds.* Ampère designated by this name a system of very small closed currents, having their centres equally distributed on a right line or a curve, which he named *direction* of the solenoïd. Magnetisation, by impressing fixed directions upon the electric currents by which the molecules of bodies are enveloped, produces solenoïds; in such sort that a solenoïd is the magnetic skeleton of magnetised substances, the magnets being an assemblage of closed currents.

Ampère had demonstrated that the action of a solenoïd depends only on the position of its extremities, and in no degree upon the form of its axis; but he did not succeed in deducing from the calculation applied to the currents of solenoïds all the same consequences as he had deduced from this same application made to the molecular currents, which, according to him, constitute magnets,—results that are perfectly in accordance with the properties of magnets. M. Savary has filled up this blank: he set out from the principle that, if Ampère's formula is true when it is applied to molecular currents, it ought to be equally so when it is applied to the circular currents of solenoïds, and that calculation ought also to give results identical with those of experiment. This experienced philosopher discovered that this, in fact, was the case; and he further showed that solenoïds, or electro-dynamic cylinders of a very small diameter, act, at distances

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* See the final note F, for the calculation relating to the mutual action of electric currents.

very great in respect to this diameter, like magnets, whose poles would be situated at the very extremities of these cylinders. This result therefore established a complete identity between a solenoïd and a magnetic filament; for the latter being composed of molecular currents, it is clear that, whatever be the distance at which it acts, the diameter of these currents is always infinitely small in relation to this distance. We will not follow M. Savary into the other consequences which he has deduced from his calculations; we shall confine ourselves to saying that they all agree with the results that had been already furnished by the experimental study of magnetism in the hands of Coulomb and other philosophers who have been engaged on this subject; so that, under the conditions laid down, a solenoïd represents a true magnet. Thus, in particular, they established by calculation, founded upon the laws of electro-dynamics alone, that the poles of two solenoïds repel each other if they are of the same name, namely, if the currents move in them in the same direction, and attract each other, if they are of contrary names. They also succeeded in establishing, that a solenoïd has no action when its direction is a closed curve; a result that agrees with what is furnished by a magnetised steel plate, which, when it is rolled into the form of a closed ring, ceases to present any traces of magnetism.

Ampère's theory, therefore, when regarded simply under the relation of the properties of magnets and of their mutual action, is found as satisfactory as that of Coulomb; but it has further this great superiority over the latter, that it accounts, upon the same principle, for all the phenomena of electro-dynamics, that is to say, the mutual action of magnets and currents, and the mutual action of magnets upon each other. It is true it also rests upon an hypothesis, that of the existence of electric currents around the particles of magnetic bodies: but this hypothesis is quite as admissible as that of the existence of two magnetisms in each particle; we shall even see further on that recent facts seem to give it a further degree of probability, although there are others which we shall also point out, that are less easily reconciled with it. It accords perfectly well with all the theoretical mathematical labours that have been gone through by M. Poisson, and by other philosophers, resting upon that of Coulomb; and cannot, therefore, but be advantageously substituted for it. With regard to the anomalies that we have pointed out, and which consist in the opposite actions that are exercised upon a current by the parts of a magnet situated on the different sides of the poles, and the nullity of action observed at the poles themselves, Ampère has shown that they are merely due to a magnet's not being able to be completely assimilated to a solenoïd, which represents only a simple magnetic filament; and that in a magnet, properly so called, the molecular currents exercise upon each other a reaction that modifies their relative arrangement, and takes from the extremities the regularity that exists in the central part. He showed, in particular, that the nullity of action at the poles proceeds from the poles being the points where the actions of the contrary currents are equal; and he has thus connected their position with the arrangement of currents, that depends itself on the general form of the magnet.

It would be easy for us, by returning to the study of the magnetic phenomena which are contained in our First Chapter, to show directly that Ampère's theory satisfies all cases. We will quote only one example. It is borrowed from the experiment in which, by breaking a magnetised needle through the middle, we thus create two new and contrary poles at the extremities that have just been disjoined. If we separate a solenoïd into two fragments by cutting it perpendicularly to its axis, we evidently obtain upon the two separated faces two currents, which, although moving in the same direction when they are one after the other, are moving in a contrary direction in regard to each other for the observer who looks at them both in front (*Fig.* 102.), or are in respect to him the two currents by which a solenoïd is terminated at each of its extremities. These currents, therefore, will determine upon the two new faces of the solenoïd opposite and contrary poles to those which are already found at the opposite extremity of the same fragment. Thus we see that this experiment, when made upon a solenoïd, by giving the same result as when made upon a magnet, is explained perfectly well in the theory which admits that magnets are an assemblage of electric currents, distributed as we have pointed out.

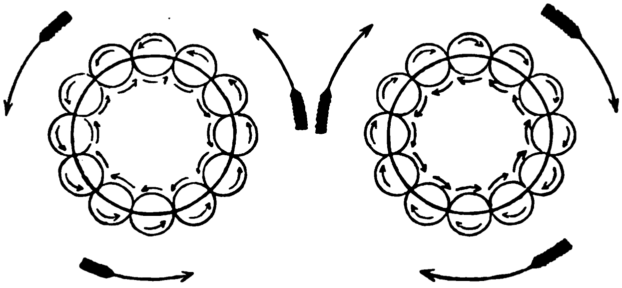

*Fig.* 102.

*Phænomena of continuous Rotation, arising from the mutual Action of Magnets and Currents, and of Currents upon each other.*

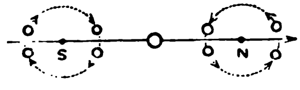

*Fig.* 103

By attentively observing the contrary action that is exercised upon a movable vertical current, either by the corresponding parts of a magnet taken on its two opposite faces, or by the points which, though situated on the same face, are on the different side of either pole, Mr. Faraday concluded that, if the current could turn freely around the pole, it would execute a continuous rotatory movement (*Fig.* 103.); and this he succeeded in realising. In order to obtain this in a decided manner, a cylindrical magnet must be placed in the centre of a capsule filled with mercury, taking care that the surface of this liquid is a little below the pole of the magnet; we then lead from a movable axis fixed vertically by means of two points between the summit of the magnet, and a piece of steel fixed to a metal support, a thin brass wire bent square, and the vertical position of which is terminated by a fine point, plunging slightly into the mercury, so as scarcely to graze its surface (*Fig.* 104.). A voltaic current is transmitted through this movable conductor by means of the mercury on the one hand and the metal support on the other. The wire is immediately seen to be set in motion, and it turns rapidly around the magnet. The direction of the rotation depends at once on the direction of the current, and the nature of the pole of the magnet around which this rotation occurs. If the pole and the direction of the current are both changed at the same time, the direction of the rotation remains the same: in order that it may vary, we must change only one or the other of these circumstances at the same time.

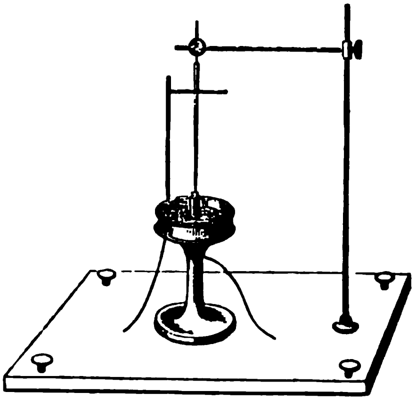
*Fig* 104.

Mr. Faraday also succeeded in determining a continuous rotatory movement in a magnet under the influence of a current, by plunging vertically into a vessel filled with mercury, by means of a ballast weight of platinum, a small magnetised bar, the summit alone of which appears above the liquid (*Fig.* 105.). A metal rod, communicating with one of the poles of the pile, descends vertically to the centre of the surface of the mercury, which is itself placed in communication with the other pole by means of a point of its circumference. Im-

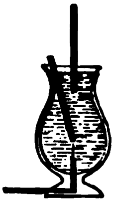
*Fig.* 105.

mediately the current was established, the magnet commenced turning around a right line formed by the prolongation of the vertical rod beneath the surface of the mercury. We must here observe that the magnet describes not a cylinder but a cone, provided its lower extremity is placed upon the axis of rotation, and remains there while its upper extremity describes a circle around the point where the vertical conductor touches the surface of the mercury. The direction of the motion in this case, as in the preceding, depends upon the direction of the current, and upon which of the two magnetic poles is on the top of the magnet.

In this experiment, as in the preceding one, the rotation goes on accelerating up to a certain point, at which its velocity becomes uniform, which is due to the resistance opposed by the mercury to the effect of the evidently accelerating force that produces the motion.

Faraday's experiments, at the time they were made, appeared irreconcileable with Ampère's ideas; but this philosopher had not at that period made known his law of angular currents, by means of which he soon succeeded in easily explaining the phenomena observed by Faraday, and adding to them certain others that are no less curious. Then, in order to add an experimental proof to the theoretic demonstration that he had given, that all these facts were not contrary to his hypothesis of the nature of magnets, he repeated them all, by supplying the place of the magnets by electro-dynamic helices or cylinders, or assemblages of parallel circular electric currents.

In order thoroughly to comprehend how an attraction or repulsion between currents can give rise to a rotatory action, we must set out from the distinction that Ampère established between *closed* and *open* currents. A *closed* current is that which, setting out from a point, returns to the same point, after having described a figure of any form (no matter what the form may be). It is not necessary, in order that the current be closed, that the whole circuit, including that of the pile, should form part of it, as occurs in floats. It is equally closed in movable conductors, one of the extremities of which sets out from a point, whilst the other returns to a very neighbouring point, situated in respect to the former in such a manner that motion can occur around a line passing through these two points, and which serves as the axis of rotation (*Fig.* 106.). It is also closed in a helix, one of the ends of which communicates with one of the poles of the pile, and the other end with the other pole. Finally, the currents, which in Ampère's theory compose a magnet, are all necessarily closed currents.

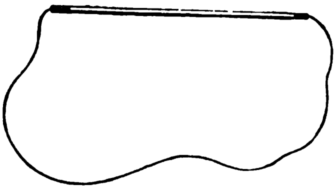
*Fig.* 106.

An *open* current is a current that traverses a movable conductor, one of the extremities of which does not return either to the point where the other is situated, or to a point situated on the same axis. Thus, in Faraday's experiments that we have described, the movable current which, setting out from the axis of rotation, terminates at a point of the surface of the mercury at a greater or less distance from this axis, is an open current; whilst it would be closed if the movable conductor setting out from this axis should return to it, whatever in other respects might be the form and length of its contour. The circuit of an open current must necessarily include a liquid: this liquid conductor is generally mercury, sometimes acidulated water. It is true that we may suppose that the movable conductor may simply glide by its point over the surface of a metal plate, whence would result a sufficient communication for the current to be transmitted: but in practice the friction would be much too considerable for the movement to occur freely; and if we employed currents sufficiently powerful to surmount this resistance, the metal point, in its point of contact with the plate, would risk being greatly altered, by the combined effect of friction and of the high temperature that is determined by the passage of the electricity.

In order that the action of a magnet or of a closed current may determine a continuous rotatory movement upon a movable current, it is necessary that the latter be open; if it is closed, it can only experience an attraction or a repulsion, and consequently a change of direction. The result to which Ampère was led by calculation was completely confirmed by experiment; and it was easy to demonstrate that all the facts, which seemed to him contrary, arose from there being open currents in the experiments by which these facts were established. If there are none, there is no continuous rotation. Thus two magnets, which are each an assembage of closed currents, cannot produce by their mutual action any continuous rotatory movement; and if, in Faraday's second experiment, we see a magnet rotate under the action of a current that seems closed, we must not forget that there is mercury in the circuit, and that there hence results an open current.

Let us therefore now see how Ampère's theory, or rather the laws that he has established, perfectly account for the production of a continuous rotatory movement by the mutual action of a closed and an open current.

Let us first examine the action of an indefinite rectilinear current upon a current also rectilinear, but being able to travel only parallel to itself. It is evident, from the law of angular currents, that whatever be the angle made by the movable current with the fixed one, as well when it is in the same plane as when it is in a different plane, the combined action of the two portions of the fixed current, situated on the two opposite sides of the summit of the angle, the one attractive and the other repulsive, causes it constantly to move parallel to itself. The direction in which it moves depends upon its direction relatively to that of the fixed current; it always advances in the angle, the sides of which are formed by the currents that are both directed towards the summit of the angle, or that both diverge from it; whilst it recedes from the angle, one of the sides of which is formed by the current that converges toward the summit, and the others by that which diverges from it. This is a consequence of the attraction that occurs in the former case, and of the repulsion that occurs in the latter. This result may be verified by direct experiment, by suspending, as represented in the figure

(*Fig.* 107.), a horizontal wire, supported by two glass rods, placed vertical to its two extremities, so that it can only move parallel to itself, either backward or forward. It is put in the voltaic circuit by means of two longitudinal glass cells filled with mercury, in which its extremities, which are slightly bent, are plunged. The vertical rods of glass must be very long, in order that the backward and forward movement may have a sufficiently large amplitude, without the points coming out of the mercury. We bring near to one of the extremities of this wire, so that it makes any angle with it, a rectilinear conductor traversed by a powerful current, and we see the motion of the movable current brought about as we have pointed out; only it is very limited, the arrangement of the apparatus preventing the wire advancing or receding indefinitely. We employ with advantage for a fixed conductor one of the sides of the rectangle formed of wire covered with silk, bent several times round a frame: by the effect of this multiplication the current is found to have a much greater degree of energy. The experiment we have just described is the most direct confirmation of the law of angular currents.

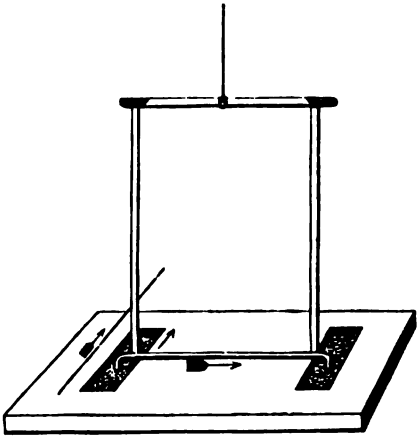

*Fig.* 107.

From the movement that we have now been producing to the continuous rotatory movement, there is but one step. In fact, let us fix the movable conductor by that extremity which is most distant from the fixed conductor, so that it may describe a circle around this extremity; at the same time, let us plunge its movable extremity into a circular canal filled with mercury, and of a radius consequently equal to the length of the wire; let us bend the fixed conductor so as to form of it a circle around and very near to this canal; finally, let us make a current pass through all these conductors, which is easy, as the figure shows (*Fig.* 108.): we then perceive the movable current describe a circle around its point of attachment, with a continuous rotatory motion. In fact, in whatever position the movable current is taken, if we examine the action that is exercised upon it by the nearest part of the fixed current, which, although it is the arc of a circle, may without sensible error be considered a right line, a tangent to the arc, we find that it is constantly driven in the same direction by the combined attractive and repulsive actions of the two parts of this arc that are situated upon the two sides of the summit of the angle that is formed with it. *Fig.* 109., in which the finite current is polygonal instead of being circular, and in which the

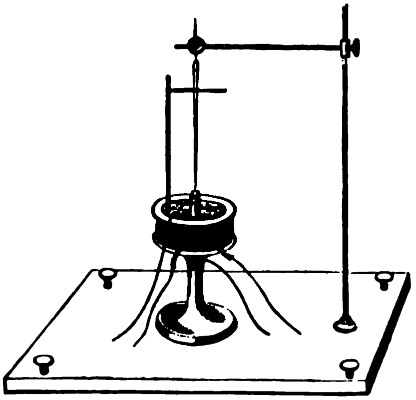

*Fig.* 108.

*Fig.* 108.*a.*

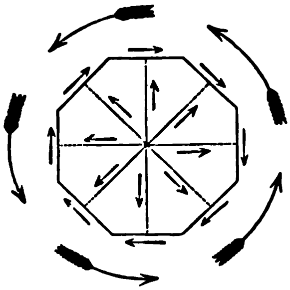

*Fig.* 109.

movable current successively occupies different positions, demonstrates in an evident manner how the action of angular currents gives rise to a continuous rotatory movement. The small arrows without feathers indicate the direction of the currents, and those with feathers the direction of the movement.

In order to render the movement more decided, we lead from the centre of rotation, which is a vertical point resting upon the bottom of a metal capsule filled with mercury, so as to be able to establish communication with the pile, two or more wires similar to that whose movement we have just analysed, and the free extremities of which are in like manner bent vertically, so as to plunge slightly into the mercury of the circular canal employed for permitting the transmission of the current. We also use the precaution of taking for the fixed conductor a wire covered with silk, and of making it have several revolutions around the circular canal, so as thus to act, by the multiplication of the fixed current, with more energy upon the movable currents, all having the same direction, that is, from the centre to the circumference, or from the circumference to the centre; and whose movement consequently operates in all in the same direction. In the figure (*Fig.* 108. *a.*), in place of mercury, there is acidulated water in a circular canal of copper; and the vertical branches of the movable conductor are all attached to a circular plate of very thin copper, which is plunged into the liquid: a copper ribbon covered with silk, and making several convolutions, conveys the fixed current.

We may substitute for the movable horizontal current a vertical current, arranged as in Faraday's former experiment (*Fig.* 104.). This current, it is true, is not in the same plane as the circular fixed current, which is in the horizontal plane; but the law of angular currents does not the less exist between them; and the vertical current experiences, by the action of this exterior current, a continuous rotatory movement. Instead of a circle or a cylinder, the movable current may equally describe a cone of any angle around the axis of rotation; for the action of the currents, the one upon the other, remains the same, whatever be the plane in which they are situated. With regard to the direction of the rotation, it depends on the relative direction of the currents in the two conductors; in order to change it we must change this direction in one and not in the other, which may be easily understood by not losing sight of the law; and which is easily brought about by a suitable arrangement of conductors.

We may, in like manner, act upon the vertical movable current by fixed circular currents placed interiorly, instead of exteriorly, to the cylinder which it describes: for this purpose we have merely to substitute for the magnet in Faraday's first experiment (*Fig.* 104.), a wire twisted into a helix around a cylinder of wood or wax, taking care to employ a wire covered with silk, so that the spirals of the helix may be well insulated from each other. Immediately a current is transmitted through this wire, the movable current executes a rotatory movement, perfectly similar to that which it executed around the magnet. In order to change its direction, we must change the direction of the current in one of the conductors alone. This last experiment, by proving that an electro-dynamic cylinder produces precisely the same effect as a magnet, is a further confirmation of Ampère's theory of the constitution of magnets.

Faraday's second experiment — that in which a magnet, plunged vertically into mercury, experiences a rotation around a vertical current — at first seems contrary to Ampère's principle that the mutual action of two closed currents cannot give rise to a continuous rotatory movement. But Ampère showed that the phenomenon was not due to the action of the vertical current upon the movable magnet, but in truth to that of the horizontal currents that are propagated over the surface of the mercury from the centre, on which the lower extremity of the vertical conductor abuts, to the circumference where there is a metal ring, by means of which the voltaic circuit is completed. These currents, which all move in the same direction in regard to each other, are consequently found to have the same direction as those which are situated on the same face of the magnet, and a contrary direction to those which are on the opposite face (*Fig.* 105.). It follows that their double effect, attractive on the one face and re-

pulsive on the other, concurs in constantly impressing upon the magnet a movement in the direction of the attracted face. The liquid constitution of the conductor by which the currents are transmitted, enables the magnet to intercept them at the very place where it passes in; whence it follows that the circuit is in fact an open circuit, and not a closed one; and that this case is properly included in the general law laid down by Ampère. It is well to cover the magnet with a thin coating of wax or gum-lac, in order that the currents shall not traverse it.

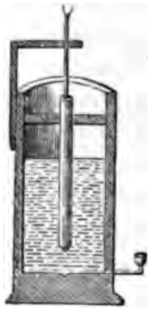

*Fig.* 110.

However, it is possible to obtain a rotatory movement by obliging a current to traverse a magnet. For this purpose it is necessary that the current that has penetrated into the magnet, shall come out of it in a direction perpendicular to its surface. Then the action of this current upon the two portions of the current of the magnet, separated by the point at which it comes out, determines a rapid rotatory movement of the magnetised bar upon its axis, as indeed ought to follow from the law of angular currents. In order to make this experiment (*Fig.* 110.), the extremity of the fixed vertical conductor must abut upon the summit of the magnet, which, by means of its platinum weight, is held vertically in the mercury: a small steel cup, screwed upon the top and filled with mercury, serves to facilitate the transmission of the current, which, after having penetrated from the conductor into the magnet, comes out of it to enter into the mercury, and radiate toward the circumference of the vessel. The direction of the rotatory movement depends upon that of the current alone, since the currents of the magnet do not change in direction.

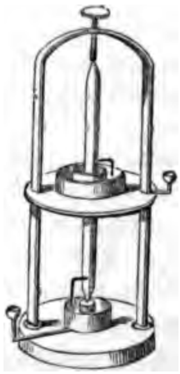

*Fig.* 111.

In order to obtain the rotation of a magnet upon its axis, may also solder to the middle of a magnetised bar, and

perpendicular to one of its faces, a wire, which, by being bent vertically at its extremity, plunges by the point in which it terminates into an annular canal filled with mercury. The magnetised bar is pointed at its two extremities, and is fixed vertically between its two points, so as to be able to turn freely. From its lower extremity proceeds a second conducting wire similar to the former, and like it plunging by its bent extremity into the mercury of an annular canal; and the current is transmitted through the magnet by means of these two canals, and the two wires that enter into them. Sometimes the bar is curved in the middle of its length, so that it presents two vertical parts of equal size, united by a small horizontal portion, upon which is screwed a cup full of mercury, from which proceeds the vertical conductor intended for transmitting the current, the circuit of which is completed, as in the preceding case, by means of a wire fixed perpendicularly into the middle of the magnet, and plunging by its curved extremity into the circular canal filled with mercury (*Fig.* 112.). It is not in this case necessary to have a second wire in the lower part. The rotation of the magnet occurs in the same manner around an axis that passes through the point upon which the lower face of the horizontal part of the magnet rests, so that the latter is in equilibrium.

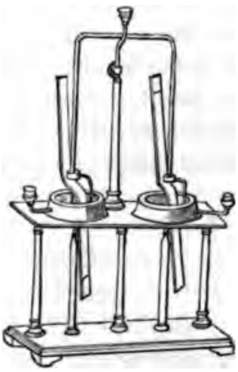

*Fig.* 112.

It must not be supposed that in these different experiments the phenomenon of rotation is due, as has been erroneously stated, to the action upon the magnet of the portions of the current that traverse it, or that traverse the conducting wires attached to the magnet, and moving with it. In fact, how could a solid system be set in motion by a force emanating from a portion of the very system itself, and connected with it in an indissoluble manner? The action can only arise from a part of the current which is independent of the system that moves: this part is the portion of the circuit

pulsive on the other, concurs in constantly impressing upon the magnet a movement in the direction of the attracted face. The liquid constitution of the conductor by which the currents are transmitted, enables the magnet to intercept them at the very place where it passes in; whence it follows that the circuit is in fact an open circuit, and not a closed one; and that this case is properly included in the general law laid down by Ampère. It is well to cover the magnet with a thin coating of wax or gum-lac, in order that the currents shall not traverse it.

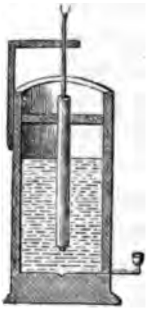
*Fig.* 110.

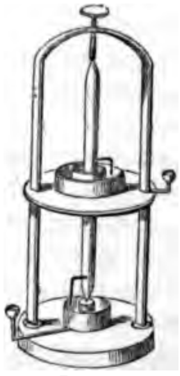
*Fig.* 111.

However, it is possible to obtain a rotatory movement by obliging a current to traverse a magnet. For this purpose it is necessary that the current that has penetrated into the magnet, shall come out of it in a direction perpendicular to its surface. Then the action of this current upon the two portions of the current of the magnet, separated by the point at which it comes out, determines a rapid rotatory movement of the magnetised bar upon its axis, as indeed ought to follow from the law of angular currents. In order to make this experiment (*Fig.* 110.), the extremity of the fixed vertical conductor must abut upon the summit of the magnet, which, by means of its platinum weight, is held vertically in the mercury: a small steel cup, screwed upon the top and filled with mercury, serves to facilitate the transmission of the current, which, after having penetrated from the conductor into the magnet, comes out of it to enter into the mercury, and radiate toward the circumference of the vessel. The direction of the rotatory movement depends upon that of the current alone, since the currents of the magnet do not change in direction.

In order to obtain the rotation of a magnet upon its axis, we may also solder to the middle of a magnetised bar, and

perpendicular to one of its faces, a wire, which, by being bent vertically at its extremity, plunges by the point in which it terminates into an annular canal filled with mercury. The magnetised bar is pointed at its two extremities, and is fixed vertically between its two points, so as to be able to turn freely. From its lower extremity proceeds a second conducting wire similar to the former, and like it plunging by its bent extremity into the mercury of an annular canal; and the current is transmitted through the magnet by means of these two canals, and the two wires that enter into them. Sometimes the bar is curved in the middle of its length, so that it presents two vertical parts of equal size, united by a small horizontal portion, upon which is screwed a cup full of mercury, from which proceeds the vertical conductor intended for transmitting the current, the circuit of which is completed, as in the preceding case, by means of a wire fixed perpendicularly into the middle of the magnet, and plunging by its curved extremity into the circular canal filled with mercury (*Fig.* 112.). It is not in this case necessary to have a second wire in the lower part. The rotation of the magnet occurs in the same manner around an axis that passes through the point upon which the lower face of the horizontal part of the magnet rests, so that the latter is in equilibrium.

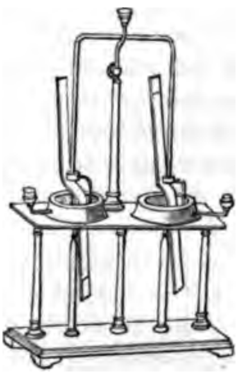
*Fig.* 112.

It must not be supposed that in these different experiments the phenomenon of rotation is due, as has been erroneously stated, to the action upon the magnet of the portions of the current that traverse it, or that traverse the conducting wires attached to the magnet, and moving with it. In fact, how could a solid system be set in motion by a force emanating from a portion of the very system itself, and connected with it in an indissoluble manner? The action can only arise from a part of the current which is independent of the system that moves: this part is the portion of the circuit

pulsive on the other, concurs in constantly impressing upon the magnet a movement in the direction of the attracted face. The liquid constitution of the conductor by which the currents are transmitted, enables the magnet to intercept them at the very place where it passes in; whence it follows that the circuit is in fact an open circuit, and not a closed one; and that this case is properly included in the general law laid down by Ampère. It is well to cover the magnet with a thin coating of wax or gum-lac, in order that the currents shall not traverse it.

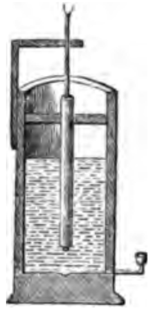

*Fig.* 110.

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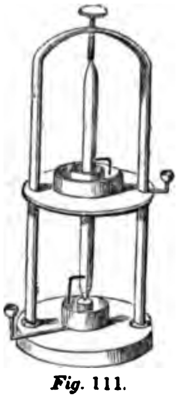

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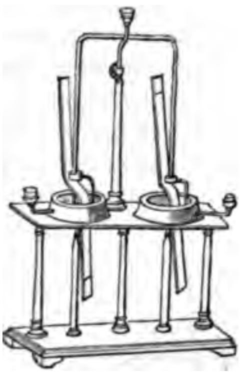

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It must not be supposed that in these different experiments the phenomenon of rotation is due, as has been erroneously stated, to the action upon the magnet of the portions of the current that traverse it, or that traverse the conducting wires attached to the magnet, and moving with it. In fact, how could a solid system be set in motion by a force emanating from a portion of the very system itself, and connected with it in an indissoluble manner? The action can only arise from a part of the current which is independent of the system that moves: this part is the portion of the circuit

which is not connected with the magnet that is set in rotation, and which, consequently, is situated independent of the system in motion. This kind of action, although tolerably complicated, has been calculated, like the others, by M. Ampère in a perfectly rigorous manner.

Ampère, who was the first to obtain the rotation of a magnet upon its axis, was led to it by a curious experiment of Savary's, intended to point out the action of angular currents, and which we will again describe. A wire rolled into a flat spiral is terminated within, perpendicularly to the plane of the spiral, and its curved extremity is plunged into a cup filled with mercury. The spiral itself is plunged into a circular vase filled with acidulated water, the side of which communicates with one of the poles of the pile, whilst the other is placed in communication with the cup of mercury. The apparatus is so arranged that the vertical stem that carries the cup traverses the centre of the copper vessel, the whole being insulated by a glass tube; it follows from this, that the stem by which the spiral is sustained, and consequently the spiral itself, may turn freely in all directions around the central axis (*Fig.* 113.).

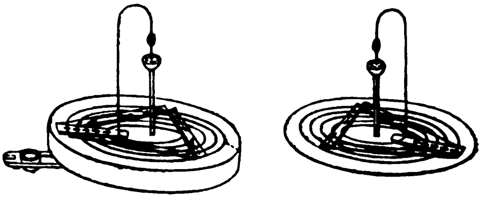

*Fig.* 113.

The currents that come out or that penetrate by the different points of the spiral wire and traverse the liquid by radiating, immediately exert an action upon the currents that circulate in the wire itself, and determine a rotatory movement of the spiral around the vertical stem, conformably to the law of angular currents. According as the spiral is wound *sinistro-girate* or *dextro-girate*, the motion occurs in one direction or the other; from this difference there results a change in the relative direction of the currents of the spiral, and of those of the liquid.

Many variations have been made in the apparatus contrived for producing the phenomena of electro-dynamic rotation. One of the most elegant is that which was devised by Mr. Marsh (*Fig.* 114.), and which consists of one element of a pile, composed of an annular copper vessel, formed of two concentric cylinders, in which is placed the conducting liquid, into which latter a zinc cylinder is immersed. A kind of support, made of two vertical metal rods connected by a horizontal one, furnished with a point in its middle, arises from the interior copper cylinder, and serves to suspend the entire vessel above a vertical magnet, placed in the axis of the apparatus: a similar support arises from the zinc cylinder, and also serves to suspend it; the point of its horizontal cross-piece rests upon the bottom of a small cup filled with mercury, which is upon the cross-piece of the support of the copper vessel, and over its point. It is by this means that the necessary metallic communication is made between the zinc and the copper of the pair. When the apparatus is thus arranged, the two supports, and consequently the cylinders to which they are attached, acquire a rotatory movement around the central magnet, but in contrary directions. It is easy, therefore, to see, that the current in fact travels in an opposite direction in each of them.

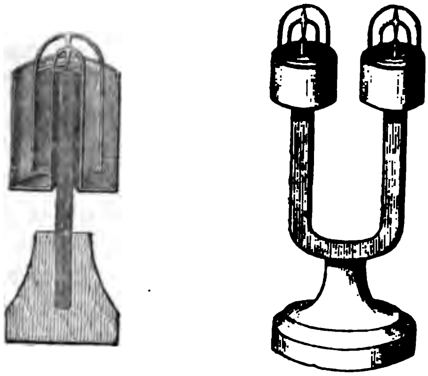

*Fig.* 114.

Davy observed that when the pole of a powerful magnet is brought towards a mass of mercury traversed by electric currents, a rapid rotation of this metal is determined around the solid conductor that is plunged in to transmit the current. The experiment succeeds well with the apparatus that is employed for demonstrating the raising of two small cones of mercury above metal points, communicating with the poles of a pile. The direction of the rotation depends upon that of the current, as well as of the pole of the magnet that is brought near to the mercury. The phenomenon is due to the action that is exercised by the magnet upon the currents which, setting out from the metal point that is plunged into the mercury, are disseminated over the surface of this eminently movable metal conductor. Mr. Poggendorff, who has made a special study of the rotation of mercury, has remarked that, when it has occurred for a certain time, it relaxes and altogether ceases. This effect appears to arise from the oxidation of the mercury, which is facilitated by its movement, and which, when it has once occurred, diminishes the liquidity of the metal by rendering it viscous. Priestley had already remarked that simple agitation in contact with air determines an oxidation of this metal, which is manifested by the blackish colour it acquires, and by a diminution of its liquidity. We may also obtain the rotation of mercury by surrounding a capsule filled with this metal with a fixed circular conductor, making several revolutions around the capsule, and traversed by a current. The same current is made to pass through the mercury, making it penetrate by the centre and come out by the borders of the movable disc, constituted of the liquid. This experiment is of the same nature as that of the movable rectilinear conductor (*Fig.* 108.) set in rotation by the action of the exterior current. Here each filament of mercury plays the part of the movable conductor. In order that the experiment may succeed well, we have merely to take care that the current be very powerful, provided it is to be distributed over the whole surface of the mercury.

An interesting observation is that of the rotatory movements assumed by mercury in the interior of a hollow magnet, and of their comparison with those of mercury placed outside this magnet. In the interior of a hollow vertical magnet, closed at its lower extremity, we place a certain quantity of mercury, greater or less as the case may be; the current arrives by a metal point plunged in the centre of the circular surface of the mercury, and radiates from the centre toward the inner surface of the hollow magnet. If the level of the surface of the mercury is lower than the plane in which the upper pole of the magnet is situated, the rotation occurs in the direction determined by the direction of the currents of the magnet; it attains its maximum of velocity when this level coincides with the middle of the magnet. If the level coincides exactly with the plane of the pole, the rotation is null; if it is above that plane, it occurs in an opposite direction. This result, which is analogous to what we have already mentioned of the opposed action of the two parts of the same face of a magnet, situated on a different side of the pole, is due, as we have already said, to the particular distribution assumed by the molecular currents at the extremities of magnets. When the hollow magnet is made to plunge into a vessel filled with mercury, taking care that the level of the exterior liquid coincides with that of the interior liquid, we see, conformably with what should follow from Ampère's theory, that the surface of the mercury assumes outside a rotatory movement, contrary, in regard to its direction, to that which occurs within.

Mr. Poggendorff, who has lately studied carefully the phenomena of the rotation of mercury under magnetic and electro-dynamic influence, has also observed, as I had previously done in 1824*, that the direction of the rotation is different according to the part of the magnet with which the surface of the mercury that transmits the current is in contact. He has remarked in particular that this direction changes, according as the section of the magnet plunged vertically into a vessel full of mercury is above or below the pole. If the currents, of which by the theory a magnet is

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* Memoirs of the Society of Physics and Natural History of Geneva, tom. iii. 2nd part, p. 127.

constituted, were all, from one extremity of the magnet to the other, quite parallel with each other, and all determined in the same direction, it ought not to be so. In fact, with an electro-dynamic helix or a solenoïd, the rotation occurs in the same direction from one end to the other; but the poles also in these electro-magnets are at the very extremity, whilst in true magnets the poles, as we have seen, are at a short distance from the extremities. It is this same circumstance which causes, as we have seen, the same current to exercise upon the same face of a magnet an attractive or repulsive action according as it acts upon the portion of the magnet situated between the two poles, or upon those which are beyond these poles, even upon the same side. This characteristic difference between a magnet and a solenoïd is very probably due, as we have already seen, to a particular arrangement of molecular currents at the extremities of magnets, itself arising from the rather complex mutual action which these currents exercise upon each other, and from the molecular constitution of the magnetic substance.

Another kind of rotation is that which is obtained by placing between the two approximate poles of a horse-shoe magnet, a metal wheel fixed vertically to a horizontal axis that passes through its centre, and around which it can turn (*Fig.* 115.). This wheel is tangent, in the lower point of its circumference, to a surface of mercury placed in communication with one of the poles of the pile, whilst the other communicates by means of the axis with the centre of the wheel. The vertical current is attracted by the combined action of the two branches of the magnet; the wheel, obeying this attraction, moves; as the part that was traversed by the current ceases to be so traversed, as soon as it ceases to be vertical, since it is no longer tangent to the mercury, the action of the magnet attracts the new part of the wheel which has replaced the former, and so on; whence results the continuous rotatory movement.

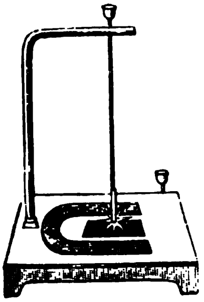

*Fig.* 115.

### *Action of the terrestrial Globe upon electric Currents.*

We have already seen, in the first paragraph of this Chapter, that a wire bent into a circle or a rectangle, in a word, forming a plane and closed curve, when traversed by a current, and movable around a vertical axis, places itself in a plane perpendicular to the magnetic meridian, and so that the current is directed from east to west in its lower part. Ampère discovered further that, if the rectangle is movable around a horizontal axis so as to be perfectly in equilibrium in all its positions around this axis, which we take care to arrange perpendicular to the magnetic meridian, it places itself in such a position, when traversed by a current, that its plane is perpendicular to the direction of the magnetised dipping needle; the current is always directed from east to west, in the lower side of the rectangle (*Fig.* 116.).

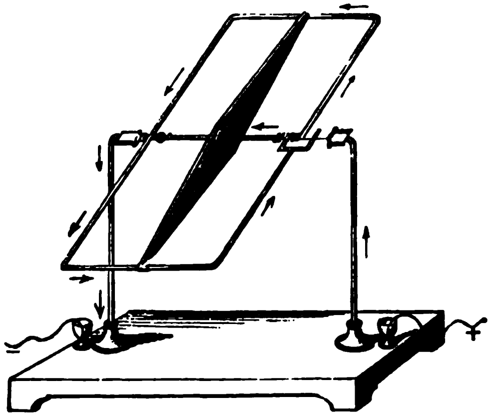

*Fig.* 116.

In all these experiments a circular current, a rectangular one, or one of any form, behaves like the section of the magnet, the form and size of which would be those of the figure formed by the wire. A ring, formed of several circular or rectangular turns of the same wire, covered with silk, as is done in M. G. de la Rive's floats, represents several continuous sections of a magnet, and is able more easily than other combinations of currents to obey the directive action of the earth, under the sway of a very small voltaic force, such as that resulting from a single pair. In these apparatus we have true compasses; they are also generally provided with small card arrows, which, by means of a piece of wood or whalebone rising vertically from the cork, are fixed by their centre perpendicularly to the plane of the current. These arrows, when the floats have acquired the position that is impressed upon them by the terrestrial globe, are found to have exactly the direction of the compass needle. Care is taken so to place the point of the arrow, that it is turned to the north side when the current goes from east to west in the lower part of the ring (*Fig.* 117.).

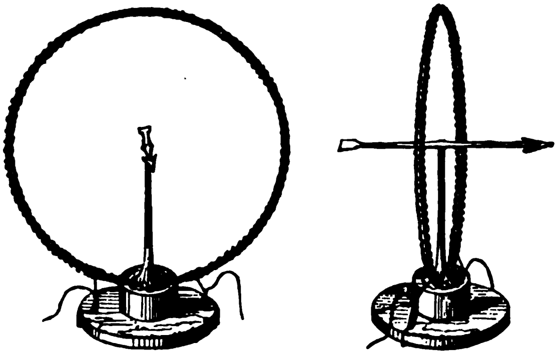

*Fig.* 117.

Finally, a helix of a not very large diameter, (from two to four inches), when its wire is traversed by a current, takes the same direction as a true magnet would take, whose axis should be the same as that of the helix. For this experiment we may employ the helices that we have already described, and of which, under the name of electro-dynamic cylinders or solenoïds, we have determined the properties as being altogether similar to those of magnets. The most convenient apparatus is a float, in which the ring is replaced by a closed helix, the two ends of which return interiorly to the middle, along the axis.

The employment of electric currents for studying the directive action of the earth, presents an incontestible advantage over the magnetised needle. With the magnet we have closed currents only; with dynamic electricity, we may have open as well as closed currents. Now, the action of the terrestrial globe upon a simple rectilinear unclosed current, may furnish interesting results, and throw new lights upon terrestrial magnetism. It was this study I made in 1822, by means of an apparatus of which I will give briefly the description.

It consists (*Fig.* 118.) of two circular canals of pipe-clay, each forming a ring, the one being of a little less diameter than the other; the larger, which is placed lowest, is from 12 to 15 inches in diameter; the other, at least $1\frac{1}{2}$ to 2 inches. The two canals are placed horizontally, one above the other, at a distance of from 15 to 20 inches, and sustained by supports so arranged that their centre is on the same vertical: each of the two circular canals is from 1 inch to $1\frac{1}{2}$ wide, and is divided into two perfectly equal parts by small transverse partitions placed upon the same diameter. These partitions, which are one half the height of the sides of the canal, may, when we wish it, be covered with the liquid that is placed in

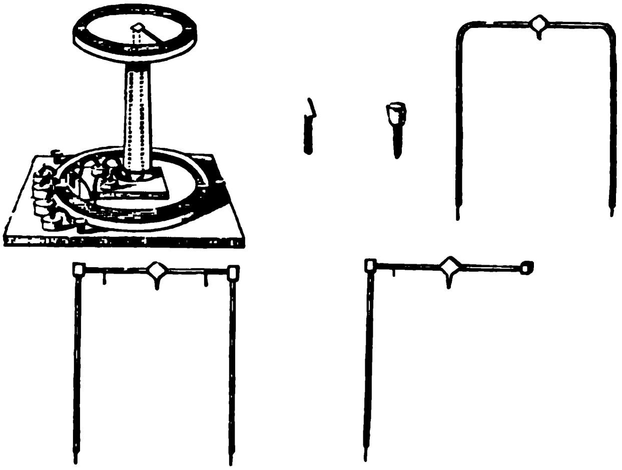

*Fig.* 118.

the canal, so that the two compartments into which it is divided form but one. In the centre of the ring formed by the upper canal is a steel cup, that may be raised or lowered at pleasure by means of a screw, and to which is attached from below a conductor that may be put into communication with one of the poles of the pile. The liquid contained in each of the four compartments may also, by means of a platinum plate, be placed in the voltaic circuit. This liquid is mercury, which is generally covered by a thin film of diluted nitric acid, so as to facilitate the motion of the points of the conductors that are plunged into it, by destroying the impurities with which the surface of the metal is always more or less covered.

I successively placed upon this apparatus a rectangle deprived of its lower side, of its upper side, and of both sides at the same time; and I found that when the remaining sides were traversed by the current, the rectangle was directed exactly as if it had its four sides. It always placed itself perpendicularly to the magnetic meridian, so that the current was ascending in the vertical branch situated on the west, and descending in that situated to the east. The inspection of the figure, both of the apparatus and of the conductor, readily explains how the current may be made to traverse the branches of the rectangle that remain. In those in which the upper branch is wanting, its place is supplied by a glass rod, furnished at the middle of its length with a point, which, resting upon the bottom of the cup that is fixed at the centre of the upper plate of the apparatus, carries the rectangle at the same time that it serves itself as a pivot around which it can turn. The parts of the conductors that are plunged into the mercury are platinum points; and care must be taken that they simply graze the surface of the liquid, so as to render the friction as trifling as possible. With regard to the communications to be established between the different parts of the movable conductors, in order to put them into the voltaic circuit, they are all affected by means of cups filled with mercury, in which the conductors are put that come from the circular canals, also filled with mercury. Finally, I reduced the rectangle to a single vertical branch fixed at the extremity of a horizontal glass stem, the other extremity of which is loaded with a counterpoise, to make equilibrium with the wire. The two circular canals were entirely filled with mercury, so that the two transverse partitions were covered with it, and the movable branch might freely pass around the apparatus without ceasing to be in the circuit. Immediately it is traversed by the current, *it places itself so that the plane that it forms with the axis around which it is situated, is perpendicular to the magnetic meridian, and is itself on the east, if the current that it transmits is descending, and to the west, if it is ascending.** This is the simple law of the directive action exercised by the earth upon a vertical rectilinear current, movable on an axis that is parallel to it.

But this is not all: it is important to know what is the action exercised by the earth upon a rectilinear horizontal current. Faraday had observed that such a current, when free to move parallel to itself, advances or recedes according as it is moving in one direction or the other, and this in whatever azimuth it is placed. This experiment may be made by suspending from its centre, by means of a long thread of waxed silk, and consequently without torsion, a wire, whose bent extremities are each plunged lightly into a glass trough filled with mercury, the two troughs are placed parallel to each other. Immediately that the wire is in the voltaic circuit, when placed perpendicularly to the magnetic meridian, it is seen to move parallel to itself towards the south, if the current is directed from east to west, and towards the north, if it is directed from west to east. It thus advances, from one side or from the other, according to its direction, and this in all azimuths. If, for example, it is situated in the direction of the magnetic meridian, it goes towards the east side if the current is directed from north to south, and towards the west if directed from south to north. In general terms, it goes towards the observer who looks at it, if it is directed from the right to the left of this observer, and moves from him, if directed from his left to his right. In order to demonstrate this law, we may employ a more convenient apparatus, which may be understood by the mere inspection of the figure (*Fig.* 119.).

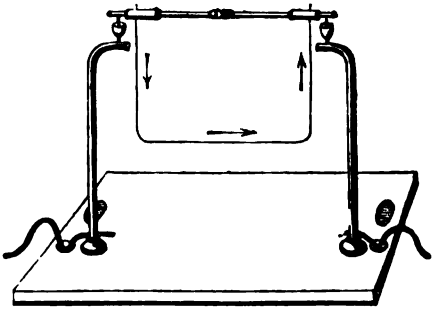

*Fig.* 119.

It follows from this law, that a horizontal current, fixed by its centre, and being able to execute no other movement than one of rotation around this centre, will remain in equilibrium under the action of the earth, since it cannot obey the effect of this action, which is to make it advance or recede parallel to itself. It is not the same if, instead of being fixed by its centre, the horizontal current is fixed by one of its extremities, the other being free; then, by tending to advance always parallel to itself, and this in whatever azimuth it is situated, we see it turn by a continuous rotatory movement around its fixed point. When the current is directed from the centre of rotation to the free extremity, the direction of the movement is such, that, by supposing the free extremity of the current to be at the west, it is first directed towards the south, continues its route towards the east, then towards the north, in order to return to the west, and begin again. The reverse occurs if the current is directed from the circumference to the centre.

This continuous rotatory movement, which is brought about by the action of the earth, may be easily obtained by means of the apparatus that we have just employed (*Fig.* 118.). A wire carries at one of its extremities a steel point, perpendicular to its length, and by means of which it is placed in the cup filled with mercury, that is at the centre of the upper part of the apparatus; the other extremity of the wire is terminated by a platinum point, that plunges slightly into the mercury with which the upper circular canal is entirely filled. A small counterpoise, placed on the side of the point opposite to that where the wire is, tends to preserve to the wire a horizontal position. One of the poles of the pile is placed in communication with the central cup, and the other with the mercury of the upper canal. The wire is thus placed in the circuit, still preserving its mobility entire. The phenomenon is still more marked when from the centre of suspension are made to come two, three, or four similar wires, all of which are plunged by their free extremities in the mercury of the circular canal. We must then employ a powerful current, which is equally divided between the two, three, or four wires. It is evident that, as the current traverses them all in the same direction, namely, from the centre to the circumference, or from the circumference to the centre, they tend to turn in the same direction, and at the same time; and that consequently their effects are added together. The experiment generally succeeds better with two branches than with a greater number, because the increase of friction, when the number of points that plunge into the mercury is very considerable, causes more force to be lost than is gained by the multiplication of the branches. The length of the vertical branches, by which the horizontal ones are placed in communication with the current, is entirely an indifferent matter, provided that there are *two* or *four* situated symmetrically in relation to the axis.

The experimental analysis that we have been making clearly shows us the part played by the different portions of the rectangular current in the two fundamental experiments of Ampère. In that of the constant direction impressed by the earth upon the vertical rectangle, susceptible of turning around a central and vertical axis, the two horizontal branches of the rectangle do not experience any effect; the vertical alone determine the direction. In the experiment of the rectangle, susceptible of turning around a horizontal axis alone, the direction perpendicular to that of the dipping needle, which is taken by the plane of the current, arises only from the action exercised upon the two branches parallel to the axis, one of which, that wherein the current moves from east to west, is carried toward the south; and the other, that wherein the current is directed from west to east, is carried toward the north. The two lateral branches, perpendicular to the axis of rotation, not being able to advance in either direction parallel to themselves, do not experience any action, and do not therefore contribute to the direction taken by the movable conductor.

The following is a much more simple apparatus than that which we have employed for demonstrating the directive action of the earth upon a vertical current (*Fig.* 120.). It consists of a vertical wire terminated above and below by two horizontal branches, the upper one of which carries a steel point, and is prolonged beyond this point to carry a counterpoise, and the lower of which is terminated by a platinum point. The steel point rests on the bottom of a cup filled with mercury, situated at the top of a metal stem; the platinum plunges into a small annular canal filled with mercury, which surrounds the base of this stem without being in metallic communication with it. One of the poles is placed in communication with the mercury of the canal, and the other with the central stem; and the vertical movable wire places itself conformably to the law that we have established. It is evident that the two horizontal branches of the same length, and traversed by the same current, but in an opposite direction, do not experience any action, because, being on the same side of the axis, their contrary effects neutralise each other. We may adapt to the floating pile a similar conductor.

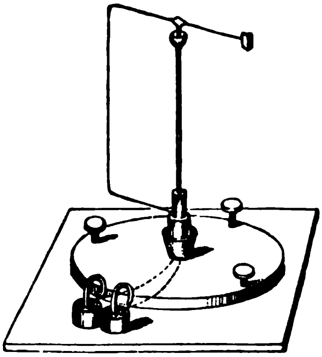
*Fig.* 120.

We have already spoken of Ampère's hypothesis of the cause of terrestrial magnetisation. He admits that the terrestrial globe is surrounded by electric currents, all directed from east to west, and situated at a small depth below the surface of the soil. These currents, like those of the magnet or of a solenoïd, have a resultant that is situated in the middle, and, consequently, in this case, in the magnetic equator; we may therefore consider their action as equivalent to that which would be exercised by a girdle of powerful currents directed from east to west on the magnetic equator. It is not difficult to prove that the action of this girdle of currents upon the movable currents ought to produce exactly the effects that have been disclosed to us by experiment. For this purpose, it is sufficient to show that it explains the two laws, to which we have seen that all the phenomena may be traced.

1st. A vertical current, movable around a vertical axis, always places itself so that the plane by which it is united to its axis is perpendicular to the magnetic meridian, and that it is itself either to the east of this axis if it is descending, and to the west if it is ascending.

2nd. A horizontal current, susceptible of moving parallel to itself, advances or recedes according as it is moving in one direction or in another, whatever be the azimuth in which it is placed.

These two laws are the consequence of the action of the equatorial current upon the movable currents.

In order to demonstrate it, in as far as the former is concerned, let us suppose an indefinite horizontal current representing that of the equator, and directed from east to west (*Fig.* 121.), and a vertical current, movable about its axis, situated in a different plane. Let us draw the right line, that measures the shortest distance between the two currents. It is the summit of the diedral angle, which they form. If the movable current is descending, it is evident that it is directed toward the summit of the angle, as well as is the portion of the fixed current situated to the east of this summit; it is therefore attracted by this portion and repelled by the other; it therefore tends to move towards the east. If we decompose the force that brings it there, and which is parallel to the direction of the indefinite currents, into two *components*, one directed to the plane that unites the current to its axis, and perpendicular to this axis, the other perpendicular to this

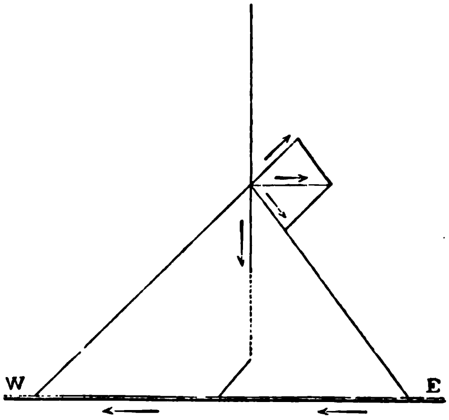

*Fig.* 121.

plane, we see that the former is destroyed by the resistance of the axis, and the latter alone causes the current to move, which consequently places itself so that its plane is parallel to the indefinite current, and is itself on the side of the east. It is in equilibrium in this position; for then the component, which causes it to move, becomes null. If the current is ascending, it is to the west and not to the east that it is carried; and it also remains in equilibrium when the plane that unites it to its axis is parallel to the indefinite current. Now this indefinite current is situated in the magnetic equator; consequently, every plane that is parallel to this equator is perpendicular to the magnetic meridian. The axis, in the two cases of equilibrium, ought to experience a traction arising from the tendency the current has always to move more to the east if it is descending, and to the west if it is ascending; a tendency by virtue of which, if it were free and insulated, it would turn constantly around the terrestrial globe, from west to east in the former case, and from east to west in the latter. But this hypothesis, as we can readily understand, is impossible of realisation, for it would be necessary that the wire that transmits the current should form part of a voltaic circuit.

The second law is a still more direct consequence, so to speak, than the former of the action of the equatorial current. Whatever be the angle that the movable horizontal current forms with the fixed current, whether this angle be acute, right, or obtuse, or even be null, as occurs when the two currents are parallel, it is evident that the two portions of the fixed current, by which the summit of the angle is separated, concur to drive the movable wire to that side of its two portions whose current is moving in the same relative direction. The mode of suspension can alone arrest the movement. If the horizontal current is movable around an axis which is parallel to it but situated above, we see it rise and place itself in the same horizontal plane as its axis, when the latter is in the magnetic meridian; we must only add to the axis a counterpoise, so as to neutralise as much as possible the effect of gravity upon the wire by which the current is transmitted. The apparatus that we have employed above to demonstrate that a closed circuit may place itself perpendicular to the dipping needle (*Fig.* 116.) is the best for making this experiment, providing we take the precaution so to place it that its axis is not perpendicular, but rather parallel to the magnetic meridian. Moreover, this horizontal position, which is assumed by the plane of the current, is entirely in accordance with the perfectly vertical direction assumed by the dipping needle, when its axis is in the magnetic meridian, or, which comes to the same thing, when the plane in which it moves is perpendicular to this meridian.

Finally, if we examine attentively the explanation that we have been giving of the two laws, we shall see that it is exactly the same, which proves that the former is only a particular case of the latter, and that they are both included in the general law of the action that is exercised by an indefinite fixed current upon a finite rectilinear current, movable around an axis which is parallel to it, and which is directed in any manner in space.

We have already seen that the continuous rotatory movement that a current undergoes by the action of the earth is a direct consequence of the second law, and is explained in the same way. We may easily obtain proof of this by casting the eye upon the figure that traces the different positions of the movable current in respect to the equatorial current, and which are all such as would result from a movement always carried on in the same direction, according to the law of angular currents (*Fig.* 122.).

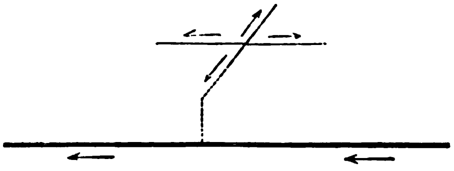

*Fig.* 122.

Ampère's hypothesis, therefore, on the nature of terrestrial magnetism, explains, in the most satisfactory manner, the action of the earth upon movable currents. Can we say as much with regard to the action of the earth upon magnetised needles? It seems that we may answer Yes! since all magnetic phenomena are perfectly well explained by supposing that magnets are only an assemblage of currents; hence the latter action is comprehended in the former. However, these currents, and those with which we have been operating, are of a finite magnitude; this is true; but at the distance at which the terrestrial currents are situated from the movable current, there is no great difference between a current of an inch or so in length, and the molecular current of a magnet. However, we must not conceal from ourselves that experiments still require to be made, in order to establish upon solid bases the identity between the cause that determines the direction of electric currents, and that which produces the direction of magnets. In particular, when once it has been well proved that it is the vertical currents, and in no degree the horizontal currents, that determine the directive action of the earth upon a rectangular current, it appears to us singular that compass needles are so thin and so wide: is there not some error in this? and would not the inverse be better?

At least the subject would deserve to be taken up, and it would be interesting, as much in theory as in practice, to determine, better than has been done, the best form that should be given to compass needles.

It would remain to us to examine to what degree the existence of currents in a direction from east to west below the surface is possible; to what cause they may be attributed; if they are reconcilable with the other phenomena of terrestrial physics: finally, if they may be perceived directly. These are so many interesting questions, of which we shall treat in the Fifth Part, the subject of which is *terrestrial electricity or magnetism.* We shall then see which hypothesis of the nature of this magnetism is most calculated to account both for its action upon electric currents and upon the magnetised needle; and if this double action may be readily included in the same explanation.

## CHAP. III.

### ON MAGNETISATION BY DYNAMIC ELECTRICITY.

We have already seen, in the preceding Chapter, that immediately after Oersted's discovery, M. Arago showed that an electric current attracts iron filings and produces magnetisation just as a magnet would do. He always found that, in order to impress a more decided magnetism upon a steel needle, it was necessary to employ a conductor bent into a helix, within the axis of which he placed the needle, instead of using the rectilinear current. The influence of this form, when given to a conductor in electro-magnetic phenomena, is altogether in harmony with Ampère's theoretical ideas. M. Arago equally succeeded in magnetising a needle, whether employing the current of the pile or the discharge of an electrical machine; and, which is still better, that of a Leyden jar. Davy, on his part, had shown that a needle may be magnetised by placing it transversely over a wire traversed by a voltaic current, or by an electric discharge. No long time elapsed before it was demonstrated that the employment of electric currents, which is excellent for magnetising soft iron, whose coercitive force is almost null, is insufficient to impress powerful magnetism upon steel needles, whose coercitive force cannot be completely overcome, especially when they are tempered, except by the discharge of one or more Leyden jars.

We will proceed, therefore, to study in succession the magnetisation of steel, produced essentially by electric discharges; that of soft iron, produced especially by electric currents; and the various phenomena, especially the molecular, that give evidence of the magnetisation developed by dynamic electricity.

### *Magnetisation of Steel.*

When a steel needle is magnetised by passing the discharge or a current through the wire of a helix, the precaution must be taken of placing the needle in a glass tube, around which the wire is coiled, in order to prevent the electricity passing through the needle, by the contact of the steel with the wire, instead of making the tour of the spirals. If we examine the position of the north and south poles in a needle thus magnetised, we find, by admitting Ampère's theory, that the discharge has determined currents in the steel pursuing the same direction as that which has produced the magnetisation; which ought to be the case in this theory, because magnetisation consists in giving a uniform direction to the electric currents, pre-existing around the particles of steel or iron. This effect is produced in the most direct and most advantageous manner by the action of exterior currents, arranged as the molecular currents should be in the magnetic body, were it magnetised, and which oblige these latter to place themselves in the same direction as they have themselves, and consequently in a position parallel to each other.

Independently of the direction according to which the discharge traverses, the direction in which the helix is wound naturally influences the direction of the currents, and consequently the position of the magnetic poles. In a *right-handed* helix, namely, one in which the wire is wound to the right, the south pole of the needle is always at the extremity through which either the discharge or the current enters; or, which comes to the same thing, at the extremity that is in communication with the positive electricity. In the *left-handed* helix, namely, that in which the wire is wound towards the left, the north pole is at the extremity through which the positive electricity enters. This also is a rigorous consequence of Ampère's theory, as is demonstrated by the directio of the

*Fig.* 123.

current (*Fig.* 123.). M. Arago, having wound a long wire around the same tube so as to make in succession several helices contrary to each other, and having placed therein a long steel needle, and after having made a powerful discharge or an energetic current traverse the system of helices, found that the needle was magnetised, but that it presented a consecutive point at the junction of each helix. With two contrary helices, we obtain the same pole at each of the extremities of the needle, and a single contrary pole in the middle; that is to say, three poles: with three helices, we obtain contrary poles at the two extremities, and two consecutive points between each pair; and so on. M. Arago also recognised that, if the helix is long in respect to its diameter, and if the spirals are very near together, the position of the needle in the interior of the tube has no influence over the degree of magnetism that it acquires, provided that it is always placed parallel to the axis. The magnetisation is very feeble if the needle is placed exteriorly to the helix, even when care is taken to place it as near as possible, and in a position parallel to the axis.

M. Nobili endeavoured to employ a flat spiral for magnetisation instead of a helix, such as Arago had employed, or a straight wire, such as Davy had used. He placed the steel needles between the spirals, insulated from each other, and perpendicularly to their plane; he passed an electric discharge through all the wire of the spiral. The needles situated near the centre were magnetised in a contrary direction from that in which those were magnetised that were at a greater distance off; and there was a point, at a certain distance from the centre, where the magnetisation was null. We should remark that, in this experiment, each needle is placed between two currents, which, moving in the same direction, ought to give it a different magnetisation; for in order that the action of the currents should conspire, it would be necessary that the current situated on one side of the needle should move in a contrary direction from the current situated on the other side. The definitive magnetisation, therefore, depends upon the relative intensity of the two currents whose individual action is opposed. We shall see further on why near the centre the one prevails, and why near the edge of the spiral it is the other. We must first analyse this class of effects in less complicated cases. This analysis was first made by M. Savary, and afterwards completed by M. Abria. We will put forth the remarkable results to which these two philosophers successively arrived.

The first of these results is, that the intensity and even the direction of the magnetisation produced upon a steel needle by a discharge transmitted through a rectilinear wire, depends upon the distance of the needle from this wire; in such sort that the intensity, far from diminishing constantly with the distance, augments with it from a certain point, where it is at its minimum; and that, on the same side of the wire for a given direction of discharge, the same magnetic poles are found placed at one extremity or at the other, according to the distance of the needle or the conductor. Thus, near the wire, the poles are placed conformably to theory; but at a greater distance, and by the mere fact of this augmentation of distance, they are found placed in a contrary direction. The wire employed by M. Savary for transmitting this discharge was of platinum, was about two yards (two metres) in length and $\frac{1}{100}$th in. in diameter. The steel needles, which were all as much alike as possible and strongly tempered, were about $\frac{1}{2}$ an inch in length (·5895 in.), and $\frac{1}{100}$th in. (·0098 in.) in diameter. He judged of the intensity of the magnetism that they had acquired by the number of oscillations they made under the influence of terrestrial magnetism. The electric discharge was produced from a battery of 22 sq. ft. of surface. In order to prevent the needles being mutually influenced, they were not placed vertically above each other; but care was taken, while still placing them at different heights above the wire, of separating them in the horizontal direction; which was easily done, in consequence of the length of the discharging wire.

The following table points out for each needle, beside its vertical distance above the wire, the duration of 60 oscillations and the direction of the magnetism that it has acquired by the effect of the discharge. The positive direction is that which corresponds to the direction of the current, conformably to theory; the negative direction is that opposed to this direction. The following is the table:—

| | Distance of the Wire in Twentieths of an Inch. | Duration of 60 Oscillations. | | Direction of Magnetisation. |
|---|---|---|---|---|
| | | ′ | ″ | |
| 1st | In contact. | | 52·4 | Positive |
| 2nd | 1 | 1 | 3·8 | do. |
| 3rd | 2 | 1 | 12·8 | Negative |
| 4th | 3 | | 44·6 | do. |
| 5th | 4 | | 40·0 | do. |
| 6th | 5 | | 41·8 | do. |
| 7th | 6 | | 44·8 | do. |
| 8th | 7 | | 58·2 | do. |
| 9th | 8 | 1 | 20·1 | do. |
| 10th | 9 | 1 | 52·0 | Positive |
| 11th | $9\frac{1}{2}$ | 1 | 18·6 | do. |
| 12th | 10 | 1 | 1·0 | do. |
| 13th | 11 | | 49·6 | do. |
| 14th | 13 | | 38·2 | do. |
| 15th | 15 | | 33·8 | do. |
| 16th | 17 | | 31·3 | do. |
| 17th | 19 | | 29·5 | do. |
| 18th | 22 (=$1\frac{1}{10}$ in.) | | 30·8 | do. |
| 19th | 27 (=$1\frac{7}{20}$ in.) | | 29·8 | do. |
| 20th | 36 (=$1\frac{4}{5}$ in.) | | 35·9 | do. |
| 21st | 56 (=$2\frac{4}{5}$ in.) | | 55·6 | do. |
| 22nd | 80 (=4 in.) | 1 | 27·6 | do. |
| 23rd | 100 (=5 in.) | 1 | 48·0 | do. |

From this table we see that, even at $\frac{2}{20}$ in. distance, the direction of the magnetisation changes, although, when in contact or at $\frac{1}{20}$ in. distance, it was positive. At $\frac{9}{20}$ in. distance it again became positive, and it remained so to 5 inches. With regard to the intensity, it is at its maximum for needles positively magnetised when in contact and when at a height of $\frac{19}{20}$ in.; the latter maximum is even sensibly stronger than the former. The maximum for negatively magnetised needles occurs at $\frac{4}{20}$ in. from the wire. The minimum occurs at the distances where the signs change. In another experiment, in which the platinum wire was reduced to a length one half less, one yard only, Savary obtained four changes in the direction of the magnetisation. The last maximum occurred at a height of $1\frac{3}{4}$ inches; while it was at $1\frac{1}{3}$ inches in the former experiments.

If, without changing the length of the discharging wire, we merely change its diameter, we modify the distances at which the changes in the direction of the magnetisation occur; with a wire of very fine diameter, for instance, $\frac{1}{300}$ in. there are no longer any of these changes; and the maximum of intensity is at $\frac{1}{3}$ an inch, namely, at a distance five times less than when we operate with a platinum wire three times thicker.

The intensity of the magnetisation, all other circumstances being the same, is greater as the length of the wire is less in proportion to its diameter. This increase, however, has a limit, and a wire of a yard gives the highest absolute maximum when it is $\frac{1}{300}$ in. in diameter: at the distance at which this maximum occurs, namely, at $\frac{1}{3}$ an inch, the needle is magnetised to saturation; for greater lengths the intensity is less. The relative maxima for each length are found nearer the wire as the latter is longer. We need scarcely remark that, in each case, the absolute intensity of the effects increases with that of the discharge.

The influence exerted by the length and the diameter of the conducting wire seems connected with the greater or less retardation which these two circumstances exert over the discharge; for, in a closed circuit of three wires of unequal diameters, joined end to end, the effect of the discharge is the same, whichever of the three wires is placed above the needle. This result arises from the discharge travelling with the same velocity in all parts of the same circuit, however different be the various conductor of which the circuit is composed, provided they are placed one after the other, and all traversed simultaneously by the discharge, or by the current.

The temper and the size of the steel needles exercise a very marked influence over the results; untempered needles do not present any change of signs, whilst those that are stiffly tempered present at least three. In like manner, if the diameter of the needle is somewhat considerable, the maximum magnetisation occurs at contact, and there is a continuous decrease of intensity, in proportion as it is removed from the wire. A tempered needle of large diameter is thus approximated to an untempered needle, which may be explained by remarking that temper only acts upon the surface, and that, in a large needle, the surface is much less, in comparison with the total mass, than in a small one.

M. Savary also studied magnetisation produced by helices, and he added some fresh facts to those that had been observed by Arago. With a brass wire, 2·62 feet in length and $\frac{3}{100}$ in. in diameter, coiled into a helix around a wooden tube about $\frac{1}{4}$ inch in diameter, so that the distance between two consecutive spirals of the helix was about $\frac{1}{8}$ in., he obtained six changes in the direction of the magnetisation by employing discharges of a successively increasing intensity. The needles, however, all similar, and tempered hard, were about $\frac{1}{100}$ in. in diameter, and $\frac{6}{10}$ in. in length. If we increase the total length of the wire without changing the portion coiled into a helix, we end by having no more reversing of magnetisation, but merely variation in the intensity, in proportion as that of the discharge increases. The length of the steel needles placed in the interior of a helix exercises no influence over the direction of the magnetism, but simply over its intensity. Fragments of long needles magnetised directly have less magnetism than similar fragments have, that are obtained by breaking a needle previously magnetised by a discharge of the same power.

Among the results to which M. Savary arrived, we have yet to point out some no less remarkable than those that we have been detailing; it is in reference to the influence exerted upon magnetisation produced by means of electricity by the interposition of certain media between the wire by which the discharge is conducted, and the steel needle that is submitted to its action. M. Arago had observed that wood, glass, and insulating bodies in general, in no degree modify this action; but it is not the same if the interposed body is a conductor of electricity. M. Savary found that, if two similar needles are placed in a helix, the one without an envelope, the other surrounded by a thick cylinder of copper insulated from the wire of the spirals, the discharge that magnetises the former powerfully does not produce any effect upon the latter. But, by gradually diminishing the thickness of the envelope, the intensity of the discharge remains the same; the enveloped needle commences experiencing an action which gradually becomes sensible. Observations of this kind are easily made by employing plates of tin-foil as envelopes, the thickness of which may be diminished or augmented at pleasure by unrolling them or rolling them up. It may even happen that, for a certain thickness, the enveloped needle acquires a more powerful magnetism than the one without an envelope. Finally, it is to be noted that the envelope sometimes changes the direction of the magnetisation. Thus of three needles, placed, one in a copper cylinder $\frac{1}{5}$ inch in diameter, the second in a tin cylinder of the same size, and the third without an envelope, the former was the least magnetised, making 60 oscillations in 2′ 35″; the second the most, making them in 45″; and the third in 1′ 52″. This latter was magnetised in a contrary direction to the other two.

It is necessary that the enveloping body should form a continuous surface: if it is in powder it does not produce any effect; it is true that, in this condition, it ceases to be a conductor of electricity. Furthermore, it is of little consequence whether the enveloping plates be separated from each other by insulating strata, or be in immediate contact: the effect remains the same, providing that each of them is continuous. Mercury behaves like other metals, only its influence is less decided.

Other experiments have been also made by M. Savary, by interposing between the rectilinear conductor that transmits a discharge, and the needle that is to be magnetised, metal plates of different natures and of different thicknesses: this curious result follows, that, for very feeble discharges, a conducting plate, such as a plate of copper, greatly weakens the magnetisation, whilst it augments it if the discharge is powerful. A thin and a thick plate may produce very different effects for the same intensity of discharge, and there is a certain thickness with which the effect is null. If the needles are placed upon the conducting plate and the wire that conducts the discharge above it, it is found that the presence of the plate increases the intensity of the magnetisation; and the more so as it is thicker. However, there is a certain intensity of discharge for which a thick plate increases, and a thin plate diminishes, the intensity of the magnetisation. For still more powerful discharges there is a diminution, whatever be the thickness; and there is even a point at which the influence of the plate gives the needle a contrary magnetism to that which the current itself developes. We see by this that the effects are very different, and even opposite, according as the plate is between the needle and the discharging wire, or as the needle is between the wire and the plate.

M. Savary repeated with electric currents the greater part of the experiments that he had made with discharges; and he found that the effects produced by these two forms under which dynamic electricity is presented are the more similar, as the pile has higher tension, and as it is charged with a liquid that conducts less. Moreover, the effects in general are less decided with currents than with discharges, especially in as far as concerns the changes which the direction of the magnetisation undergoes when there is a variation in the distance of the needles from the conducting wire. Magnetisation is brought about in a very decided manner, if steel needles are placed in the interior of a helix traversed by the current. The influence of conducting envelopes is also felt in this case; but what is curious is, that it is more sensible as the pile that produces the current is feebler.

We shall not at present endeavour to connect the facts that we have been relating with any theory. Those which relate to the direction and to the degree of magnetisation of the interposed or surrounding conducting media, will find their explanation further on, in the phenomena of induction, upon which we shall be engaged in the Fifth Chapter. With regard to the extraordinary influence exercised by the distance of the needle from the conductor that is traversed by the discharge that magnetises it, it is also in great part due to the same cause. It is, however, probable that it is equally connected with that reaction exercised by the magnetisms of the molecules upon each other, a reaction that produces the consecutive points in the ordinary processes of magnetisation, and which depends essentially upon the dimensions and the degree of temper of the steel, as well as on the manner in which it is magnetised.

M. Abria, in his researches upon magnetisation, instead of employing electric discharges, made use of currents produced by a constant pile. He convinced himself that the degree of temper possessed by a needle has a considerable influence over the magnetic intensity that it is susceptible of acquiring under the same circumstances. Thus, in order to protect himself from this influence, he took all possible precautions to give the needles that were intended for comparative experiments a state of temper as constant and as regular as possible, which is not a difficult matter if care be taken to heat them all in the same manner at the same time, and to temper them together in cold water. He further proved that, whatever be the length of the needle, provided it is not longer than the helix, its poles are always placed at the two extremities of the part inserted, and that the portion which is outside the helix is not magnetised. The intensity of the magnetism acquired by each needle is determined by the duration of its oscillations, which may be appreciated to about one or two hundredths of a second.

M. Abria found, by magnetising needles of variable lengths and diameters in the same helix, that not only is the magnetic intensity absolute, but also the law followed by the variation of this intensity with the variation of the force of the current, changed with the length and the diameter. If we magnetise in the same helix, by the action of a current, with a gradually increasing intensity, needles similarly tempered, the magnetic intensity increases the more rapidly as the length of the needle is more considerable, the diameter not varying, or, when the diameter is less, the length remaining constant. So that, if the diameter does not vary, the magnetic intensity increases for a certain length with the intensity of the current, and for a length greater than this, as the square of this intensity; for intermediate lengths it varies more rapidly than according to the first law, and less rapidly than according to the second. The length for which the developed magnetisation increases, according to the same law, increases at the same time as the diameter does.

With a longer helix, the length for which the magnetic intensity increases as the square of the intensity of the current, increases very rapidly with the diameter. Moreover, the absolute length of the helix has no influence over the magnetic intensity, so long as the needle is not longer than the helix. The diameter of the helix exercises a very marked influence this way;—that, of two helices of the same length, the narrower produces a stronger magnetisation; but this is not true, except when the helices are short; for, if we increase sufficiently the length of the same narrow one, the difference disappears. Thus, a helix of 1·34 in. in length, and $\frac{2}{5}$ in. in internal diameter, magnetises more strongly needles of different diameters and of different lengths, than a helix of ·67 in. in length, and at most 1·5 in. in internal diameter.

Of two helices of the same length, but containing a different number of convolutions, the most energetic is that which has the greater number of convolutions; when the intensity of the current is a little powerful, the degree of magnetisation communicated to the needles is very nearly proportional to the number of the convolutions of the helix; it is not the same for more feeble intensities. Furthermore, this influence of the number of convolutions of the helix, varies also with the length and diameter of the needles. The metallic envelopes with which the needles are surrounded within the interior of the helix, and which form, as it were, cases in which they are placed, do not exercise any kind of influence over the direction and the intensity of the magnetism that is communicated to them, which establishes a remarkable difference between magnetisation by currents and magnetisation by electric discharges. It follows, as a matter of course, that the metallic envelopes in question are not to be made of a magnetic substance, for the influence would then not be null.

A tempered needle, submitted in any manner to the action of a current, possesses, after a very short interval of time, all the magnetism that it can acquire. If the needle already magnetised is subjected to currents acting in an inverse direction and gradually increasing, the magnetic intensity diminishes in proportion as the energy of the contrary current increases; it becomes null for a certain intensity of the latter, less than the intensity of the current by which the needle was previously magnetised; beyond this, inverse magnetisation takes place. When a needle has been demagnetised by the action of an inverse current, it does not behave as it formerly did; the new magnetic intensity that it acquires under the influence of a given current is sometimes greater, sometimes less, than that which it had previously acquired. There is also a change in the law by which the intensity of the current is connected with that of the acquired magnetism.

The irregularities and the very anomalies that are presented by the phenomena successively discovered by MM. Savary and Abria are, for the most part, due, as we have already remarked, to the important part played in magnetic actions by the molecular forces, which have themselves hitherto escaped the rigorous laws to which we have endeavoured to subject them.

### *Magnetisation of soft Iron by electric Currents.*

Before making any further advances in the study of the phenomena that are connected with the magnetisation of steel, let us now turn our attention to that of soft iron. There are very considerable differences in the circumstances that determine, as well as in those that accompany this magnetisation, compared with the similar circumstances as far as steel is concerned.

M. Arago was the first to observe that a wire, when traversed by a powerful electric current, and plunged into iron filings, retains around it a considerable quantity, which form a cylindrical mass of the thickness of a quill. At the moment when the current ceases to pass through the wire, the mass immediately falls. This phenomenon evidently proves the susceptibility of the particles of iron to acquire a powerful magnetism under the influence of a current, and to lose it as soon as this influence ceases. Subsequently experiments were made by surrounding a bar of soft iron, bent into the form of a horse-shoe, with copper wire covered with silk and wound into a helix, care being taken that the helix of the second branch was the continuation of the helix of the first; so that if the bar had been straightened, the two helices would have formed but one, both *right-handed* or both *left-handed*. A feeble electric current, such as that produced by a single pair of copper and zinc, is sufficient, on being transmitted through the wire, to magnetise the bar powerfully. The magnetisation is instantaneous; it occurs as soon as the current commences passing, but it ceases almost entirely with the current. It is so energetic that, with a suitable pile, we can make a bar of soft iron sustain as much as a ton. These temporary magnets are called *electro-magnets* (*Fig.* 124.), to distinguish them from permanent magnets of steel, and electric helices or solenoïds. The discovery of electro-magnets has caused magnetism to make a very great progress, by furnishing us with a means of acquiring immense, and we may say almost unlimited magnetic power. We shall see in the following Chapter, and especially in the Sixth, the immense advantages that science has derived from it. I shall confine myself to quoting here the works of M. Delesse, a French philosopher, who has very cleverly applied the power of electro-magnets to the determination of the magnetic properties of a very great number of rocks, which would not have been manifested under the action of ordinary magnets, even the most powerful. It has also been proved that electro-magnets may act upon magnetised bars as they would act upon unmagnetised soft iron, that is to say, would impart to them a temporary magnetism contrary to what they possessed before, without, however, destroying the latter, which would re-appear after the action of the electro-magnet had ceased.

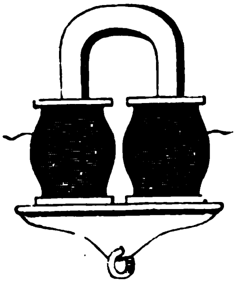
*Fig.* 124.

Many experiments have been made in order to determine the conditions most favourable for the developement of powerful magnetism in electro-magnets. The length and diameter of the branches of the horse-shoe, the number of convolutions of the conducting wire and its diameter, have successively been the subjects of numerous investigations. The force and the nature of the pile employed for producing the current have also been varied, and researches have been made as to whether it is better that the wire coiled round the two branches of the electro-magnet should be continuous, so as to be traversed successively by the whole of the current; or, if it would be preferable for it to be divided into one or a greater number of wires, among which the total current should be divided. MM. Moll, Henry, Liphaus, and Quetelet, and many others, are still engaged upon this subject. Lastly, MM. Jacobi and Lenz have determined what they call the laws of electro-magnets. But, in fact, results have not as yet been obtained that may be regarded as very general. This arises from there being nothing absolute in these laws. Thus, with a current of a certain intensity, or developed by a certain pile, a certain system of electro-magnet is preferable, whilst for another current, of a different intensity or origin, another system would be preferable. I shall therefore, for the present, confine myself to quoting certain results that appear very well proved, and that I have myself had the opportunity either of verifying or of determining.

The quality of the iron exercises a great influence over the power of the electro-magnet; it must be as soft as possible: thus old iron, and especially Swedish iron, is preferable to all others. It is not a bad plan to anneal it several times, in order to soften it, taking care to allow it to cool very slowly. The rapidity with which iron loses its magnetisation, as soon as the current ceases, depends essentially upon its nature: however, it likewise depends upon the dimensions of the bar. Horse-shoes whose branches are long lose their magnetism much less easily and much more slowly than those whose branches are short—four inches, for example. The presence of the armature at the extremities of the branches of an electro-magnet contributes towards its preserving its magnetism. Mr. Watkins remarked that an electro-magnet which could sustain 120lbs. whilst the electric current was magnetising it, sustaining only 50lbs. as soon as the current had ceased to pass, continued to support the latter for a considerable time, so long as the armature was not disturbed. But, on removing the armature violently away, all the magnetism disappeared. This same property was also recognised in soft iron magnetised by other means than by the electric current. However, if the armature is removed immediately after the soft iron has become saturated with magnetism, or after it has remained in its place several weeks, the electro-magnet, notwithstanding this separation, still preserves some traces of magnetism. This influence of the armature appears to be due to a state of equilibrium that is established between all the parts of what might be called a *closed magnetic circuit*, that is to say, of a horse-shoe magnet, the two extremities of which are connected with an armature. When this circuit is suddenly opened by snatching away the armature, the equilibrium that was established ceases, in order to give place to a second equilibrium which brings back the whole of the magnetic forces of the soft iron to the natural state of ordinary neutralisation. M. Alexandre observed that, if we strongly heat an electro-magnet with a spirit-lamp, at the same time that the wire by which it is surrounded is traversed by powerful electric currents, we render it, by this double action combined, capable in every case of losing its magnetism immediately the electric current ceases to be transmitted. In this experiment, we must evidently put in place of the silk, with which the conducting wire, for the sake of insulation, is generally covered, gum-lac or resin, which, under the action of heat, forms a liquid mass, still capable of producing the necessary insulation.

Mr. Moll was the first to observe that, when the direction of the current is reversed, that of the magnetism, namely, the place of the magnetic poles, immediately changes. However, the second magnetism is never so powerful as the first, especially if the latter had remained a considerable time before the change has been produced in the direction of the current; however, a great number of successive changes end by rendering an electro-magnet susceptible of being magnetised as easily in one direction as the other. A strongly magnetised steel needle may also, under the influence of powerful currents, acquire poles the opposite to its primitive poles: for this purpose, we must so place it that it is not able to obey the directive action which these currents would impress upon it. We may also advantageously magnetise steel needles and bars by employing powerful electro-magnets. It is of no importance whether their magnetism be temporary or not, providing that it remains the time necessary for magnetisation. Endeavours have also been made, and with some success, to apply against the two extremities of an electro-magnet those of a steel horse-shoe that had been heated to red-white, and to allow it to cool in this position. After the cooling it was found to have acquired a powerful and permanent magnetism.

The facility with which soft iron acquires and loses magnetism, with the cause by which it is produced, and by which it is magnetised alternately in one direction or the other, has given rise to several pieces of apparatus, and even to practical applications such as those of the electric telegraph, and many others also, to which we will turn our attention in the Sixth Part of this work. We shall confine ourselves for the present to describing three pieces of apparatus, which give evidence of this double property in the most elegant manner.

In the first apparatus, the principle of which was devised by Mr. Ritchie, we place vertically upon a horizontal support four cylindrical electro-magnets of equal length, in such a manner that they are situated at the four angles of a square, and their upper surfaces are exactly on the same horizontal plane (*Fig.* 125.). Care is taken to turn them so that each of the four has alternately its north and its south pole upwards. Two small electro-magnets, placed cross-wise in a horizontal plane around a vertical axis, passing through their crossing point, are so arranged that when one of the four extremities of their two branches is opposite one of the magnetic poles, the others are also respectively opposite the other magnetic poles. Each electro-magnet is surrounded by a wire

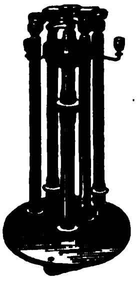

*Fig.* 125.

covered with silk, and which is used for transmitting the current necessary for magnetisation. The two extremities of each of the two wires dip, so as simply to graze the surface, into the mercury of two small concentric annular canals, which are both hollowed in a piece fixed upon the top of the apparatus, and withinside the magnets. Each of these canals is divided into four compartments, and the little transverse partitions by which they are separated are situated in the parts of the canals, that exactly correspond to the situation of each magnet. One of the poles of the pile communicates with the two opposite compartments of the interior canal, and with the two others of the exterior canal; the other pole communicates with the four in the other compartments; the extremities of the same wire always plunge, one into one of the compartments of the exterior canal, and the other into the corresponding compartment of the interior canal; but the arrangement is such that if the extremities of one of the wires are in certain compartments, those of the other are in the compartments that follow or that immediately precede this. It follows that the currents traverse the wires of the two electro-magnets in opposite directions; that, consequently, the extremities of these electro-magnets are attracted by the contrary poles of the fixed magnets. But, when they have arrived opposite to these magnets, the ends of the wires each pass from one compartment into the following one; and hence there occurs a change in the direction of the current of each of the two wires, and consequently a change in the direction of the magnetisation of each electro-magnet. The four poles of the electro-magnets are immediately repelled by the four poles of the magnets before which they have been respectively brought; they are consequently attracted by the contrary poles of the following magnets. When arrived before them, the same change of compartments is brought about for the ends of the wires; consequently the same inversion in the direction of the currents occurs, and the same repulsion as before is immediately manifested, and so on; whence there results a continuous rotatory movement, which may attain to an extraordinary rapidity, which proves with what promptitude the change of direction may be brought about in the magnetisation of soft iron. We see that the ends of the wires can pass from one compartment to the other without being arrested by the partitions that separate them, and while still continuing to be plunged in the mercury: this is due to the latter, by virtue of its capillarity, being raised a little above the sides that form the canals, and consequently above the partitions which separate them into several cells, and which are at the same height as these sides. Only it sometimes happens that the mercury, being drawn along by the points, covers the partitions, and so establishes a communication between two consecutive compartments; which must be avoided, for the movement immediately ceases, since the current no longer traverses the wires of the movable electro-magnets, the two poles of the pile being in direct communication by the mercury.

The second apparatus, which shows with what rapidity soft iron can acquire and lose its magnetisation, was contrived and constructed by M. Froment, a skilful Parisian artist. It consists (*Fig.* 126.) of a small electro-magnet, the armature of which, being composed of a very light plate of iron, is able to oscillate between the two poles on the one hand and a stop on the other hand, against which a spring tends to make it press. An electric current, introduced into the apparatus, passes through the iron plate and its stop, so that the circuit is interrupted as soon as the two pieces are separated. This effect is produced of itself by interposing in the circuit the wire by which the electro-magnet is surrounded; for the latter then attracts the plate of soft iron, and by separating it from its stop interrupts the passage of the current: the magnetisation immediately ceases; the plate of iron, being pressed back by the spring, returns and strikes the stop, and again forms the circuit; a fresh magnetisation, a fresh interruption of the circuit; and so on with a rapidity which we have the power of regulating, and

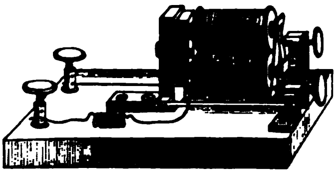

*Fig.* 126.

which may attain to several thousand beats in a second. By turning the screws, which serve to vary the amplitude of the vibration and the power of the spring, we can make the instrument give out all the sounds of the musical scale, which enables us to deduce the number of vibrations. This instrument, which shows that in one second the iron of an electro-magnet may be several thousand times magnetised and demagnetised, presents applications to which we shall turn our attention when we are treating on induced currents. We shall confine ourselves for the present to point out one: it consists in the instrument being so regulated as to produce a fixed sound; the least variations in the intensity of the current employed are detected by a change in the sound, arising from a change in the number of corresponding vibrations.

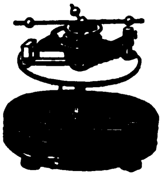
*Fig.* 127.

Finally, a third apparatus, constructed by Mr. Watkins (*Fig.* 127.), consists of a balance-wheel, similar to but much larger than that of a watch, and connected in like manner to a spiral spring. This balance-wheel is provided with a small piece of soft iron, placed very near to the poles of an electro-magnet, so that when an electric current traverses the wire of the electro-magnet it is attracted by it, and comes and adheres to its poles, drawing with it the balance-wheel. But a small ivory disc, in which is inclosed a metal plate, is fixed to the balance-wheel, and moves with it. A metal spring, resting against the circumference of the disc, is thus sometimes in contact with the metal, at other times with the ivory of the disc. In the former case, which occurs when the piece of soft iron is distant from the poles of the electro-magnet, the current is transmitted and the piece is attracted: in the latter case, which occurs when the piece is in contact with the poles, the current is no longer transmitted, the electro-magnet is no longer attracted, and the piece of soft iron, being no longer retained near the poles, the spiral spring that had been stretched is released, and causes the balance-spring to return back. The latter thus executes in a given time a greater or less number of vibrations: this number depends upon the intensity of the current transmitted, and may thus serve as its measure.

In order to study thoroughly and in detail the magnetisation produced by electric currents, it is necessary to have one or two wooden bobbins, each surrounded by several convolutions of copper wire covered with silk, through which the current is to be transmitted (*Fig.* 128.). It is well that this copper wire, which thus forms superposed helices, should be from $\frac{1}{12}$ in. to $\frac{1}{3}$ in. in diameter, in order that an energetic current may be transmitted through it without its becoming sensibly heated. If to the opening of such a bobbin, whose wire is in the voltaic circuit, a rod of soft iron or even of steel be presented, we perceive it to be attracted and to rush into the bobbin until it is so placed that its middle coincides with that of the enveloping helix; a result which is equally obtained whether the rod is shorter or longer than the axis of the bobbin, or is equal to it. Balls of soft iron, of any diameter, when placed at the opening of the bobbin, and being free to roll upon a very horizontal plane, in like manner rush in and stop at the middle: it is the same with discs and rings of soft iron; except that when they are presented to the opening of the bobbin, so that their plane is perpendicular to the axis of the helix, they immediately turn and place themselves in the middle, so that their plane or their diameter is parallel to the axis. This fact, and a great number of other similar ones, show, in the most evident manner, the disposition

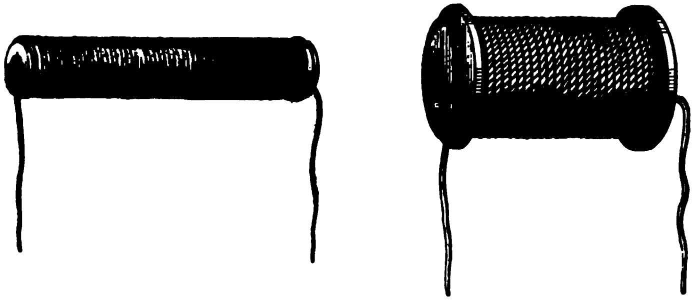

*Fig.* 128.

possessed by magnetic bodies of always becoming magnetised in the direction of their longest lengths, so that the opposite poles are as far as possible from each other. We have a further proof of this by making the experiment with a bobbin whose opening has a large diameter—five or six inches, for example (*Fig.* 129.), and by particularly observing the arrangement that is assumed by iron filings when placed in the interior of this bobbin. In order that this observation may be well made, it is necessary that the axis of the bobbin be vertical; we then introduce into one of the openings a disc of wood or pasteboard, provided with a rim, and upon which the iron filings are placed. At the opening, as well as at the bottom of the bobbin, the filings form a multitude of small heaps, which all tend toward the centre, namely, toward the point where the axis cuts the plane by which they are supported; but in proportion as we approach the middle of the bobbin we perceive the small heaps which, when separated from each other, were from three quarters of an inch to an inch in height, avoid the centre and all approach the edges, namely, the outer boundary of the bobbin. It appears that each of these heaps forms so many small magnets, which mutually repel each other by the effect of the repulsive action of their homonomous poles, as would be the case with the magnetised needles of a magnetic bundle, if they were movable. If, instead of iron filings, we place within the bobbin fragments

*Fig.* 129.

of iron wire shorter than its interior diameter, as soon as a current traverses the copper wire coiled into a helix, we see them quit their horizontal position to take a vertical one, all of them receding from each other, and even remaining suspended in this position, when the support upon which they had formerly been placed is removed from beneath them.

A soft iron cylinder, of greater length than the bobbin, and placed in its interior, becomes magnetised, whatever be its length, in such a manner that its poles are always situated at the points immediately outside the bobbin; we may judge this from the position assumed by the iron filings. The magnetised portion extends to a certain distance beyond the bobbin; and if the two portions that emerge out are of unequal length, the longer is the more powerfully magnetised. When a hollow cylinder of iron is introduced into the interior of the bobbin, so that one of its extremities or both pass at least half an inch or so beyond the opening of the bobbin (*Fig.* 128.), we find it to be magnetised exteriorly like a solid cylinder, but interiorly not the slightest trace of magnetism is manifested; however, if we place a small iron ball at about a quarter of an inch from either of its extremities, we observe it to move rapidly toward the opening, and there, making the tour of the edge, to slide over the exterior surface, to which it remains adhered, notwithstanding its weight, at a distance of a quarter or half an inch from the edge. Iron filings, introduced into the interior, but near to the edge, experience the same effect in an equally instantaneous manner.

Not only does the cylinder of soft iron present no traces of magnetism interiorly, except near its edges, but it interrupts all the magnetic action of the helix upon iron introduced into it. It is not the same if the cylinder is split horizontally, providing this cleft goes from end to end; or if it is simply formed of sheet iron, the edges of which are brought near together, and riveted without being soldered. In this case the interior magnetic effects of the helix are manifested as usual: it is the same when we introduce into the helix a hollow cylinder of copper or any non-magnetic metal, even when these latter cylinders have their surface perfectly continuous.

I have, however, observed a case in which the action of the bobbin upon the points situated in its interior is nearly the same in intensity, whether there be a hollow cylinder of soft iron within it or not. I place a stratum of mercury, about $\frac{1}{3}$ in. in thickness, in a circular capsule, a little less in diameter than the interior of the bobbin, into which, by means of a vertical stem, I introduce it to a greater or less distance from the opening. An electric current traverses the stratum of mercury, radiating from the centre to the circumference, whence is produced a rotation of the liquid under the influence of the current of the bobbin, the direction of which is, for all positions, in accordance with Ampère's law of angular currents. The rotation is the same in direction, but merely stronger, if the bobbin contains a continuous soft iron tube, into the interior of which the stratum of mercury is introduced.

### *Vibratory Movements and molecular Effects determined in magnetic Bodies by the Influence of electric Currents.*

Mr. Page, an American philosopher, had observed, in 1837, that on bringing a flat spiral, traversed by an electric current, near to the pole of a powerful magnet, a sound is produced. M. Delezenne, in France, also succeeded in 1838 in producing a sound by revolving a soft iron armature rapidly before the poles of a horse-shoe magnet. In 1843 I myself remarked that plates or rods of iron give out a very decided sound when placed in the interior of a helix whose wire is traversed by a powerful electric current; but only at the moment when the circuit is closed, and when it is interrupted. Mr. Gassiot in London, and Mr. Marrian in Birmingham, had also made an analogous experiment in 1844. Attributing this singular phenomenon to a change brought about by the magnetism in the molecular constitution of the magnetised body, I went through a great number of experiments, in order to study this interesting subject.

It is above all things important, in order to obtain a numerous series of vibrations, to be provided with a means of interrupting and of completing, many times in a very short space of time, the circuit of which the wire that transmits the current forms a part; in other words, to render a current *discontinuous* or *continuous*. With this view, I made use of one of the numerous apparatus, called *Rheotomes*, or *cut-currents*, and which are intended, when placed in the circuit, to render a current discontinuous. One of the most convenient (*Fig.* 130.) consists of a horizontal rod, carrying two needles, inserted perpendicularly and parallel with each other, so arranged, that when they are immersed simultaneously in two capsules filled with mercury, and insulated from each other, the circuit is closed; and when they are not immersed it is open. A clock-work movement, or simply a winch moved by the hand, gives a rotatory movement to the axis; whence it follows that, in a given time, a second for example, the circuit may be closed or interrupted a great number of times. The apparatus of *Fig.* 130. presents four needles instead of two, and consequently four compartments corresponding with the four needles. We shall have occasion hereafter to see the use of the second system of two needles; for the present a single one is sufficient; and, consequently, in all the experiments that will follow, in order to place it in the

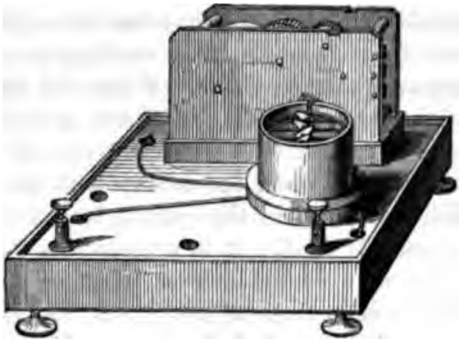

*Fig.* 130.

circuit, we shall employ indifferently either the one that is nearest to the clock-work movement, or the one that is most distant. There is a risk of the mercury being projected when the movement is too rapid; to prevent this inconvenience, we must cover the capsules, the needles, and the axis that carries them, with a small glass shade. When the current is very powerful, the mercury is oxidised by the effect of the sparks that occur at the moment when the needles emerge; in this case it is necessary to remove the oxide, or to change the mercury. We may do without mercury, and supply its place by two elastic metal plates resting on a cylinder, or on the circumference of a varnished wooden or ivory wheel, in the edges of which are inserted small pieces of metal, in metallic communication together. When the elastic plates, by means of the rotation of the cylinder or of the wheel upon its axis, come in contact with the metal part of the surface, the circuit is closed; when the contact with this metal part ceases, which occurs when the contact is with the wood or ivory, the circuit is open. It is necessary in this case that the two plates, as were the mercury cups in the preceding case, shall be in the course of the circuit, that is to traverse the wire of the helix, and shall press strongly against the circumference.

We may also interpose in the course of the current merely a toothed wheel and an elastic metal plate, which presses upon the teeth of the wheel (*Fig.* 131.). By giving the wheel a movement upon its axis, we cause the plate to leap from one tooth to another; each leap produces a rupture in the circuit, which is closed again immediately afterwards. The musical tone given out by the plate, when we have no other means of measuring it, gives us exactly the number of times that the circuit has been opened and closed, that is to say, interrupted, in a second. I have dwelt upon these several kinds of *Rheotomes* because we frequently make use of one or the

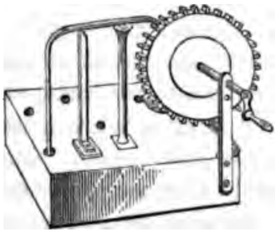

*Fig.* 131.

other of them. For the present, we shall apply them to the study of the vibratory movement experienced by magnetic bodies under the influence of discontinuous currents.

When we place a magnetic but unmagnetised body, such as iron or steel, in the interior of a bobbin, this body experiences very remarkable vibratory movements, as soon as we pass a series of discontinuous currents through the wire with which the bobbin is encircled. These movements are made manifest under the form of very decided and varied sounds, when the body has a cylindrical, or even an elongated, form. The sound is less decided, but more sharp and more *metallic*, with steel than it is with soft iron. Whatever be the form or the size of the pieces of soft iron, two sounds are always to be distinguished; one a series of blows or shocks, more or less dry, and very analogous to the noise made by rain when falling on a metal roof; these blows exactly correspond to the alternations of the passage and the interruption of the current: the other sound is a musical sound, corresponding to those which would be given by the mass of iron, by the effect of transverse vibrations. We must take care in these sounds to distinguish those that are due to the simple mechanical action of the current upon the iron,—an action which, being exercised throughout the entire mass, may deform it, and consequently produce, by its very discontinuity, a succession of vibrations. However, this is not sufficient for the explanation of all the sounds; and we must admit that there is, in addition, a molecular action, namely, that the magnetisation determines a particular arrangement of the molecules of the iron, a rapid succession of magnetisations and demagnetisations gives rise to a series of vibrations. How, for example, can we otherwise explain the very clear and brilliant musical sound given out by a cylindrical mass of iron 4 inches in diameter, and weighing 22 lbs., when placed in the interior of the large helix (*Fig.* 129.), while traversed by a discontinuous current. Rods of iron half an inch and upwards in diameter, when fixed by their two extremities, also give out very decided sounds under the same influence. But the most brilliant sound is that which is obtained by stretching upon a soundingboard well annealed wires, one or two twentieths of an inch in diameter and a yard or two in length. They are placed in the axis of one or several bobbins, the wires of which are traversed by electric currents, and they produce an assemblage of sounds, the effect of which is surprising, and which greatly resembles that to which several church bells give rise when vibrating harmonically in the distance. In order to obtain this effect, it is necessary that the succession of the currents be not too rapid, and that the wires be not too highly strained. With a wire 5 ft. 2 in. in length, and $\frac{7}{100}$ in. in diameter, I found that the maximum of effect occurs when it is stretched by a weight of from 57 lbs. to 117 lbs., if it is *annealed;* and from 64 lbs. to 126 lbs. if it is *hardened.* Beyond these limits, in proportion as the tension increases, the total intensity and the number of different sounds notably diminish; and, at a certain degree of tension, we no longer hear the sound due to the transverse vibrations, but simply that arising from the longitudinal vibrations. The reverse occurs when the wire is slackened.

Sounds entirely analogous to those we have been describing may be produced by passing the discontinuous electric current through the iron wire itself. We remark, in like manner, a series of dry blows, corresponding to the interruptions of the current; and stronger and more sonorous musical sounds, in some cases, than those that are obtained by the magnetisation of the wire itself. This superiority of effect is especially manifested when the wire is well annealed, and of a diameter of about one-twelfth of an inch; for greater or less diameters, the magnetisation by the helix produces more intense effects than those which result from the transmission of the current. Moreover, the same circumstances that influence the nature and the force of the sound in the former case, exercise a similar influence in the latter. The transmission of the discontinuous current produces sounds only when transmitted through iron, steel, argentine, and magnetic bodies in general; but in different degrees for each, depending on the coercitive force that opposes the phenomenon. Wires of copper, platinum, silver, and, in general, any metals, except the magnetic, do not give forth any sound, whether under the influence of transmitted currents, or under that of ambient currents, such as the currents that traverse the convolutions of a wire coiled into a helix around a bobbin. The sound that is produced when a discontinuous electric current is made to pass in an iron wire, explains a fact that had been for a long period observed, and had been described as far back as 1785, by the Canon Gottoin de Coma, a neighbour and a contemporary of Volta. This fact is, that an iron wire, of at least ten yards in length, when stretched in the open air, spontaneously gives forth a sound, under the influence of certain variations in the state of the atmosphere. The circumstances that accompany, as well as those that favour the production of the phenomenon, demonstrate that it must be attributed to the transmission of atmospheric electricity. This transmission, in fact, does not occur in a continuous manner, like that of a current, but rather by a series of discharges. Now, Mr. Beatson has demonstrated that the discharge of a Leyden jar through an iron wire causes this wire to produce a sound, provided it does not occur too suddenly, but is a little retarded by passage through a moist conductor, such as a wet string.

The sounds given out by iron wire and by magnetic bodies, under the circumstances that we have been describing, seem to indicate, in an evident manner, that magnetism produced by the influence of an exterior current, as well as by the direct transmission of a current, determines in them a modification in the arrangement of their particles, that is to say, in their molecular constitution. This modification ceases and is constantly produced again by the effect of the discontinuity of the current; whence results the production of a series of vibrations, and consequently different sounds.

A great number of observations, made by different philosophers, have in fact demonstrated in a direct manner the influence of magnetisation upon the molecular properties of magnetic bodies. M. de Wertheim, in an extensive work on the elasticity of metals, had already observed, that magnetisation produced by means of a helix whose wire is traversed by the electric current produces a diminution in the coefficient of elasticity in iron wire and even in steel; a diminution which, in the latter at least, remains in part even after the interruption of the current. M. Guillemin has also remarked more recently, that a bar of soft iron, fixed by one of its extremities whilst the other is free, and which, instead of remaining horizontal, is curved by the effect of its own weight, or by that of a small additional weight, immediately raises itself, when the current is made to pass in the wire of a helix with which it is surrounded, which helix is itself raised up with the bar, all the movements of which it follows, since it is coiled around it. This experiment possesses this important feature,—it shows that magnetisation determines a modification in the molecular state of iron; for it cannot be explained by a mechanical action, which could only occur if the helix is independent of the bar.

Furthermore, an English philosopher, Mr. Joule, succeeded in determining the influence that magnetisation can exercise over the dimensions of bodies. By placing a soft iron bar in a well closed tube, filled with water and surmounted by a capillary tube, he first satisfied himself that this bar experienced no variation of volume when it was magnetised by means of a powerful electric current, which traversed all the coils of an enveloping helix. In fact, the least variation of volume would have been detected by a change of the level of the water in the capillary tube; now not the slightest is observed, however powerful the magnetisation may be. This result is in accordance with what M. Gay-Lussac had discovered by other methods, and with what M. Wertheim had also obtained by operating very nearly in the same manner as Mr. Joule. But if the total volume is not altered, it is not the same for the relative dimensions of the bar, which, under the influence of magnetisation, experiences an increase in length at the same time as it does a diminution in diameter, at least within certain limits. It was by means of a very delicate apparatus, similar to the instrument employed in measuring the dilation of solids, that Mr. Joule discovered that a soft iron bar experiences a decided elongation, which is about $\frac{1}{780000}$th of its total length, at the moment when the current by which it is magnetised is established, and a shortening at the moment when it is interrupted. The shortening is less than the lengthening, because the bar always retains a certain degree of magnetism. It would appear that the lengthening is *proportional, in a given bar, to the square of the intensity of the magnetism that is developed in it.* When we make use of iron wires instead of bars, it may happen that it is a shortening and not a lengthening that is obtained at the moment of magnetisation: this change in the nature of the effect is observed when the degree of tension, to which the wire is subjected, exceeds a certain limit. Thus an iron wire, 12½ in. in length by $\frac{1}{5}$ in. in diameter, distinctly lengthens under the influence of the magnetism, so long as it is not exposed to a greater tension than 772 lbs.; but the less so, however, as it approaches nearer to this tension. Setting out from this limit, and for increasing tensions, which in one experiment were carried up to 1764 lbs., the wire was constantly seen to shorten at the moment when it was magnetised. Tension exercises no influence over highly tempered steel; so there is never any elongation, but merely a shortening, which commences when the force of the current exceeds that which is necessary to magnetise the bar to saturation.

M. Wertheim, on his part, at the close of long and minute researches, succeeded in analysing the mechanical effects that are manifested in magnetisation. He found that, when an iron bar is fixed by one of its extremities, and the bobbin is so placed that its axis coincides with that of the bar, no lateral movement is observed, but merely a very small elongation, which rarely exceeds ·00078 inch. This elongation is the greater as the bobbin is situated nearer to the free extremity of the bar; and diminishes in proportion as it approaches the point by which it is fixed. When the bar ceases to be within the axis of the bobbin, the elongation still remains; but it is accompanied by a lateral movement in the direction of the radius of the bobbin. The bobbin that was employed by Mr. Wertheim was 9·84 in. long, and

7 in. in interior diameter; glasses of a magnifying power of about 20 diameters, and containing two steel wires, were used to measure the elongation and the lateral displacement. This displacement, or, what comes to the same thing, the versed sine of the curvature of the bar, measured at its extremity, was determined for different intensities of current; and it appeared that it was in general proportional to this intensity, but it varied for each position of the bar in the interior of the bobbin. However it may be, we are able to find for each of these positions the mechanical equivalent of the unit of the intensity of the current, namely, the weight which, when applied at the extremity of the bar, would produce the same versed sine. Thus, for example, by calling the length of the part of the radius, comprised between the axis of the bar and the axis of the bobbin, D, the versed sine of the curve *f*, the weight that would produce the same versed sine P, the following results have been obtained by acting successively upon three bars of iron, the respective masses of which were 100, 40·5, and 25·5 : —

| No. of Bars. | For D = 80. | | For D = 50. | |
|---|---|---|---|---|
| | *f* | P | *f* | P |
| 1 | ·4386 feet | 98·92 grs. Tr. | ·2385 feet | 53·86 grs. Tr. |
| 2 | 3·0632 — | 41·26 — | 1·5573 — | 23·04 — |
| 3 | 1·5249 — | 22·57 — | ·9360 — | 12·55 — |

We calculate P from the formula $P = \frac{fgbc^3}{44^3}$, in which *f* is the versed sine of the curvature, *g* the coefficient of elasticity, which is 27122653 lbs. avoirdupois per square inch for soft iron, *b* and *c* the width and thickness of the bar, and L its length from its fixed point to its free extremity. From the preceding table, we deduce the value of the mechanical forces that are between them; for D = 80, as 100 : 41·71 : 22·81; and for D = 50, as 100 : 40·50 : 23·34. So we may conclude, since the masses of the three bars are together as 100 : 40·5 : 25·5, that the effect, which is here an attraction, is proportional to the mass of iron upon which the current is acting We, in like manner, find that it is proportional to the intensity of the current; which would render it an easy matter to construct upon this principle a very sensible galvanometer, by employing a prismatic bobbin and a wide and thin iron band.

Thus, all the experiments that we have been relating, lead us to recognise that there is produced, by the effect of magnetisation, a mechanical traction due to a longitudinal component and to a transverse component; that the latter becomes null when the bar is situated in the centre of the helix; that they are both proportional to the intensity of the current and to the mass of the iron.

It is a more difficult matter to verify the effect of the transmitted current than that of the exterior current, by which magnetisation is produced. In fact, in the former case, the mechanical effect of the current is very difficultly separated from its calorific effect. However, it follows, from some of Mr. Beatson's experiments, that an iron wire, at the instant it is put into the circuit, appears to undergo a small sudden expansion, and one very distinct from the dilatation that results in it, as in other metals, from the heating produced by the passage of the current.

These mechanical effects being once well studied, we can return, with greater knowledge of the cause, to the study itself of the sounds that accompany both magnetisation and the transmission of currents.

M. Wertheim has in a perfectly accurate manner verified the existence of a longitudinal sound in an iron or steel bar when placed in the centre of helices traversed by discontinuous currents. This sound, which is similar to that produced by friction, is due, as is proved by direct experiment, to vibrations actually made in the direction of the axis. With wires substituted for bars, the effects are the same, except that, when the tension diminishes, we hear, in addition to the longitudinal sound, a very peculiar metallic noise, which seems to run along the wire, as well as other peculiar noises. With transmitted currents we also hear the longitudinal sound: and it remains nearly the same in intensity whether the current traverses only a part of the bar, or traverses the whole; a proof of the analogy existing between the action of the transmitted current and that of any other mechanical force, such as friction; equally a proof that the sound is not due to vibrations of a particular kind, engendered by the current. The longitudinal sound occurs equally in bars and in wires; but when we operate with wires, if they are not well stretched, the longitudinal sound is accompanied by the divers noises of which we have spoken. In fine, whether with bars or wires, every time the current is transmitted, but only in the parts where it passes, we hear a dry noise, a crepitation similar to that of the spark, and which is transformed into a distinct sound only in the stretched portion, if it is a wire that is in the circuit.

Such are the facts established by M. Wertheim's researches: they are of a nature to confirm the deduction I had drawn before him from the simple study of the sonorous phenomena, namely, that magnetisation on the passage of the electric current produces a molecular derangement in magnetic bodies, and that the sounds arise from the oscillations that are experienced by the particles of bodies around their position of equilibrium, under the influence of currents, whether exterior or transmitted. But what now is the nature of this molecular derangement? and how is it able to determine both the mechanical effects and the sonorous effects that we have described?

When the action of exterior currents is in question, we may form a tolerably exact idea of the nature of the molecular derangement brought about by magnetisation. For this purpose, we have merely to refer back to the experiment in which either fragments of wire or iron filings are placed in the interior of a helix whose axis is vertical. As soon as the current is made to pass through the wire of this helix, the fragments of iron wire all place themselves parallel to the axis, that is to say, vertically, and the filings arrange themselves in small elongated pyramids in the direction of the axis, which destroy themselves and rapidly form again when the current is intermittent. The action of the helix, therefore, upon filings consists in grouping them under the forms of filaments parallel to the axis, filaments which gravity alone prevents being as long as the helix itself. This experiment succeeds equally well with impalpable powder of iron as with filings; it succeeds equally well with powder of nickel and cobalt. Only if the current that traverses the helix is discontinuous, very different effects are observed with each of these three metals—effects that depend, as to their particular nature, upon the greater or less number of interruptions which the current experiences in a given time. The pyramids of filings are at their maximum of height when the disc that sustains them is in the middle of the helix. They turn under the influence of discontinuous currents, providing the succession of these currents is not too rapid, so that there are not more than 60 or 80 in a second. With 160 there is no longer any effect. These differences are indirectly due to the fact, that the softest iron has still some coercitive force, and that it requires a certain time for magnetising and demagnetising. By comparing under this relation *iron, nickel*, and *cobalt*, all reduced to an impalpable powder, and prepared by hydrogen, we find that nickel still manifests movements for a velocity of succession of currents, at which iron ceases to manifest any; and that cobalt, on the contrary, ceases to manifest them before iron, which is quite in accordance with what we know of the coercitive force of these three metals.

The following is an experiment of Mr. Grove's, which demonstrates in an elegant manner this tendency of the particles of magnetic bodies to group themselves, under the influence of magnetisation, in a longitudinal or axial direction. A glass tube, closed at its two extremities by glass plates, is filled with water holding in suspension fine powder of a magnetic oxide of iron. On looking at distant objects through this tube, we perceive that a considerable proportion of the light is interrupted by the irregular dissemination of the solid particles in the water. But, as soon as an electric current traverses the wire of a helix, with which the tube is surrounded, the particles of oxide arrange themselves in a regular and symmetrical manner, so as to allow the larger proportion of the light to pass. The particles in this case are not small fragments of iron wire, artificially disaggregated from a more considerable mass, but iron precipitated chemically, and consequently in its natural molecular state, such as constitutes a solid body by its aggregation.

This disposition of the particles of iron and of magnetic bodies to approach each other in the transverse direction, and to extend in the longitudinal direction, under the influence of an exterior magnetisation, which is probably due to the form of the elementary molecules and to the manner in which they are polarised, is now established in an irrefragable manner by direct and purely mechanical proofs.

It is easy to see that it accounts in the clearest manner for the production of sound in a bar or a wire subjected to the influence of the intermittent current of the helix. The particles contending against cohesion arrange themselves in the longitudinal direction when the current acts, and return to their primitive position as soon as it ceases: there follows from this a series of oscillations, which are isochronous with the intermittence of the current. All these effects are much more decided in soft iron than in steel or hardened iron, because the particles of soft iron are much more mobile around their position of equilibrium.

I have also remarked that both iron and steel, when they are already magnetised in a permanent manner by the current transmitted through a second helix, or by the action of an ordinary magnet, do not experience such strong vibrations when the discontinuous current tends to magnetise them in the direction in which they are already magnetised, but stronger ones in the contrary case. It is evident that, in the former case, the particles already possess, in very nearly a permanent manner, the position that the exterior action to which they are submitted tends to impress upon them; while, in the latter case, they are farther removed from it than they are in their natural position. Much more powerful oscillations, therefore, ought to occur to them around their position of equilibrium in the latter case, and less powerful in the former, than when they are in their normal position, at the moment when the discontinuous current exercises its action.

The effects of the transmitted current are due to an action of the same order, but acting in a different direction. In order to analyse this action well, we must study the distribution of iron filings around a wire of iron, or of any other metal traversed by a powerful electric current. These filings always place themselves so as to form lines perpendicular to the direction of the current, and consequently parallel to each other. This is very readily perceived by fixing the conducting wire in a groove formed in a wooden plank, covered with a sheet of paper, upon which the filings are placed. The latter arrange themselves transversely above the wire, whatever be the manner in which it is curved, forming small filaments of the sixth or eighth of an inch in length, which present opposite poles at their two extremities. When the conducting wire is free, these filaments, instead of remaining rectilinear, join together by their two edges and envelope the surface of the wire, forming around it a closed curve, like a species of envelope composed of rings, that cover each other and are pressed against each other. Now, the arrangement assumed by the particles of iron filings round any conducting wire, as well iron as every other metal, when it transmits a current, ought to be in like manner assumed by the molecules of the very surface of a soft iron wire itself traversed by a current, under the influence of the current transmitted by the entire mass of the wire. This also is equally demonstrated by the mechanical effects studied by Joule and Beatson. It follows, therefore, that when the transmitted current is intermittent, the particles of the surface of the iron wire oscillate between the transverse position and their natural position, and that there is consequently a production of vibrations. These oscillations ought to be the more easy, and consequently the vibrations more powerful, as the iron is softer: with hardened iron, and especially with steel, there is a greater resistance to be overcome; thus the effect is less sensible. If the wire that transmits the discontinuous current is itself traversed by a continuous current, moving in the same direction as the discontinuous one, the oscillatory movement ought to be annulled, or at least notably diminished, since the transmission of the continuous current impresses upon the particles in a permanent manner the position which the passage of the discontinuous current tends to give them in a temporary manner. Thus the sound in this case would completely disappear, or notably diminish. If the wire is of steel, or of well hardened iron, the continuous current is on the contrary favourable, by its presence, to the oscillating action of the discontinuous current, because it deranges the particles from their normal position, without, however, being able completely to impress upon them the transverse direction on account of the too great resistance they oppose to a displacement, which is easily brought about in soft iron. The two currents united produce what a single current would not be able to accomplish, or would accomplish less effectually, and the sound is then reinforced, as is proved by experiment.

In support of the explanation that I have just given, I have found that a copper wire, with a thin envelope of iron which is contiguous to it, gives rise to the same effects, and of nearly the same intensity, when the discontinuous current traverses it, as if it were entirely of iron; the sound is merely less musical; it resembles that which M. Wertheim designated under the name of "metallic" (*iron-y, feraille*). As this result might be attributed to a part of the current traversing the iron envelope itself, instead of circulating exclusively through the copper wire, I insulated the latter by means of a thin covering of silk or wax, so that the iron cylinder that surrounds it is not able to communicate metallically with the copper. The effect is exactly the same as in the preceding case, that is to say, the discontinuous current that traverses the copper wire determines a series of vibrations in the iron envelope, which proves that we may admit that the same effect is produced upon the surface of an iron wire, which itself transmits the current. With regard to the envelope, we can easily prove that it experiences a transverse magnetisation, when the copper wire is in the voltaic circuit; for, if we make in it a small longitudinal groove, we perceive that the iron filings are attracted upon its two edges, which have also an opposite polarity.

The detailed explanation that we have given of the molecular phenomena, which, in magnetic bodies, accompany the action of currents both exterior as well as interior, finds a further confirmation in the observation of several facts of different kinds. Thus I have remarked that permanent magnetisation, whether impressed upon a soft iron rod by the action of an enveloping helix, or by the action of a powerful electro-magnet, increases, in a very decided manner, the intensity of the sounds that are given out by this rod, when traversed by a discontinuous current. This reinforcement is in fact evidently due to the conflict that is established between the longitudinal direction that is impressed upon the particles of iron by the influence of the magnetisation, and the transverse direction that the passage of the current tends to give to them. The oscillations of the particles ought necessarily to have greater amplitude, since they occur between more extreme positions. The effect is more decided with soft iron rods than with those of steel, and especially tempered steel. Mr. Beatson arrived at a similar result by quite another method. He observed, that if a continuous current traverses a wire, and if, at the same time, it is subjected to the action of a helix in which a discontinuous current is passing, the wire will undergo a series of contractions and expansions which become inappreciable, if the continuous current ceases to be transmitted, even when the helix continues to act in the same manner. The author drew from this the same conclusion that I had deduced from the sonorous effects, namely, that the action of the helix impresses upon the particles of iron an opposite state to that which is produced by the transmitted current, and that one of these actions has the tendency to invert the arrangement which the other tends to establish.

A very curious fact is that magnetisation tends to impress upon the particles of soft iron an arrangement similar to that which they possess in tempered steel, even before it is magnetised. What confirms the correctness of this remark is, that the sound which magnetised soft iron gives out under the action of the transmitted current, is not only more powerful than it is when there is no magnetisation, but it also acquires a peculiar dry tone, which makes it resemble that which steel gives out without being magnetised.

The very remarkable influence of tension, which, beyond a certain limit, diminishes in soft iron wires their aptitude to give sounds, is a further consequence of our explanation. In fact, the molecules, by the effect of tension, undergo a permanent derangement in their normal position, and are consequently found crippled in their movements, and are no longer able, under the influence of exterior or interior causes, to execute the oscillatory movements, and consequently the vibrations which constitute the sound.

Two facts, of a character altogether different from the preceding, still further show that the magnetisation of iron is always attended by a molecular change in its mass. The first of these facts was discovered by Mr. Grove. It is, that an armature of soft iron experiences an elevation of temperature of several degrees when it is magnetised and demagnetised several times successively by means of an electro-magnet, or even of an ordinary magnet set in rotation in front of it. Cobalt and nickel present the same phenomenon, but in a somewhat slighter degree; whilst non-magnetic metals, placed under exactly the same circumstances, do not present the slightest traces of calorific effects. This experiment can only be explained by admitting that the development of heat arises from the molecular changes which accompany magnetisation and demagnetisation. The second fact, which is no less important, is due to Dr. Maggi of Verona, who proved that a circular plate of very homogeneous soft iron conducts heat with more facility in one direction than in the other, when it is magnetised by a powerful electro-magnet; whilst, when it is in the natural state, its conductibility is the same in all directions, and, consequently, perfectly uniform. The plate is covered with a thin coating of wax melted with oil, and the heat arrives at its centre by a tube that traverses it, and in the interior of which the vapour of boiling water is passing. The plate is placed horizontally on the two poles of a powerful electro-magnet, several insulating cards preventing contact between it and the iron of the electro-magnet. So long as it remains in its natural state, the curves that bound the melted wax assume the circular form, which indicates a uniform conductibility for heat in all directions. But, as soon as the electro-magnet is magnetised, the curves are deformed; and they are always elongated in a direction perpendicular to the line that joins the magnetic poles; which proves that the conductibility is better in the direction perpendicular to the magnetic axis than in the direction of the axis; a result in accordance with the fact that we have established, that the particles of iron approach each other, by the effect of magnetisation, in the direction perpendicular to the length of the magnet, and recede in the direction of that length, which is always the magnetic axis.

### *Influence of Molecular Actions upon Magnetism produced by Dynamic Electricity.*

We have seen that heat, tension, and mechanical actions generally facilitate magnetisation.* M. Matteucci has found that torsion and percussive and mechanical actions, not only facilitate the magnetisation produced upon soft iron by a helix that is traversed by a powerful current, but they also contribute, when the current has ceased to pass, to the destroying the magnetism in a very rapid manner. The same philosopher has likewise observed, that torsion, when it does not pass beyond certain limits, augmented the magnetisation produced upon steel needles by discharges of the Leyden jar.

M. Marianini, who has made numerous and interesting researches upon magnetisation, arrived at curious results upon the aptitude that iron bars may acquire of becoming more easily magnetised in one direction than in another, and even in being little or much magnetised by the influence of the same cause. When an iron bar has been magnetised by

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* M. Lagerhjelm observed that iron becomes strongly magnetic by rupture.

the influence of an instantaneous current that circulates around it, and when it has lost this magnetisation by the action of a contrary current, it is more apt to be magnetised afresh in the former case than in the latter. We are able, by contrary currents, to give it even more aptitude to be magnetised in the latter direction than in the former. The augmentation of aptitude that it acquires of being magnetised in one direction is equal to the loss of aptitude that it experiences for being magnetised in the other direction. But, by reiterating the action of the currents upon the same bar, the increase of aptitude in one direction, and the corresponding diminution in the other, become always more and more feeble. The modifications of aptitude for acquiring magnetisation are accompanied by modifications in the aptitude for losing this magnetisation; but in such direction that the latter is the reverse of the former.

Willing to enter more deeply into the study of the effects that we have been relating, M. Marianini subjected iron to different physical and mechanical actions. First of all, he satisfied himself that neither elevation of temperature, nor especially the cooling by which it is followed, neither percussion nor torsion, nor a violent shock, nor any mechanical action, even the most energetic, are able of themselves to determine magnetisation; nor, indeed, does the discharge of a Leyden jar through an iron bar magnetise it. But these various operations, incapable of magnetising, may all serve to destroy the polarity of magnetised bodies; the quantity of magnetic force that they thus lose, when their aptitude has not been altered, is the greater as the magnetisation has been more feeble. But if, after having undergone one of these actions, the bar has still preserved a little magnetism, it can no longer lose it by this or by any similar action.

What is very remarkable is, that when the magnetism of a bar has been destroyed, on remagnetising it in a contrary direction by a succession of instantaneous currents, so that its magnetisation is null, we may restore to it its former magnetism by means of a violent shock, — by letting it fall, for instance, on the pavement from the height of a couple of yards. The greater the height of the fall, the more powerful is the magnetism it recovers. Thus, a bar, that made a needle deviate 60°, having been brought by a succession of discharges to exercise no deviation beyond 0°, gave 14° on falling from a height of 12·8 ft., 15° 30′ on falling from a height of 15·0 ft., and 21′ on falling from a height of 6·4 ft. This new polarity was in the same direction as the primitive one.

Even when, by destroying the primitive magnetisation of the bar, we have actually imparted to it a new one in a contrary direction, we find, on letting it fall upon the pavement, that we restore to it the first that it possessed. M. Marianini would be disposed to believe, from this experiment and other similar ones, that the bar had retained its former magnetisation while still acquiring the contrary one, which neutralised the effect of the first, and even surpassed it; and the shock merely destroyed the second, either in whole or in part, which permitted the former to reappear. Flexion, friction, heat, or an electric discharge traversing the iron directly, may take the place of the shock, particularly when very fine wires are in question.

The action that is exercised by an instantaneous discharge through the wire of a helix upon a body already magnetised, increases or diminishes the magnetism of this body according to the direction in which it is sent; but this increase or diminution is the less sensible as the iron is more magnetised. In any case, a given instantaneous current produces proportionately more effect when it is made to act with a view of diminishing the polarity in the magnetised bodies than when it is made to act with a view of increasing it.

M. Marianini, in order to explain the results of these experiments, admits a difference between what he calls *polarity* and *magnetism*. Thus, the same magnet, although deprived of polarity, may very readily retain magnetism, when magnetised at one time in two contrary directions with an equal force. We must then suppose that contrary magnetic systems, producing equilibrium, are able to exist in iron, and that exterior forces, such as a current or a mechanical action, do not act with the same energy upon the opposite systems.

This opinion, which does not as yet appear to us to rest upon facts sufficiently numerous, has, however, nothing in it that is inadmissible; nothing, in fact, opposes there being in the same bar a certain number of particles, arranged so as to produce a magnetisation in a certain direction, and others so as to produce magnetisation in the opposite direction; as, for example, the interior particles may be found to have in this respect an arrangement the opposite of those on the surface; and that such exterior action operates proportionately with greater force upon the one than upon the other. This point would need to be made clear by further observations, and especially by comparative experiments made upon bars of different forms and different dimensions; upon hollow and solid cylinders, for example.

But if some doubts still remain upon the conclusions that M. Marianini has drawn from his experiments, there are not any upon the new proof which they bring in favour of the connection that exists between magnetic and molecular phenomena. The different degrees of aptitude acquired by iron under the influence of certain actions, of becoming more easily magnetised in one direction than in the other, are all quite in harmony with the disposition with which the particles of bodies are endowed, to arrange themselves more easily in one direction than in another. This loss of aptitude, after the multiplied repetition of the contrary actions, corresponds with the indifference to arrange themselves in one manner or the other, which is finally presented by the particles of bodies, after having experienced numerous derangements in different directions.* Finally, the remarkable effects of shock, flexion, heat, in fact, of all those actions that change the relative position of the particles, come in support of the relation that we have endeavoured to establish.

The whole of the magneto-molecular phenomena that we have been studying, lead us to believe that the magnetisation of a body is due to a particular arrangement of its molecules,

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* We have a remarkable example of this in the fragility presented by iron, when it has been for a long time subjected to rapid and frequent vibrations, as are the axles of locomotives.

originally endowed with magnetic virtue; but which, in the natural state, are so arranged, that the magnetism of the body that they constitute is not apparent! Magnetisation would therefore consist in disturbing this state of equilibrium, or in giving to the particles an arrangement that makes manifest the property with which they are endowed, and not in developing it in them. The coercitive force would be the resistance of the molecules to change their relative positions. Heat, by facilitating the movement of the particles in respect to each other, diminishes, as indeed does every mechanical action, this resistance, that is to say, the coercitive force.

There remains an important question to be resolved. Are mechanical or other actions—disturbers as they are of the electrical state—able of themselves to give rise to magnetism? or do they only facilitate the action of an exterior magnetising cause, for example, terrestrial magnetism, which, in the absence of all others, is ever present? M. Marianini's researches would seem to be favourable to the latter opinion: however, the facts that are known do not appear to us sufficient as yet to establish it in an incontestable manner. Let us remark that, even although it should be established, yet the non-existence of a previous and proper polarity of magnetic bodies, or of electric currents, circulating around them in a determinate direction, would not necessarily follow. We should merely conclude from it that, in the absence of an exterior acting cause, the particles, when left to themselves, constantly arrange themselves so as to determine an equilibrium between their opposed polarities; whence results the nullity of all exterior action.

# CHAP. IV.

## GALVANOMETER-MULTIPLIERS.

### *Electro-magnetic Galvanometers.*

WE have pointed out, in the First Part of this work, that we may make use of the calorific and chemical properties of the voltaic current in order to measure its intensity; and we have also given certain details of galvanometers, founded upon these properties. But the action exercised by a current upon a magnetised needle has furnished a means in every respect far superior to the preceding, for determining the existence and appreciating the force of an electric current. This action, in fact, is the only one that is general, that is to say, which always, and in all cases, accompanies the presence of dynamic electricity, whatever be the nature of the circuit and the feebleness of this electricity; whilst the other actions occur only when the circuit contains a conductor capable of manifesting them, and when the current is endowed with a certain energy. Furthermore, the electro-magnetic effect of the current is instantaneous, whilst the electro-chemical effect must necessarily endure for a certain time, in order to be appreciated; and, though the calorific action is equally instantaneous, it possesses the inconvenience of not giving the direction of the current, whilst this direction is indicated in the most prompt and decided manner by the direction of the deviation of the magnetised needle.

We have seen that a conductor traversed by a current placed *above* a needle, but very near to it, and parallel to its axis, makes this needle deviate to the east or to the west, according as it is moving in a direction from north to south, or from south to north. If it is *below*, it makes it deviate to the east, when it is moving in the direction from south to north, and to the west when it is moving in the direction from north to south. It follows from this, that, if the conductor that transmits the current, passing first above the needle, is bent so as to return below, and so to form two parallel branches, between

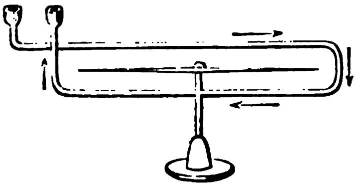

*Fig.* 132.

which the needle is suspended (*Fig.* 132.), the current, that traverses the upper branch, tends to make the needle deviate in the same direction as the current that traverses the lower one, precisely because it has in the former a contrary direction to what it has in the latter. By thus arranging the wire by which the current is transmitted, we obtain an action upon the needle twice as powerful as if, being retained rectilinear, instead of being bent, it had acted only above or below. But, instead of bending it once only, we may bend it twice, which doubles the effect; three times, which trebles it; in a word, we can cause the wire to make a very great number of convolutions, and can so multiply by a considerable quantity the action of the current upon the magnetised needle. It follows from this that a very feeble current, whose action would be scarcely sensible if the wire by which it is transmitted made but one convolution, is able to exert a very marked action when the number of convolutions becomes considerable. This apparatus has therefore been named the *galvanometer-multiplier.* It is also sometimes called, and rightly so, the *Rheometer*— measurer of a current. It is to a German philosopher, M. Schweigger, that we owe the original idea of the galvanometer-multiplier.

In order to construct it, we take the precaution to employ a copper wire covered with silk, so that the different convolutions may be juxtaposed and superposed, without there being a direct metallic communication from one convolution to the other, and so that the current may thus traverse the wire in all its length. We coil the wire round a wooden or metal frame, solidly fixed upon a stand, and which leaves between its lower and upper surface the smallest possible space; it is in the interior of this space that the magnetised needle is suspended: the two ends of the wire, which are carefully deprived of the silk that covers them, serve to place the galvanometer, that is to say, the wire of the instrument, in the circuit (*Fig.* 133.). At the moment when a circuit is thus closed, providing that a current is propagated in it, we see the needle move; the direction in which it moves indicates the *direction* of the current, the *presence* of which is detected by this movement; and the number of degrees, or the size of the arc of deviation, enables us to appreciate its *intensity*.

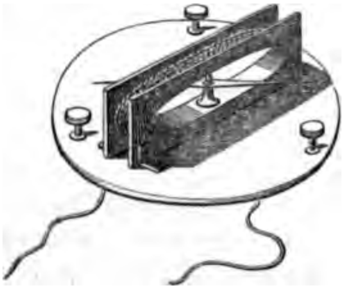

*Fig.* 133.

### *Nobili's Galvanometer-multiplier.*

In order to increase the sensibility of the galvonometer-multiplier, M. Nobili conceived the ingenious idea of neutralising the directive force of terrestrial magnetism, which tends, in opposition to the action of the current, to maintain the needle in its normal direction, or to bring it back to it, by employing, instead of a single magnetised needle, two needles that are fixed parallel to each other, the reverse poles facing each other at the extremities of a small rod of straw or metal, which passes through their centres of gravity. One of the needles is placed within the frame and the other without; so that, as may be easily seen, the deviation which the current tends to impress upon the former accords with that which it produces upon the latter, the position of the poles being in the one the reverse of what it is in the other; for, if they had their homogeneous poles turned on the same side, they would on the contrary deviate in opposite directions, the one being above and the other below. Thus, there follows from the addition of this second needle, a considerable increase in the sensibility of the apparatus. It is necessary that the two needles should be as similar as possible; they are suspended to a cocoon filament fixed to the upper extremity of the small stem by which they are united. If they had exactly the same magnetic force, this system would be *astatic;*—that is to say, would not experience any directive action on the part of the earth, and would remain in equilibrium in all azimuths. It would be a difficult matter to obtain this result: moreover, it is necessary that the system of two needles should have a slight directive force, in order to be able to assume a determinate position; and that, consequently, one of the needles should have a little more powerful magnetism than the other.

We must be careful, in the construction of the galvanometer, to choose a copper wire as much deprived of iron as possible, which is not always easy; in this respect copper, not brass, is preferable. With regard to the dimensions of the wire, they depend upon the kind of circuit into which it is to be introduced. If it is a circuit whose conductibility is imperfect, which contains liquids, for example, it is advantageous to have a long and consequently a fine wire, in order that its convolutions may be as near as possible to the needle; in fact, the introduction into the circuit of such a wire as this does not sensibly modify its conductibility. But, if the circuit is a good conductor, all metallic, for example, the current would be too much enfeebled by the addition of a long and fine wire, and more would be lost by this cause of weakness than would be gained by the increase of sensibility of the apparatus, resulting from a more considerable number of convolutions. It would be better in this case to employ a shorter wire and one of larger diameter. We shall have occasion, in a more general manner, to treat upon this question, which is connected with

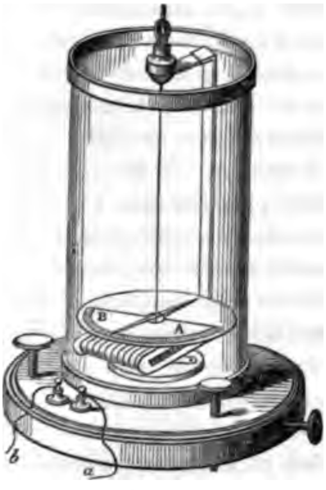

*Fig.* 134.

the propagation of dynamic electricity, in the Fourth Part of this work. For the present, we shall confine ourselves to describing Nobili's galvanometer-multiplier (*Fig.* 134.), remarking that, according to the purpose to which it is proposed to be applied, the dimensions and the number of the convolutions of the wire must be varied; and, if we have not beforehand a very decided object in view, it is well always to have two instruments at command, one with a short wire, the other with a long one.

First, the following are the dimensions of the frame:—The width is 1 inch, and its length $1\frac{3}{4}$ in. The opening in the upper part is $\frac{1}{4}$ in. The external height between the two horizontal cheeks is $\frac{1}{4}$ in., and the interior length between the two vertical sides is 2 in. It is within this interior and vacant space, 2 in. long by $\frac{1}{4}$ in. high, that the lower needle moves. The upper needle is situated above the frame, but as near as possible to the wires that are coiled around it. The silk-covered wire is less than $\frac{1}{130}$ in. in diameter; and it makes 800 convolutions around the frame. The needles are two ordinary sewing needles $1\frac{1}{2}$ in. in length, and magnetised to saturation. They are placed parallel to each other, with the reverse poles facing, at a distance of $\frac{3}{4}$ in., and are fixed at each of the extremities of two small copper wires twisted upon each other. The suspension thread is a doubled thread of the cocoon, from 4 to 6 inches in length. The frame is placed upon a movable support, which enables us to give it all possible positions in respect to the needles. With this view it is fixed upon a pivot, which turns upon its axis by means of a wheel and pinion, that is made to move at pleasure, in one direction or another, by means of an external knob. In order that this movement of the frame may be executed, it is necessary that the two ends of the silk-covered wire should have sufficient length from the point where they quit the frame, and that to which they are fixed upon the frame of the instrument.

The cocoon filament is suspended to a bracket stem, and by means of a small drum moved by a wheel, the two-needle system may be made to descend or to ascend by insensible degrees, so as to be placed exactly at the height required. A circular division, whose centre exactly coincides with the prolongation of the suspending thread, is placed above the frame and the wires by which it is surrounded. It is upon this division that the upper needle indicates the degrees of deviation. We generally adjust to one of the ends of this needle a fragment of very fine bristle, which points out the degrees of deviation upon the divided circle, the dimensions of which may thus be rendered much greater. With regard to the needles, whatever precautions are taken that the system formed by them shall be astatic, there nevertheless remains to this system an appreciable directive force, which does not prevent the apparatus possessing a great degree of sensibility. If the directive force is too great, it is diminished by a process pointed out by M. Nobili himself. We discover which of the four poles of the needle has the most magnetism; we remove from it a portion by touching it slightly with the opposite pole of a bar feebly magnetised, and we continue this until the system moves out of the magnetic meridian in order to approach more or less the position perpendicular to this meridian. We then make the system oscillate, and judge from the number of oscillations in a given time if the action of the terrestrial magnetism is sufficiently diminished. As we have already mentioned, we must leave to the system only just as much directive force as is necessary to maintain it in a fixed position, in order that it may abandon this position under the action of the most feeble current. This is the principal cause of the sensibility of the apparatus: we must therefore use every effort to attain to it.

The instrument is covered with a bell-glass, the upper part of which is pierced with a hole, that allows a passage to the knob by means of which the toothed rod carrying the cocoon filament may be lowered or raised.

The galvanometer-multipliers differ from each other only in the dimensions of the silk-covered copper wire; there are some whose very fine wire makes more than one or two thousand convolutions, as also there are some, the larger wire of which makes only a few convolutions: a wire $\frac{1}{40}$th in. in diameter, making thirty convolutions, is the type of a short wire galvanometer.

The insulation of the convolutions is a condition of importance to be well fulfilled; for if the electric current, instead of traversing all the convolutions of the wire, should pass laterally from one layer to the other, the effect, if not totally annulled, would be at least singularly weakened. This insulation is not always so easy to be obtained as may be imagined; it is necessary that the silk by which the wire is covered should be very closely packed, and should form a tolerably thick envelope. These precautions are especially necessary when we wish to detect, by means of a galvanometer, the electric current resulting from the discharge of the conductor of an electrical machine or Leyden jar. M. Colladon, who was the first to succeed in making a magnetised needle deviate by the action of this current, employed a galvanometer of at least 500 or 1000 convolutions, the wire of which was doubly covered with silk, and each series of convolutions was separated from the following one by gummed silk. Without this double precaution the electricity would easily pass from one convolution to another. In order to obtain the action of the electricity of a machine upon the needle of a galvanometer, M. Colladon, after having put one of the ends of the wire in communication with the cushions of the machine, brought the other, which was terminated by a fixed point and held by an insulating handle, to different distances from the conductor, in order to draw off the positive electricity. At four inches distance the deviation was 18°, at eight inches it was not more than 10°, and at thirty-nine inches it was still 2°.

It is easy, as may be understood, to determine the direction of the current by which a galvanometer is affected, when we know the direction in which the wire is wound around the frame, and know the position of the poles of the two magnetised needles. In fact, in like manner as when we know the direction of the current, we are able beforehand to determine the direction of the deviation of the needle, so also, when knowing the direction of the deviation, we may conclude from it the direction of the current. For this purpose, we have only to apply the law that was discovered and formularised by Ampère. But it is shorter and more convenient to obtain this determination by a direct experiment, by making one of the ends of the wire of the instrument communicate with a small plate of zinc, and the other with a plate of copper or platinum: these two plates are plunged in water, and we then take notice of the direction in which the upper needle deviates, recollecting that the current which produces this deviation goes from the copper to the zinc through the wire of the galvanometer: this will in like manner be the direction of every current that shall bring about a deviation in the same direction; whilst every current that shall bring about a deviation in the contrary direction will have an opposite direction. In order to avoid the tedium of frequently repeating this testing, we mark a letter, the letter *a* for example, on the foot of the instrument, at the place where one of the ends of the galvanometer wire terminates, and the letter *b* at the place where the other terminates; then the letter A upon the side of the circular division toward which the north point of the upper needle turns when the current enters by *a*, and the letter B on the side toward which the same point turns when the current enters by *b* (*Fig.* 134.). It must not be forgotten that care is to be taken to turn the movable frame of the instrument, so that the system of wires is perfectly parallel with the direction that the magnetised needles naturally assume, and that the north pole of the upper needle be situated between A and B.

A very important precaution is not to act upon a galvanometer with a current too powerful for the instrument; for the action of such a current would risk modifying the magnetism of the needles, either by diminishing the intensity or even by inverting it: the sensibility of the galvanometer is thus greatly altered, and we run the risk of afterwards committing errors, either in regard to the force or to the direction of the currents that we may desire to appreciate.

It even frequently happens that the needle of a galvanometer, by remaining for a certain time under the influence of a current that is not very powerful, undergoes a modification in its magnetism. The magnetic axis, as Peltier has observed, by obeying the action of the current, which tends to place it perpendicularly to its proper direction, recedes from the axis of the form of the needle. It follows that, as this axis makes a greater angle with the magnetic meridian, the needle is solicited with greater force by terrestrial magnetism, which establishes a new equilibrium between the two contrary actions,—the terrestrial magnetism, that tends to bring back the needle to 0°, and the current, that tends to drive it to 90°. Some moments after the circuit has been broken, the magnetic axis of the needle returns to its primitive position. Thus a constant current makes the needle deviate 50°: at the end of ten minutes, the needle approaches towards the 0°, and stops at 49°, or even at 48°; the circuit is broken, and the needle is left free for a minute only: it is subjected anew to the action of the current; the primitive 50° are again obtained, although care has been taken during the repose of the galvanometer to keep the circuit closed, so as not to change anything in the circumstances of the experiment,—a proof that the effect is entirely due to a derangement of the magnetic axis, and not to a weakening of the current.

### *Differential Galvanometer.*

When we desire to compare the relative force of two currents, it is very convenient to make use of the differential galvanometer (*Fig.* 135.). This name is applied to a galvanometer formed of two wires, perfectly equal in length and in diameter, and of the same nature, in a word, perfectly similar, which are wound simultaneously round the frame, and which are similarly situated in respect to the needles, so that when opposite and equal currents are made to pass through each of them, the needles remain at zero, that is to say, they experience no deviation on account of the two equal and contrary actions to which they are exposed. But if the system of needles is moved, the direction in which the deviation occurs indicates that one of the currents is more powerful than the other, and also indicates which it is that is the more powerful. The amplitude of this deviation enables us to appreciate approximately how much more powerful it was.

Such a galvanometer as this possesses also the advantage of being able to serve as either a long or a short wire galvanometer. In fact, as there are two wires, there are four ends terminating at the foot of the instrument. Let *a* and *b* be the two extremities of the former wire, and *a′* and *b′* those of the latter. When we desire to have a long wire galvanometer, we connect, by a small metal arc, the extremity *b* of the former wire with the extremity *a′* of the latter, in such a manner that the current, entering for example by *a*, and coming out by *b′*, traverses successively and in the same

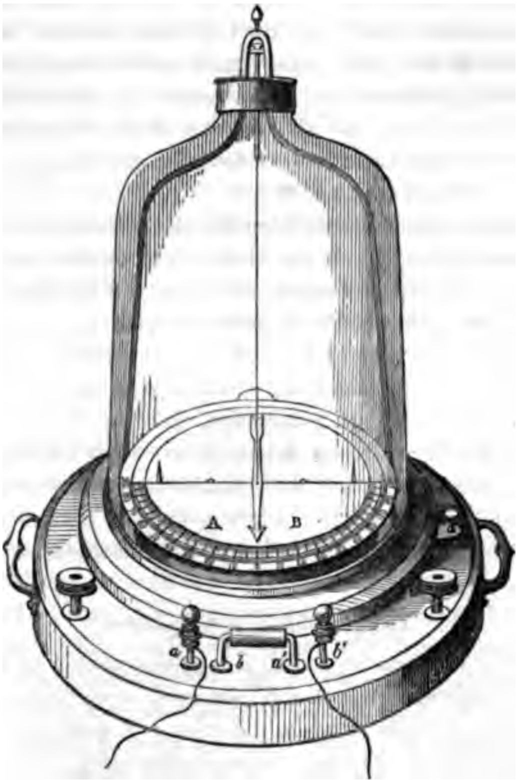

*Fig.* 135.

direction both the wires *a b* and *a′ b′*. When we wish to have a short and thick wire galvanometer, we connect by a metal arc *a* and *a′*, and do the same for *b* and *b′*; we make the current enter by the two united ends (*a* and *a′*), and come out by the two others (*b* and *b′*); so that it traverses simultaneously the two wires in the same direction, which amounts to the same thing as if it traversed only one of the same length as one of them, and of double the sectional area. Finally, by using but one of the wires, namely, by making the current enter by *a* and come out by *b*, or else enter by *a′* and come out by *b′*, we have a galvanometer of short and fine wire. The same instrument may thus fill the office of three galvanometers at the same time that it serves the purpose of a differential galvanometer. The letters A and B marked on the frame, indicate that the current enters by *a* or *a′* if the north pole of the upper needle deviates towards A, and by *b* or *b′* if it deviates towards B.

*Fig.* 135. represents a differential galvanometer, constructed of large dimensions, on account of the facility we have of seeing its indications from a distance. With this view, the upper magnetised needle is covered with a long and very light slip of fine whalebone cut into the form of an arrow, which, by moving over a white frame upon which the divisions are traced, is extremely visible. This instrument is very sensible; for, on placing two very clean plates of platinum, communicating with the ends of the wires, the one under the tongue and the other over, we obtain a current capable of producing a deviation of several degrees.

### *Comparable Galvanometers.*

We have hitherto regarded the galvanometer as an instrument fitted for detecting the presence of even the most feeble current, and of indicating its direction; it now remains to us to examine how it may determine its intensity.

This intensity may be appreciated approximately by means of the amplitude of the deviation; but it is far from being proportional to it, at least on as far as 90°; although from 0° to 20° we may, without sensible error, as experiment has proved, admit this proportionately; so that a current that produces a deviation of 12° has a double intensity to that which produces a deviation of only 6°, and triple of that which produces one of only 4°, and so on.

The most simple means for determining in a galvanometer the relation existing between the forces and the angle of deviation, is to roll around the frame several wires independently of each other, placed similarly in respect of the needles, and to pass the current first through one, then through two, then through three, and so on; so that we thus act upon the needle with forces as 1, as 2, as 3, &c. It is merely necessary that the wires be sufficiently large and not too numerous, so that the current, in traversing them all successively, does not experience any sensible diminution in intensity by the effect of their resistance of conductibility. By operating in this way, we may satisfy ourselves that just below 20°, and for stronger reasons beyond it, the deviations are no longer proportional to the force of the current, but proportionately less considerable.

Beyond a limit which cannot surpass 20°, and which frequently does not attain to that, there are two circumstances which prevent the intensities of the currents being proportional to the angle of the deviations. One is, that the directive force of the globe, which, by tending to bring back the system of needles into the magnetic meridian, produces equilibrium with the force of the current that moves it from it, is proportional not to the angles, but to the sines of the angles of deviation; and that from about 20° the difference between the arc and its sine, which was but little sensible until then, becomes too considerable to permit of their being taken indifferently for each other. The second circumstance is, that as soon as the needle or the two needles recede from the magnetic meridian in which they are naturally retained, and in which the movable frame is to be placed, so that they may be parallel to the wires, their position in respect to these wires is no longer the same; and, consequently, the currents can no longer act upon them in the same manner. It is easy to see that if, in the normal position, that in which the wires are parallel to the needles, the force possesses its whole intensity, as soon as there is a deviation from the meridian it acts only by a component less in proportion as the angle of deviation is greater. This circumstance, the influence of which is but little sensible for the first degrees of deviation, becomes excessively so as soon as this deviation increases. In order to remedy this, M. Peltier had proposed to substitute for each of the two needles of the astatic system two needles crossed at a right angle in the same plane. It follows, from this arrangement, that, when the needles that are parallel to the frame are driven from it, the others tend to enter into it, and that one of the effects almost compensates for the other. M. Peltier found that the indications of this instrument up to 45° are exactly proportional to the intensities of the current.

But if we desire, for measuring currents, to have galvanometers in which this proportionality is perfectly exact, we must employ the *sine* galvanometer or the *tangent* galvanometer. It is true that as these two instruments contain but a single magnetised needle, they lose in sensibility what they gain in accuracy. They are therefore essentially applicable to the determination of certain laws in which we act upon currents that may be procured as intense as is necessary.

The *sine galvanometer* (*Fig.* 136.), the principle of which I had described as far back as 1824[*], and which M. Pouillet

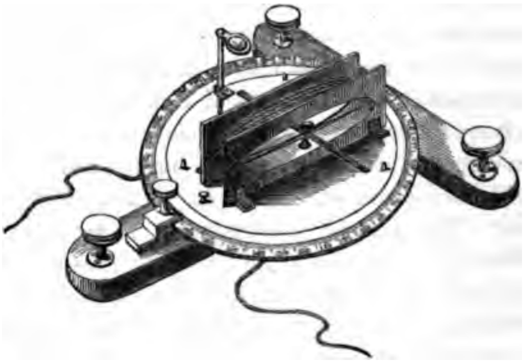

*Fig.* 136.

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[*] Mém. de la Soc. de Phys. et d'Hist. Nat. de Genève, tom. iii. part I. p. 117.

has constructed more recently under a slightly different form, consists of a compass needle from 4¾ in. to 6 in. in length, furnished with an agate cap, by which it rests upon a steel point placed exactly in the middle of a low and narrow metal frame, around which is carefully wound a wire or a ribbon covered with silk, which makes a greater or less number of convolutions, according to the degree of sensibility that we desire to impart to the apparatus. The multiplier and its needle are fixed upon the movable transom of a divided circle; and when they are both in the plane of the magnetic meridian, the apparatus is at the zero of the division. The needle, by its position in the interior of the frame of the multiplier, to which its axis must remain parallel, accommodates itself with difficulty to the exact determination of its real direction. In order to obtain the direction with precision, and in a convenient manner, we add to the needle, perpendicularly to its length, a thin and light slip of wood, upon which we have traced an index-line, that enables us to judge of the true position of the needle itself. We are sure that it is exactly parallel to the mean plane of the multiplier, when the index-line, of which we have just spoken, falls beneath the wire of a lens that is fixed to the movable piece upon which the galvanometer is adjusted. In order to operate with this instrument, we begin by placing it at the zero of the division, the needle being quite parallel with the wires, and, at the same time, in the magnetic meridian. We then pass the current through the wire of the multiplier. The needle is deviated; and we turn the transom that carries the multiplier until the wire of the lens coincides with the index-line: the division traced upon the fixed circle indicates the number of degrees it was necessary to turn it from the 0°, in order to obtain this coincidence. This is the exact measure of the deviation of the needle, namely, the angle that it forms with the magnetic meridian. But, in this new direction, the needle has preserved the same position in respect to the wires of the multiplier; that is to say, in respect to the current, which consequently acts upon it in the same manner. The amplitude, therefore, of the deviation of the needle can depend only upon the intensity of the current. The forces between which equilibrium is established, and which consequently are equal, are thus, on the one hand, that of the current, on the other hand, the directive force of the earth, which tends to bring the needle back to the meridian from which the former had removed it. Now the latter being proportional, as we have seen, to the sine of the angle of deviation, the former, that is to say, the intensity of the current, is the same also. By means of this instrument, therefore, taking care to operate with precision in each case, we may determine with accuracy the relations of intensity existing between the different currents that are transmitted through the wire of the multiplier.

We may, as may be imagined, give the sine galvanometer various degrees of sensibility, either by bringing the wire nearer to or farther from the needle, or by increasing or diminishing the number of convolutions; we may even cause the wire to make but a single turn. It is convenient to have multipliers fulfilling these divers conditions, which may all be fixed in the same manner upon the movable transom, and in the interior of which the same needle may be placed. It is necessary to take every precaution in the fabrication and the magnetisation of this needle, which should be a good compass-needle without consecutive poles.

The *tangent galvanometer* (*Fig.* 137.) consists of a large circle, open within, of from fifteen to twenty inches in diameter, provided with an exterior groove not more than $\frac{3}{4}$ in. wide, wherein a wire is placed, or, which is better still, a copper ribbon covered with silk, and which is made to have one or several convolutions around the circle. The two extremities of the wire or the ribbon, being bent back very near to each other, are prolonged below in the direction of the vertical diameter, so as each to plunge into a cup filled with mercury, in order that the transmission of the current may so be brought about. The circle, whose circumference is traversed by the current, is fixed vertically upon a divided and horizontal circle, the centre of which coincides with its own; this circle is intended for measuring the deviations of a magnetised needle, moving around the same centre, and suspended either by means of a silk thread without torsion, or by means of a cap resting upon a point. Great care must be taken that the centre of the needle is exactly in the centre of the vertical circle, so that the deviation of the needle coincides with the plane of the current when the latter is exactly in the magnetic meridian; a position which we commence by giving it when we desire to make use of the instrument. We should add that it is necessary for the length of the magnetised needle to be as short as possible, in relation to the radius of the circle, which does not prevent its being powerfully magnetised; but, as it is important to be able to estimate very small fractions of degrees, we fix transversely to the magnetised needle a long and very light copper needle, the extremities of which traverse the divisions of the azimuthal circle. It is important that the apparatus be constructed with great precision; for an error of a few fractions of degrees, especially when the deviation is considerable, would introduce a very great one into the appreciation of the intensity. In order to be sure that this condition is well fulfilled, it is necessary to prove that the deviations indicated by the two extremities of the copper needle are always and every where equal to each other, and that, when passing the same current, sometimes in one direction, sometimes in the other, the deviations that are obtained, one in one direction, the other in the other, are also quite equal.

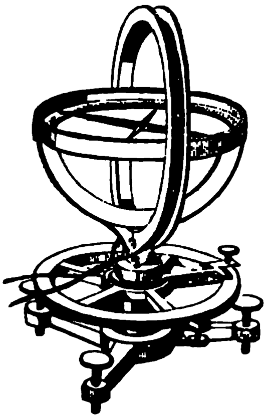

*Fig.* 137.

When different currents are transmitted through the ribbon or the wire that is wound around a circle, they produce a deviation of the magnetised needle, the character of which indicates their direction, at the same time that their relative intensities are proportional to the tangents of the angles of deviation. In fact, for each deviation, when it is constant, there is an equilibrium or an equality between two forces, one of which is the directive force of terrestrial magnetism, which is proportional to the sine of the angles of deviation, and the other the force of the circular current, which is proportional to the co-sine of this same angle. This, in fact, is very easy of proof, by remarking that the needle, being very small in respect to the circular current, we may consider the latter as exercising its action only upon the centre of the needle, that is to say, in Ampère's theory, upon a current that is the resultant of all those whose assemblage constitutes the needle. Now by supposing that the angle of deviation described by the needle under the action of a current is $i$, the force which tends to bring it back into the magnetic meridian, and which produces equilibrium to the deviating action of the current, would be $f$ sine $i$, $f$ being the force of terrestrial magnetism for the angle whose sine is 1, namely, for the angle of 90°. On the other hand, if $F$ represents the action of the current upon the needle when the latter is placed parallel to the current, this force will become $F$ *co-sine* $i$, when the needle makes an angle $i$ with the direction of the current; for $F$ *co-sine* $i$ is the component of $F$ acting under the angle $i$. $F$ *co-sine* $i$ therefore is the expression of the component of the deviating force of the current upon the needle, when the angle of deviation is $i$; it is consequently equal to $f$ *sine* $i$, since it makes equilibrium with it. From $F$ *co-sine* $i = f$ *sine* $i$, we deduce $F = f\frac{\textit{sine } i}{\textit{co-sine } i}. = \textit{tang. } i.$ But $f$ is a constant quantity, at least in the place where the observation was made, because it is the directive force of the earth; therefore $F$, or the force of the current, is proportional to the tangent of $i$, or of the angle of deviation.

A galvanometer that also gives very well the relations between the intensities of different currents that it transmits, is Ritchie's *torsion galvanometer* (*Fig.* 138.). It is a true torsion balance, in which the magnetised needle, when it is at 0° of torsion, is situated at once in the magnetic meridian, and in the mean plane of the frame, around which a silk-covered wire is wound, so as to make one or several turns.

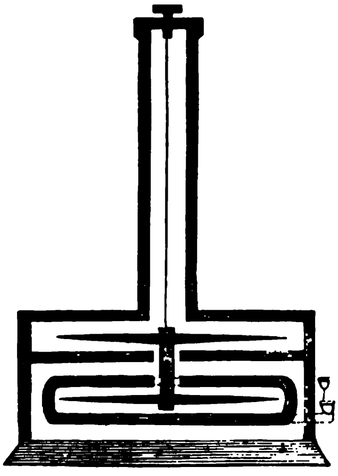

*Fig.* 138.

The magnetised needle is brought back by torsion to its normal position, when the current that traverses the wire draws it from this position; so that it is still situated, both in the magnetic meridian, and in the same position with respect to the currents. It necessarily follows that the intensities of the currents are proportional to the angles of torsion, which are requisite in each case to bring back the needle to its starting-point. Mr. Ritchie found that the apparatus was more sensible if a thread of glass was substituted for the torsion wire.

Finally, M. Becquerel, in order to obtain an exact measure of electric currents, suggested the use of an apparatus which he termed the *electro-dynamic balance* (*Fig.* 139.). It consists of a sensitive steel balance, which can turn at about a hundredth of a grain. Below each of the pans is suspended a magnetised steel bar, by means of a silk thread; these two bars must be about $\frac{1}{10}$th in. in diameter, and 3 inches long. They are magnetised to saturation, and their south pole is turned below, so that they may lose their magnetism less readily. Once in equilibrium, the two beams of the balance ought to turn at least by $\frac{1}{30}$th grain. We take two glass tubes or bobbins; we wind around the tubes or bobbins a wire covered with silk, so as to make a greater or a less number of convolutions, as with galvanometers, according to the object in view. The two bobbins are fixed vertically upon small horizontal platforms, movable in two directions perpendicular to each other, by means of a thumb-screw, so that we are able to centre them in respect to the bars beneath which they are placed. If the current traverses only one of the helices, the bar, and the side of the beam of the balance with which it is connected, rises or falls according to the direction of this current. In order to increase the effect, we may

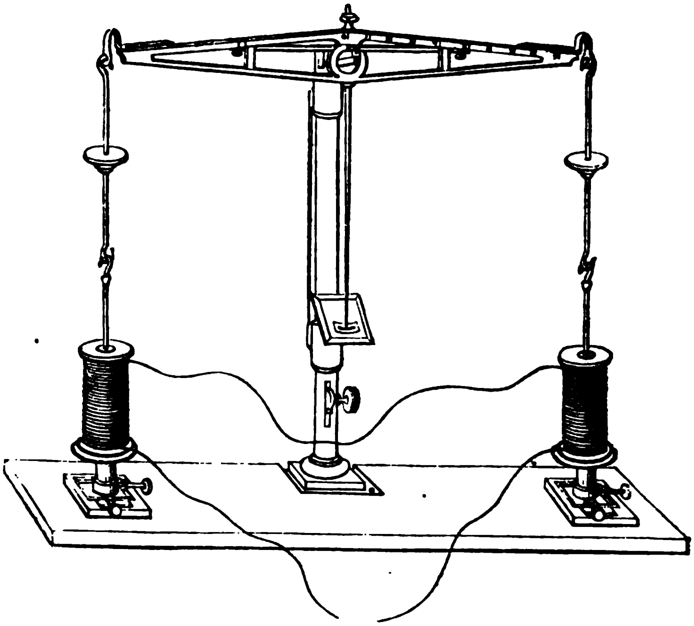

*Fig.* 139.

pass the same current through the wire of the second helix, in such a direction that the second branch of the beam falls if the first rises, and reciprocally; in other words, so that the movement of the beam is executed in the same direction: the actions that the two helices thus exercise upon the two bars, are necessarily added together. By means of weights placed in the raised scale, equilibrium is established, which brings back the currents and the magnets to the same respective position: we have therefore, in the quantity of weight requisite for establishing equilibrium, the exact expression of the intensity of each current; or, rather, we deduce from the relations existing between these weights the relations that exist between the intensities of the currents. Thus, to give an example, we passed into the two helices the current produced by two plates, the one zinc, the other copper, each having $\frac{2}{3}$ sq. in. of surface, and immersed in about 154 grains of distilled water. The balance turned, and it required a weight of $\frac{1}{25}$ grain to establish equilibrium: without making any change in the apparatus, we plunged into the water the end of a tube moistened with sulphuric acid; and it then required a weight of $\frac{1}{2}$ grain to establish equilibrium, which, on taking the relation between the two weights, indicates that the second current was about fourteen times stronger than the first. We shall have occasion hereafter to return to several interesting experiments made by M. Becquerel with his electro-magnetic balance. We may add that this instrument can also be used as a differential galvanometer, providing that the two bobbins and the two magnets are perfectly similar to each other. It rests, as may be seen, upon a simple and rigorous principle; but it cannot be employed for the study of currents of feeble intensity, not being sufficiently sensible.

To sum up: of the four instruments that may be employed for the measure of electric currents, the most convenient is the tangent galvanometer, because it gives its indication immediately; for this we have merely to measure the angle of deviation. The sine galvanometer, the torsion galvanometer, and the electro-dynamic balance, all require that we should go through an operation of a certain length, in order to determine the quantity that is to give the measure of the current. This is a great inconvenience, especially when currents of variable intensity are in question, the force of which it is of importance to be able to determine in a given instant, and which is usually very short. But there are other cases in which this inconvenience does not exist, and, as they are numerous, it follows that the three other apparatus, especially the sine galvanometer, are, as we shall see, frequently used.

### *Different Galvanometric Processes.*

When the currents are very powerful, we may, in order to measure them, content ourselves with passing them successively through a long vertical conductor, and making a proof needle always oscillate at the same distance. In the number of oscillations executed in a given time, we have an exact measure of the force of the current according to the formula of the pendulum. We may also, especially when we are engaged in appreciating the relative intensities of electric discharges or instantaneous currents, make use of the magnetisation of small needles produced by these discharges, taking care to make the needles as similar as possible. We then determine the degrees of magnetisation that the needles have acquired, by counting the number of oscillations made by each of them under the influence of terrestrial magnetism. We shall not dilate further on these means of measuring, which are processes and not instruments, and the description of which besides is naturally found most in place when we are called to make use of them.

This last process, however, presents an advantage over those which serve as the basis of the construction of galvanometers, in that they are independent of the magnetic force of the needles or bars. This force may undoubtedly vary, and yet we regard it as constant. The best apparatus would therefore be that in which there was no other force called into play than that of the current itself which we desire to measure, and perhaps also the magnetic force of the terrestrial globe, which may, without sensible error, be regarded as constant in the same place. Thus, a galvanometer-multiplier in which, instead of a magnetised needle, there should be a small bar of soft iron which the current itself that causes it to deviate would magnetise, might be usefully employed: it is true it would not be so sensible as the ordinary galvanometer. We might also, in M. Becquerel's electro-magnetic balance, make use of bars of soft iron instead of magnetised bars. In this case, we need employ only one scale-pan, and by the weights necessary to produce equilibrium, we should measure the force wherewith the scale-pan beneath which the soft iron rod is fixed, would tend to descend, by virtue of the attraction exercised upon the soft iron by the current transmitted throughout the helix. Finally, we have already pointed out, in the Chapter devoted to magnetisation, the possibility of measuring the intensity of the current by means of the greater or less flexion exercised upon a plate of soft iron by the current that is made to pass through the wire of a prismatic bobbin in the interior of which the plate is placed. We have also already described two pieces of apparatus, founded upon the attraction exercised upon soft iron by an electro-magnet, magnetised by the current that we are desirous of measuring. In one (*Fig.* 127.), it is by the number of the oscillations of a balance-wheel; in the other (*Fig.* 126.), by the note given out by a little spring, from which we estimate the number of times that the piece of soft iron has been attracted by the electro-magnet, and consequently the force of the current, which is approximately proportional to this number. The greatest obstacle presented by the practical application of these different processes consists in the difficulty that we experience of finding iron sufficiently soft to lose the whole of the magnetism that has been developed in it by the electric current, when this current ceases. The preparation of such a soft iron as this is not impossible, although it is very difficult. We ought not, therefore, to despair of one day seeing this principle serve as the basis of a more perfect instrument than those we at present possess.

### *Graduation of Galvanometer-multipliers.*

Up to this point, we have succeeded in finding in the galvanometer an instrument calculated to detect for us the presence of an electric current, to indicate to us its direction, and to furnish us with comparable results as to its intensity. But, in order that the indications of the instrument may have a signification, it is always necessary to have in view at least two currents, and to propose seeking their relation of intensity. In other words, the instrument is not graduated in this sense, in that it does not give immediately the relation existing between any current with which we act upon it, and a current always the same, and of a determinate intensity, which serves as the point of comparison. We have used great endeavours thus to graduate galvanometers; and, by turning our attention to the different sources of electricity, we shall have occasion to say a few words upon these experiments. But, independently of the difficulty of finding this perfectly constant current, we have been arrested by obstacles inherent in the very nature of the question itself. In fact, a galvanometer graduated in this manner, may be employed with sufficient accuracy to the appreciation of the relative intensity of currents, arising from a source similar to, but merely more or less energetic than the current which had been employed in graduating it. But as soon as we are concerned in currents arising from another source, or even simply engendered under other circumstaces, the instrument will no longer give comparable results, and will even risk the giving erroneous ones. Thus, if we have graduated in the same manner, and taking as the term of comparison the same constant current, two galvanometers, the one with a short and thick wire, the other with a long and fine wire, it may thus very well happen that any current transmitted successively through each of these two galvanometers may not only appear more feeble with one than with the other, but even, when judged of by one, may seem of a less intensity, and by the other, of a greater intensity than that of the current that has been employed for the graduation.

Thus the galvanometer-multiplier, even of the most perfect kind, must be considered only as an instrument fitted for giving the relations of intensities between currents of a similar origin, or which, when arising from the same origin, are subjected to modifications whose influence upon their energy we desire to appreciate. Therefore is it indispensable to have several galvanometers with wires of different lengths, so as in each case to be able to apply that which is best suited to the species of current that we are studying, at least so far as we are able to determine *à priori*, which is not always equally easy. We shall study further on the means by which they may be compared together in reducing them to conditions as similar as possible, means altogether independent of the galvanometer itself, that is employed for this comparison.

### *Very Sensitive Galvanometers.*

In a recent work on Electro-Physiology, M. Dubois Reymond, of Berlin, has very closely studied the astatic needle galvanometer, and the means of augmenting the sensibility of this instrument to the highest degree, for the detection and the study of very feeble currents. He analysed with great care the causes of the irregularities that are presented by very delicate galvanometers, and which frequently rendered the employment of them both difficult and uncertain; and he has then described the means of reconciling the fidelity of the indications with the sensibility of the apparatus.

M. Dubois Reymond remarks, first, that the axes of the needles never being rigorously parallel, either on account of an irregularity in the magnetisation, or in consequence of a defect in the suspension, it follows that the system is never in the meridian, and that it deviates from it the more as it is more completely astatic. He was also led to perceive, that, if the magnetism of the stronger needle is diminished, so as to render the system of the two needles more and more astatic, the result is, that it at last places itself perpendicularly to the magnetic meridian, being the case in which the instrument attains its maximum of sensibility.

A second cause of irregularity is the magnetism of the galvanometer wire, probably due to the presence of a small quantity of iron in this wire. It follows from this, that the position of the needle, in respect to the spirals of the wire, exercises an influence over the direction in which it places itself. Thus, the needle being fixed in equilibrium, at a certain distance from the zero of graduation, if the frame is made to turn, so that the zero travels towards the side of the needle, the latter seems at first to recede; but, in fact, it becomes less displaced than the frame has been, and, consequently, its distance from the zero diminishes. However, it is not possible to bring it back exactly to zero; but this distance may be reduced to a minimum. If this minimum is exceeded, the needle goes rapidly towards zero, passes beyond it, and places itself in equilibrium, at a certain distance from the other side.

In some rare cases, the needle has a position of stable equilibrium at zero itself; but the position of equilibrium is generally unstable between the two positions of stable equilibrium that are on the two sides of zero. M. Nobili, who had already observed these effects, showed that they were a consequence of the attractive actions of the two parcels of the galvanometer wire upon the system of the two needles; actions which are concordant, notwithstanding the inverse position of the poles, because the wires act like a magnetic body, such as soft iron, and not like a magnetised body.

The combination of these two causes of irregularity gives rise to various results, which may be determined by calculation, and which vary according as the system of the two needles is less or more astatic; because the part played by terrestrial magnetism becomes thus more or less important.

Different processes of correction had been devised for banishing, or at least diminishing, these causes of perturbations. Kleiner proposed the employment of small masses of copper, placed in the interval, by which the two parcels of the galvanometer wire are separated, so as to neutralise the disturbing attraction of the latter. Nobili compensated the attraction of the galvanometer wire by that of a magnetised bar placed at a distance. M. Dubois Reymond has perfected this latter process, the inconvenience of which was, that the magnet exercised its action almost with the same energy in all positions of the needle. In the place of this magnet, he substituted a small magnetised fragment only $\frac{1}{25}$ in. in length, placed in the interior of the galvanometer facing the zero. The action of this small magnet is only sensible so long as the needle is near zero; and it then compensates the disturbing actions. But as soon as the distance is a few degrees, when the compensation ceases to be necessary, its action becomes almost entirely null.

Upon this principle, and by taking many precautions, he constructed a galvanometer of 27,000 turns, as remarkable for its accuracy as for its sensibility. We shall see further on how, with this instrument, he detected the existence of electric currents in nerves and in muscles.

# CHAP. V.

## ELECTRO-DYNAMIC INDUCTION.

### *Magnetism by Rotation.*

We owe to M. Arago the first experiment, which showed that motion is a means of developing magnetism or electric currents in all bodies. We must not confound this action with what had been discovered by Coulomb, namely, that magnets are capable of acting upon all bodies generally in the same manner, except in regard to intensity, as they act upon iron. This species of action will be the subject of the following Chapter. The phenomena, with which we are engaged in the present, are those to which motion gives rise, that is to say, the change of place of the cause that acts, in relation to the body, upon which it acts. The term *magnetism by rotation* is applied to the form under which M. Arago first made manifest this class of phenomena.

Having oscillated a magnetised needle, freely suspended in a circular copper cage, the bottom and sides of which were very near the needle, M. Arago remarked that the oscillations of the needle rapidly diminished in extent, and very quickly ceased, as if the medium in which they were being produced had become more resistant. Furthermore, the neighbourhood of the copper exercised no other influence than upon the amplitude, and not upon the duration of the oscillations, which are accomplished in exactly the same time as in the free air. By making the needle oscillate above planes of different natures, and at variable distances from the same plane, M. Arago became satisfied that distance considerably diminished the intensity of the effect, and that metals acted with more energy than wood, glass, &c. Mr. Seebeck, who repeated M. Arago's experiment immediately after its discovery, obtained analogous results. Thus he found that if the needle oscillated above a plane of marble, it was necessary that it should accomplish 112 oscillations, in order that the amplitude should be reduced from 45° to 10°; whilst it only required 71 oscillations above a plate of zinc, and 62 above one of copper. Unfortunately, M. Seebeck's experiments, not having been made with plates of the same dimensions, and in particular of the same thickness, the results are not comparable.

After the first experiment that we have been relating, M. Arago conceived the idea of trying whether the plate, which possessed the property of diminishing the amplitude of the oscillations of a magnetised needle without altering their duration, would not draw the needle with it, when itself put in motion. This in fact is verified.

We fix to a rotation apparatus, such as a table made for experiments on the centrifugal force, a copper disc about 12 inches in diameter, and about $\frac{1}{10}$ in. thick (*Fig.* 140.); above it, and very near, we suspend, by a silk thread, without torsion, a magnetised needle, in such a manner that its point of suspension is exactly above the centre of the disc; care is taken to interpose between the disc and the needle a screen of glass or pasteboard, so that the agitation of the air resulting from

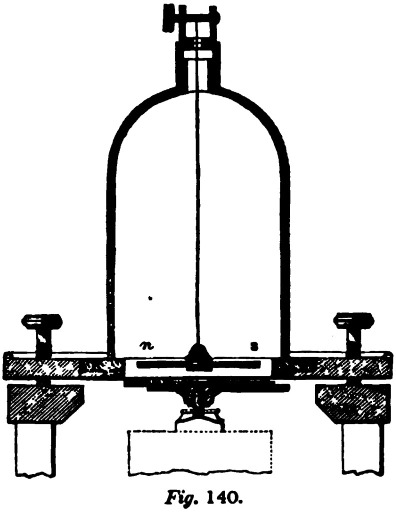

*Fig.* 140.

the motion impressed upon the disc may be without influence upon the needle. The disc is put in rotation, and the needle is seen to deviate from its normal direction, in the direction of the movement impressed, and to make with the magnetic meridian a greater or less angle of deviation, according to the velocity of the rotation. If the movement becomes very rapid, the needle is finally drawn with it, and rotates with the disc itself.

The force diminishes very rapidly with the distance of the needle from the disc, in a relation, as it appears, greater than the square; the angles of deviation within certain limits are proportional to the velocity. The power of the copper disc is considerably diminished by cutting slits in it in the direction of rays: these solutions of continuity, which in no degree alter the mass, exercise a great influence upon the intensity of the action.

Independently of the preceding observations, M. Arago, by analysing the force called into play in these experiments, discovered that, from drawing or *tangential* to the disc which it is, it may become *perpendicular* to its plane, and even act in the same direction as its radii; which proves that the total force may be regarded as a resultant of three components, one perpendicular to the radius of the disc, the second perpendicular to the plane of the disc, and the third parallel to its radii. We have already proved the existence of the first in the fundamental experiment. In order to prove the existence of the second, we have merely to place a magnet vertically above, and very near to the disc, which is easily accomplished by suspending it to the scale-pan of the balance. Immediately that the disc is in motion, the scale-pan rises, which proves that the vertical magnet is repelled by the disc, and the weight necessary to be placed in the scale-pan, in order to re-establish equilibrium, indicates the energy of this repulsion. With regard to the third component, its existence is demonstrated by placing vertically over the disc a needle, movable, like the dipping needle, around a horizontal axis, and in such a manner that this axis is perpendicular to the radius of the disc. If the needle is over the centre, it experiences no action, neither does it experience any if it is situated over a point nearer to the edge than to the centre of the disc, namely, at a distance from the centre equal to about two-thirds of the radius. But between this point and the centre, the lower pole of the needle is constantly attracted towards the centre; beyond this point, namely, between this point and the edge, the pole is attracted towards the edge.

Whilst M. Arago was analysing, as we have just seen, the force that he had discovered, MM. Babbage and Herschel, Harris, Barlow, and others, endeavoured to study the causes which may make the intensity vary and may modify it. MM. Babbage and Herschel had repeated M. Arago's experiment by inverting it. They had found that discs of copper or other substances, when freely suspended over a horse-shoe magnet put into rotation, turned in the same direction as the magnet, with a movement at first slow, but whose rapidity gradually increased. The magnet was so arranged as to be able to receive a rapid movement around its symmetrical axis, placed vertically with the poles upward. The movement of the disc changed in direction with that of the magnet. The interposition of plates of glass and of non-magnetic metallic plates in no degree modified the effects: it was not the same when the interposed plates were of iron; the action was then extremely reduced, or even entirely annihilated, when there were two plates one above the other.

By subjecting to experiment discs of the same diameter but of various natures, the two philosophers found great differences between these discs with regard to their faculty of being drawn onward by the magnet in rotation, although the velocity of the movement impressed and their distance from the magnet were the same. Thus, zinc and copper appear in this respect to possess an energy four times more powerful than lead, and a hundred times more powerful than antimony. But the discs unfortunately were not all of the same thickness, which renders the results of the experiments but little comparable as, within certain limits, thickness exercises a marked influence over the intensity of the phenomena. It is probably to this cause that we must attribute the little power that MM. Babbage and Herschel had found in gold. On the other hand, they did not obtain any effect with wood, glass, resin, sulphur, and sulphuric acid.

These two philosophers verified the accuracy of M. Arago's observations on the influence of solutions of continuity, either parallel or total, in the masses subjected to experiment. Thus, a light disc of copper, suspended at a given distance above a magnet, executed its revolutions in 55″. When cut in eight places, in the direction of a radius near the centre, it required, under these circumstances, 121″ to execute the same number of revolutions. But the cut parts having been soldered in again with tin, the primitive effect was almost entirely re-established; in such sort, that the disc was able to make its six revolutions in 57″; that is, almost in the same time as when it had not been cut. The same effects were in a similar manner obtained with the other metals, employed either as discs or solderings. We shall soon see that all these results, as well as the effects themselves, of magnetism by rotation, are very readily explained by the presence of electric currents, that are determined in the disc by its vicinity to a magnet, and the circulation of which is prevented when there are solutions of continuity in the conducting body. Thus no action is obtained when we rotate in relation to each other two discs of any kind, or a piece of soft iron or non-magnetised steel, and a disc of metal. It is absolutely necessary that one of the bodies in motion shall be a magnet.

Sir W. Harris, who made a great number of experiments on the same subject, not only found great differences between bodies with regard to the faculty they possess of drawing onward the needle, but also with regard to the property they possess of intercepting this action. He recognised that iron, and magnetic substances generally are not the only ones that are thus able to arrest the effect of magnetism by rotation. Only it is necessary to give a very great thickness (from 3 to 5 in.) to the plates of non-magnetic substances, such as copper, silver, and zinc, in order that, when interposed, they may arrest the action of a magnet in motion upon a movable disc, and reciprocally. Finally, as it results from numerous experiments, Mr. Christie succeeded, as we shall see, in deducing from the force with which different substances draw along the magnetised needle in their rotatory movement, the conducting power of these substances for electricity.

But one of the most important facts is due to MM. Ampère and Colladon, who found that, in all the experiments on magnetism by rotation, the place of the magnet might be supplied by a helix, through which was transmitted an electric current; thus establishing a new analogy between a magnet and an assemblage of electric currents, circulating all in the same direction, in closed circuits parallel to each other, transversely to an axis. The helix traversed by a powerful electric current was movable, and a copper disc, in rotation beneath it, drew it along with it as it would have drawn along a magnetised needle.

Very numerous experiments have been also made with discs of iron and steel, and with solid and hollow iron spheres. When the iron is very soft, the results are greatly similar to those that are obtained with other metals, only they are more energetic; but a steel disc does not produce any appreciable effect upon the magnetised needle, which, after a few irregular oscillations, remains in its position of equilibrium. M. de Haldat, to whom we owe these observations, concludes from them, that the drawing force is for magnetic bodies in inverse ratio to the coercitive force. We shall see further on that this conclusion cannot be admitted, the phenomenon not being a magnetic phenomenon, properly so called, but an electric phenomenon.

Mr. Barlow studied in detail the influence that is exercised by an iron sphere in motion upon a magnetised needle. He took the precaution to neutralise, by the neighbourhood of a fixed magnet suitably placed, the influence of terrestrial magnetism upon this needle. The latter was placed sometimes tangentially to the iron sphere, sometimes parallel to its axis of rotation, which axis itself, from the construction of the apparatus, might have different directions. According to the direction in which the sphere rotated, either the north or the south pole of the needle was seen to recede from it; the repulsion exercised upon either of the poles depended also upon the part of the iron sphere towards which the needle was placed; in other words, the direction of the deviation of the needle changed according as it was placed on the south or on the north of the moving sphere. All these effects are evidently due to the combined influence exercised upon the iron globe, both of terrestrial magnetism, and of the magnetised needle placed in its neighbourhood. It would have been curious to have proved the influence of the first cause alone by putting a needle of soft iron in place of the magnetised needle.

A very important point, that was established by Mr. Barlow, is the great difference in the action exercised by an iron sphere according as it is solid or hollow. This difference is completely null when the globe and the magnetised needle are at rest, which arises, as we have said, from the ordinary magnetic force being entirely concentrated upon the surface; but as soon as there is motion this ceases to be the case. Thus, under the same circumstances, and by employing the same needle, a solid iron cannon-ball, making 640 turns per minute, and weighing 68 pounds, and being 7·87 in. in diameter, determined a constant deviation of 28° 24′; whilst a hollow ball of the same diameter, but weighing one-half less, determined a deviation of only 15° 5′. These two numbers are the mean of many experiments made with great care.

M. Poisson, who had already submitted to mathematical analysis the labours of Coulomb upon magnetism, endeavoured to explain by the same theory the phenomena of magnetism by rotation. Attributing all magnetic phenomena to two imponderable fluids subjected to the general laws of equilibrium and of motion, which attract and repel each other in the inverse ratio of the square of the distance, he established that the great difference existing between these fluids and those to which electric actions are due, is, that the latter are able to pass from one molecule to another; whilst the magnetic fluids, during magnetisation, undergo only feeble displacements, which are not directly appreciable. M. Poisson gave the name of "magnetic elements" to these small portions of bodies, in which the south and north magnetic fluids are able to move, and which are separated from each other by intervals impermeable to the magnetism. All bodies are susceptible of having their natural magnetism decomposed; but more or less easily according to their coercitive force. It is to this force, which is insensible in some bodies, that M. Poisson attributes the difference existing between them with regard to the actions they exercise according as they are in rest or in motion. In the state of rest, bodies whose coercitive force is null should not exercise any sensible action upon the magnetised needle, or, at least, should exercise only a very feeble action; but, in the state of motion, calculation demonstrates that things are not the same. M. Poisson also succeeded in determining in this case *à priori* the existence of the three components that M. Arago had discovered by experiment.

However, the theory that serves as the basis to M. Poisson's calculations was overthrown by the subsequent discoveries of Mr. Faraday, which give an entirely different explanation to the phenomena of magnetism by rotation. So that we will not detain ourselves with them longer, merely remarking that mathematical analysis may be further consulted usefully by those who, by resting on hypotheses different from those which serve for M. Poisson's starting-point, would submit them to the proof of calculation. We shall therefore now pass on to the phenomena of induction, with which Faraday enriched the science in 1832; and in which, as we shall see, are naturally included those of magnetism by rotation.

### *Production of Induced Currents and Explanation of Magnetism by Rotation.*

In 1832, Faraday discovered that an electric current or a magnet is able by induction to develope at a distance electric currents in a conducting wire; just as a body, charged with static electricity, electrises an insulated conductor by induction. The following is the mode by which this remarkable result is obtained.

We wind round a wooden cylinder two silk-covered wires, so as to make two perfectly similar helices, and the spirals of which are parallel, and as near to each other as possible (*Fig.* 141.). The two ends of one of the wires are made to communicate with a galvanometer, and the two ends of the other with the two poles of a pile. At the moment when this latter communication is established, the first having been established previously, the needle of the galvanometer is seen to deviate; but this deviation immediately ceases, even though the current of the pile continues to circulate. As soon as this current is interrupted, the needle of the galvanometer a second time experiences a sudden and non-permanent deviation; but this deviation occurs in a contrary direction to that in which the former had occurred. Thus the voltaic current that traverses one of the wires determines in the other an instantaneous current, at the moment when it commences to pass, and determines in it a second, at the moment when it ceases to pass. These two currents are called *induced currents*, and the current of the pile the *inducing current;* the induced currents, as we see, are instantaneous: let us further add that the former has a contrary direction to that of the inducing current, and the latter a similar direction.

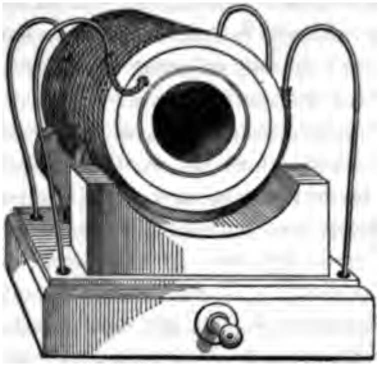

*Fig.* 141.

The experiment may be made under another form. We wind round a wooden or glass tube a single silk-covered wire, the two ends of which are in communication with the wire of a galvanometer; we then suddenly introduce into the tube an electro-dynamic cylinder, namely, a helix traversed by an electric current, and we then draw it out in the same manner. At the moment of the introduction, we obtain in the outer helix a current of induction, the movement of which is in a direction contrary to that of the current of the electro-dynamic cylinder; at the moment when we withdraw the cylinder we obtain a second induced current, the movement of which is in a direction the same as its own. In order that these two currents may be sensible, the electro-dynamic cylinder must be introduced and withdrawn very suddenly. This experiment, as may be readily seen, comes to the same thing as the preceding one: in the latter, we possess the advantage of creating and destroying the electro-dynamic cylinder instantaneously by closing and opening the circuit; whilst in the other we introduce it and withdraw it,—an operation which cannot be executed with so much rapidity. We shall see further on, that there results an essential difference between the induced currents; those which are produced according to the latter mode having a duration in a slight degree sensible, whilst those that are produced according to the former mode are altogether instantaneous.

Whatever may be the case, the two experiments equally prove that, when we suddenly bring near to a part of a conductor, forming a closed circuit, a conductor traversed by a current, we determine in the former an instantaneous current, moving in a direction contrary to that of the current brought near to it; and that, when we remove it, we determine a second instantaneous current, moving in the same direction as the current that is removed.

The analogy existing between the properties of magnets and those of electro-dynamic cylinders, led Faraday to suppose that the same results would be obtained by introducing into the interior of the hollow helix of the second experiment a magnet instead of an electro-dynamic cylinder. This is what in fact happened. For this experiment we may employ the double helix (*Fig.* 141.), by uniting the two wires by their corresponding ends; or, if we prefer it, by using either one or the other of them. By introducing a magnet within the helix, we determine in its wire an instantaneous current, moving in a contrary direction to those which constitute the magnet in Ampère's theory; we determine another, in like manner instantaneous, but moving in the same direction as those of the magnet, at the moment when we withdraw it. These two induced currents, when the magnetised bar is tolerably energetic, are much more intense than are those produced by inducing currents. In order to increase their force, the magnet must be introduced and withdrawn as suddenly as possible. We may in like manner employ another process, which is more convenient and more certain. It consists in introducing a bar of very soft iron into the interior of a helix, whose two ends are in communication with the galvanometer. By means of a horse-shoe magnet, or the opposite poles of two magnetised bars, we suddenly magnetise the soft iron; we immediately obtain the first induced current; it is, in fact, as if we had introduced a magnetised bar into the interior of the helix. We remove this horse-shoe magnet, or the magnetised bars; the soft iron cylinder is immediately demagnetised, and the second current of induction appears; it is the same as if we had removed the magnetised bar from the interior of the helix.

Finally, by making the experiment with the double helix, according to the mode first pointed out, but by introducing into the interior a soft iron cylinder, we may obtain a still more considerable effect. In fact, the current that traverses one of the helices, at the moment when it is established, not only determines a current of induction in the other, but at the same time magnetises the soft iron, which for this same reason also determines in it a current in the same direction, and much more powerful. In like manner, when the current ceases to pass, the soft iron being demagnetised, there is a development of a second induced current, which is also added to that resulting from the direct effect of the inducing current.

A very difficult question for solution here presents itself;

namely, to know what is the state of the induced conducting wire whilst it is under the influence of the inducing current or of the magnet. It would seem that this is not a natural state, since at the moment when the influence ceases the wire gives rise to a current while passing back to its natural state; on the other hand, the wire, whilst this influence lasts, does not manifest any current or any particular property, either electric, magnetic, or of any other character. Faraday termed this particular condition *electro-tonic.* We shall see further on that Faraday was led, by fresh researches, to renounce this supposition of the electro-tonic state in the wire; and to admit that the second induced current is due, like the former, to a particular and immediate action, and is not simply the effect of the return of the wire to its natural state,—a state which has not ceased to exist.

The intensity of the induced current depends on many circumstances: first, on the length and diameter of the wires of the helices, then on the energy of the inducing current or the strength of the magnet. We can give no precise rule on either of these points. In general, it is advantageous to take very long wires, and even to add several helices end to end one after the other; but then, if we are not producing the induction with a magnet, it is necessary to employ an inducing current, arising from a pile of a great many pairs. Moreover, these data vary with the nature of the effects, and consequently with that of the conductors, that the induced currents are called upon to traverse; and also with the length and the diameter of the wire of the galvanometer, that is employed for detecting these currents.

Hitherto, in order to produce the phenomena of induction by electric currents, we have made use of two conductors, the one intended for conducting the inducing current, and the other in which the induced current is developed, under the influence of the former. Experiment has shown that the phenomenon of induction may be manifested with a single conductor, in which the inducing current is transmitted and at the same time the induced current is perceived; it is this particular form of induction that is termed induction of a current upon itself. As early as 1832, Mr. Henry, of Princetown in America, had observed that, when the poles of a small battery are united by a copper wire by means of two capsules filled with mercury, a brilliant spark is obtained at the moment when the circuit is broken, by raising one of the ends of the copper wire out of the mercury, but only if this wire has a length of from twelve to fourteen yards; if the length is only twelve or fourteen inches there is no spark. The effect is greatly increased by coiling the copper wire into the form of a helix. Mr. Jenkins also, on his part, remarked that, when the two plates of a simple electro-motor, that is to say, of a simple pair, are connected by means of a wire wound as a helix around a soft iron cylinder, a shock is experienced every time the circuit is interrupted, when the two extremities of the wire are held one in each hand; at the same time, a brilliant spark is observed at the point where the circuit is broken. No effect is obtained under the same circumstances, if we use merely a copper wire to complete the communication between the two plates of the pair.

Faraday, as it results from a long experimental study of this particular point, succeeded in showing that, at the moment when we interrupt the circuit of a single pair formed by a long copper wire, an *extra-current* is produced in this wire, which may be directly perceived by soldering to each end of the wire an appendix or plate of copper, and connecting these two plates by various conductors. A fine platinum wire is made red-hot and melted; water is decomposed; the magnetised needle is deviated by means of the current transmitted between the two appendices. If the conductor by which they are connected is imperfect, the spark is then very brilliant at the point where the circuit is interrupted; it is, on the contrary, null if it is perfect: this is because, in the former case, the extra-current, developed in the long wire that unites the poles of the pile, accomplishes its circuit through the pile itself, since it cannot pass elsewhere; whilst in the latter it accomplishes it through the body by which the two appendices are connected, provided this body is found to be a good conductor. This extra current may give rise to a spark between the two appendices, when they are brought almost in contact, one near the other: when they are held in the hands, a shock is produced.

The energy of the extra-current is much more decided when the wire, by which the two poles of the pile are united, is coiled into the form of a helix, and especially when this helix contains in its interior a cylinder of soft iron. This circumstance, joined to others besides, is a proof that this extra-current is truly a current of induction, with only this difference, that it is developed in the same conductor by which the inducing current is transmitted. The mutual action of the spirals upon each other, each of which serves at the same time as inducing body and induced body,—the influence of the soft iron, which, when magnetised by the inducing current, increases also the intensity of the induced current,—are altogether in accordance with all the conditions essential to induction, as well as is the direction itself of the extra-current, which may be appreciated either by chemical decomposition or by the galvanometric effect. This direction in fact is such, that in the circuit formed by the long wire that connects the plates of the pair, and by the conductor that connects the two appendices, the current moves in the long wire in the same direction according to which the current of the pair itself travelled. We must not forget that the induced current here in question is that which is produced at the moment when the circuit is interrupted, and not at the moment when it is established: now this current is always moving in the same direction as the inducing current. With regard to the first induced current, it cannot be perceived, since it circulates in the same circuit that transmits the current itself of the pair, and cannot be developed until this current is established, and consequently not until the circuit is closed. But, as it moves in a contrary direction, it diminishes for an instant the intensity of this primitive current: we shall see, further on, that this diminution may become sensible, and we may thus detect, in a decided manner, the existence itself of the first induced current.

A method of producing induction that we have not yet mentioned, is to employ terrestrial magnetism. Faraday, in his beautiful researches on induction, was the first to demonstrate that induced currents, as we might have expected, may be developed by the magnetic force of the globe, even as they are developed by means of a magnet or by the influence of closed currents.

The following is his fundamental experiment. We take a copper wire about 8 ft. long, and $\frac{1}{20}$ in. in diameter; we attach it by one of its ends to one of the extremities of the wire of a galvanometer-multiplier, and by the other end to the other extremity; we then give it the form of a rectangle, and place it perpendicular to the magnetic meridian, the lower side of it being interrupted by the wire of the galvanometer. The wire itself is so arranged that we can give the rectangle a movement of rotation around its lower side, or, which comes to the same thing, can describe around this side a surface cylindrical on the upper side. If it is made to traverse from the side of the west to that of the east, the needle of the galvanometer indicates the presence of an induced current directed from the south to the north; if it is made to traverse from the east to the west, the induced current travels in the movable wire from north to south. The phenomenon is the same in all azimuths. There is only one case in which no effect is obtained; it is when the movable part of the wire moves parallel to the direction of the dipping-needle; but provided it be inclined in relation to this direction, there is a development of an induced current, and when it is perpendicular to it, this current is at its maximum of intensity. It is not essential to give the wire the form of a rectangle; the same phenomena are observed by giving it the form of any closed curve, the plane of which is arranged in a similar manner to that of the rectangle. The longer the portion of the wire is, to which a movement is impressed, and the greater the space is that it is made to traverse, the more considerable is the effect experienced by the galvanometer.

It evidently follows from the phenomena we have been describing, that the terrestrial globe acts for the production of induction as a powerful magnet would act, if placed in the interior of the globe in the direction of the dipping-needle, or as a girdle of electric currents moving in a direction from east to west around the magnetic equator.

The first currents of induction that Faraday had obtained by the influence of terrestrial magnetism were manifested in a helix, the wire of which communicated by its two extremities with those of the galvanometer, and which was turned a greater or less number of times in the plane of the magnetic meridian. An iron bar introduced into the helix greatly augments the intensity of the effect; but, in this case, the induced current is not due to the direct action of terrestrial magnetism, but to that of the bar, which is itself magnetised by this magnetism.

The facility with which terrestrial magnetism is able to develope electric currents in bodies in movement, leads to a consequence which may appear extraordinary at the first moment; it is, that there is not a piece of metal which, being put in motion and remaining at the same time in contact with other conducting bodies in rest, or animated with different velocities, is not for this very reason traversed by electric currents. This must especially happen with the different pieces of a steam-engine in motion. Faraday succeeded by simply impressing a rotatory motion upon a horizontal disc of copper, and consequently inclined it nearly 70° to the dipping-needle in obtaining currents of induction which were always directed from the centre to the circumference, or from the circumference to the centre, according to the direction of the rotation. In order to perceive this current, care was taken to place one of the extremities of the galvanometer in communication with the axis, and the other with the circumference of the disc. No effect occurred when the disc rotated in the plane of the magnetic meridian, or in any other plane passing through the line of the dip; but as soon as the plane in which it was situated was inclined only a very small angle to this direction, the rotation immediately gave rise to a current which, for a constant velocity of rotation, had its maximum of intensity when this angle was 90°. With a copper globe arranged so that its axis of rotation is inclined to the direction of the dipping-needle, but remains in the plane of the magnetic meridian, by giving it a rotatory movement about its axis, we obtain currents of induction which are sufficiently energetic to exercise immediately a deviation upon a magnetised needle brought near to it, without the intervention of a galvanometer being necessary. We take care to make use of an astatic needle, suspended to a very fine silk thread, and to place it in a bell glass, so as to protect it from the agitation of the air. We bring the astatic system near to the globe while in motion, so that the upper needle is in the horizontal plane that passes through the centre of the globe; if it is on the east, and the globe moves from east to west, its north pole deviates to the east; it deviates to the west when the rotation occurs from west to east. The effects occur in an inverse direction, if the astatic system of the needles is transported to the west of the globe when in movement.

The effects that are produced in a copper globe set in rotation are exactly of the same nature as those obtained by Mr. Barlow with an iron globe placed under the same circumstances; which proves that the deviation exercised upon a magnetised needle by a sphere of iron when in motion is not due to magnetism, but to currents of induction developed by the induction of terrestrial magnetism,—a circumstance that establishes, as well in the cause as in the nature of the effects, a great difference between the action of an iron globe at rest and the action of an iron globe in motion.

On seeing terrestrial magnetism capable of producing by induction continuous currents in conducting bodies when in movement, whatever be their form, we are led to presume, with a certainty almost complete, that the action of magnets may produce the same. Thus, we find the explanation of the phenomena of magnetism by rotation by connecting them with the production of currents by induction. It is also to Faraday that we owe the verification of this conclusion. He first showed that a copper disc, when put in rotation around an axis in any plane, gives rise to electric currents when it is made to circulate so that its edge passes between the two opposite poles of two magnets, or of a horse-shoe magnet (*Fig.* 142.). The neighbourhood of a single pole is sufficient; but the effect is less decided. One of the extremities of the galvanometer by which the current is detected, communicates

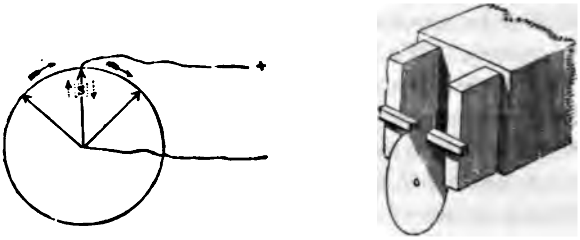

*Fig.* 142.

with the axis of the disc, and the other with its circumference, which is carefully amalgamated, in order to render the contact more perfect. The current produces upon the needle of the galvanometer a permanent deviation, the direction and the intensity of which depend upon the direction and the rapidity of the rotation, all other circumstances remaining the same: so long as the rotation is executed in the same direction, the current preserves the same direction, even though the point of the circumference that is touched with the conductor is on the left or the right of the part that passes near the pole, or is this part itself. Only the intensity diminishes in proportion as it is more distant from it. The two ends of the galvanometer may be also put in communication with the edge of the disc: and currents are obtained the direction of which is determined according as one or other of the ends is nearer to the place where the poles of the magnet are situated. If they are both at the same distance from this place, one on the left, the other on the right, the current is null; which is due to there being two equal and contrary currents that neutralise each other.

Faraday obtained exactly the same effects on replacing the ordinary magnet by an electro-magnet, or even by a simple helix traversed by a current, but without an iron core in the interior. Every precaution had been taken that the results should not be influenced by terrestrial magnetism. It was easy to prove that this was the case by determining that there was no longer any effect as soon as the magnet, the electro-magnet, or the helix, was withdrawn from the disc.

The learned English philosopher endeavoured to establish a relation between the direction of the currents that he obtained in his experiments, and the direction of the lines of magnetic force or magnetic curves emanating from each of the poles of the magnet, the force and position of which are determined by the distribution of filings. He concludes that, so long as the direction of the movement of the disc is the same, the relations of the position of the metal with the resultant of the magnetic force remaining also the same, the direction of the current ought not to vary; but that it ought consequently to change if the direction of the movement becomes the inverse of what it was. He succeeded in explaining in a similar manner, by connecting them with the phenomena of the continuous movement of rotation of electric currents and magnets around each other, the different forms under which M. Arago discovered that the mutual action of discs and magnets in movement may be manifested.

All the effects that are connected with the production of the currents of induction, as well in surfaces or metallic masses as in simple wires, appear to me explicable in a more simple manner by tracing them to the primitive law of induction discovered by Faraday himself, and by regarding magnets as Ampère did, as being an assemblage of currents all moving in the same direction, in planes perpendicular to the magnetic axis; a consideration much better justified here, inasmuch as a similar assemblage of currents produces all the same phenomena as are obtained with a magnet.

Let us first examine, under this aspect, Faraday's experiment of the disc that rotates under the influence of a magnet, the pole of which is either above or beneath the surface. One of the ends of the galvanometer is in contact with the axis of the disc, and the other with the points of the circumference, which all pass at the same distance from the magnetic pole or poles. If these points have not yet passed near the pole, it is evident that, at the moment when they are approaching it, there is developed in the portion of the disc to which they appertain, a current of induction parallel to that of the nearest face of the magnet, and moving in a contrary direction. This current, which traverses the length of the radius of the disc, completes its circuit by means of the wire of the galvanometer. If the points of the disc that successively touch the second end of the galvanometer are those which have already passed under the influence of the pole, the current of induction that travels and is collected in the same manner as that which was developed in the first case, is found to be moving in the same direction as the current situated on the face of the magnet, near to which the portion of the disc under consideration has just passed. But this face of the magnet has its currents moving in a contrary direction to the currents of the first face; since the currents that constitute the magnet circulate around its surface. It follows from this, that the current of induction of the first case having a contrary direction to that of the currents of the face of the magnet toward which it is tending, and the current of induction of the latter case having a similar direction to that of the currents of the face it has just quitted, these two currents travel in the same direction; since the currents of the two faces have an opposite direction.*

When the two ends of the galvanometer each communicate with two portions of the circumference, situated on opposite sides of the magnetic pole, then the induced current that is detected by the wire of the instrument is no longer that which travels from the circumference of the disc to the centre, but that which is developed, parallel to the edge, by the influence of the currents of those faces of the magnet parallel to that edge which is the nearest to them. Now, this influence gives rise to two induced currents moving in a contrary direction: one in the part of the disc that tends towards the face of the magnet; the other in the part of the disc that is moving from it. These two currents necessarily traverse the same circuit; a circuit formed of the part of the disc comprised between the two points of contact of its cir-

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* To be more brief, I have employed the word *current* for *the part of the disc in which the current is travelling.*

cumference with the two ends of the galvanometer, and of the wire itself of this instrument. If the two currents are equal, the effect is null. This occurs when the two points touched are in either direction equally distant from the point placed under the influence of the magnet. When the two points are unequally distant, the two currents are no longer equal, and there is an effect arising from their difference of intensity; the one that is developed in the portion of the disc corresponding to the point that is nearest to the pole being always the stronger, because it is the nearer to the cause producing the induction.

The details into which we have just entered, in order to explain Faraday's two experiments, enable us to dispense with giving the description of many experiments of the same kind, made either by this philosopher himself or by others. We shall simply confine ourselves to showing further how the same principles furnish a satisfactory explanation of Arago's phenomena of rotation. Here the currents of induction, that are developed by the successive approach and removal of the magnet, accomplish their entire circuit in the disc itself, since there is no communication established by the wire of a galvanometer or in any other manner; however, it is naturally always the portion of these currents, that is situated in the part of the disc nearest to the magnet, which determines the attractive or repulsive action. The three actions recognised by Arago occur, the one perpendicular to the radii of the disc, the second perpendicular to the disc itself, and the third in the direction itself of the radii. The first—that which draws along the needle—arises from the currents of induction that are determined in the disc itself, and parallel to its plane, by the lower face of the magnetised needle; the currents, which move in a contrary direction to those of the needle in the points of the disc that are approaching toward it, repel it at the same time that it is attracted by the induced currents developed in the points of the disc that are distant from it, and which travel in the same direction as its own current. This double action draws along the needle in the same direction as the disc, or draws along the disc in the same direction as the poles of the magnet, if it is the latter that are set in motion.

The second kind of action, which consists in the repulsion exercised by the disc when in motion upon a vertical magnet suspended above it, arises from the repulsion that occurs between the currents of the magnet and the currents of induction moving in a contrary direction that are acquired by the part of the disc which is approaching it, from the very fact of its approaching it. When once repulsion is brought about, the currents induced in the part of the disc that is moving away are no longer able, on account of their too great distance, to attract the magnet, although they are travelling in the same direction as its own currents; whilst the currents induced in the part of the disc that is approaching continue to repel it. The consequence of this explanation is, that if the magnet is suspended over the very centre of the rotation of the disc it must remain in rest; and this is actually confirmed by experiment.

The third kind of action occurs in the direction of the radius of the disc, and is exercised upon a vertical needle movable around a horizontal axis, in a vertical plane, passing through the centre of rotation of the disc. If the needle is over the very centre, there is no effect, as in the preceding case, and the needle retains its vertical position: this is due to the same cause, namely, to the currents induced in contrary directions being equal in number and in intensity, and acting at the same distances. When the needle is no longer placed above, but at a small distance from the centre, it is repelled toward this centre by the induced currents, developed in the exterior part of the disc, as it was formerly repelled vertically; but if we remove it further from the centre, the currents induced in the interior part of the disc are no longer without effect; they also repel it, and there exists a position in which, the two repulsions being equal, the needle acquires no movement. Beyond this position, namely, nearer to the circumference, the needle is repelled far from the centre, because there is a greater total surface, and consequently more repulsive induced currents withinside than without.

MM. Nobili and Antinoni succeeded in supporting the preceding explanations upon direct experiments, by which they established the presence in the disc of the induced currents to which we attribute the movements of the magnetised needle. With this view, they fixed to the two ends of a galvanometer two wires terminated by two conical metal points, sufficiently stout not to bend under the pressure of the fingers, which points they applied as probes on the different parts of the disc in motion, so as thus to seize upon the currents that pass under these points. It is not necessary, in order to insure communication, to press the points strongly against the disc; by taking this precaution, we avoid the currents to which the liberation of heat would give rise, arising from friction under too powerful a pressure. The results of this species of probing carried out on different positions of the discs in relation to the magnets, constantly show that on the parts of the disc that are entering under the magnetic influence is developed a system of currents contrary to those of the magnet, and on the other side a system of currents having the same direction as those of the magnet, and consequently contrary to the former. With regard to the actual distribution of these currents, and the form of the circuit that they traverse on the disc, by multiplying the probes we are able to determine it with greater or less precision. MM. Nobili and Antinoni endeavoured to accomplish this. *Fig.* 143. gives the graphical tracing of these currents upon a disc set in rotation under the action of the two poles of a powerful horse-shoe magnet placed symmetrically, and the projections of which are represented by N′ and S′; the larger arrows indicate the direction of the rotation of the disc ONES, and the others the direction of the currents in the different points where the probes are applied.

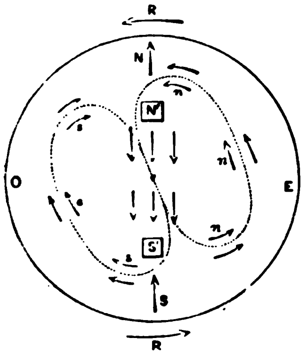

*Fig.* 143.

It is now an easy matter to comprehend the influence over the phenomena of magnetism by rotation, arising from solutions of continuity in the disc. If they diminish the action more as they are more numerous, it is that they oppose the circulation of the currents of induction, and thus diminish their number and intensity; in fact, we have merely, as Herschel and Babbage observed, to fill up the slits of the disc with a conducting metal, in order to re-establish the interrupted circuits, and so to restore to the action almost the whole of its primitive energy.

The differences of force observed by the philosophers that we have just named, between discs made of different metals, is equally well explained by the difference existing between them with regard to their conducting power, and consequently with regard to the greater or less degree of facility that they present to the circulation of the induced currents. Faraday confirmed this explanation by determining, in a direct manner, the force of the induced currents in wires of different kinds. With this view, he coiled together, so as to make a double helix, two wires of the same length and the same diameter, and both covered with silk, but one being of copper and the other of iron. He fixed the two extremities of the copper to the two ends of one of the wires of the differential galvanometer (*Fig.* 135.), and the extremities of the iron wire to the two ends of the other wire of the same galvanometer; so that, if the two wires are traversed by currents having the same direction, they make the needle deviate in the opposite direction; and that, consequently, the needle does not move when the currents possess the same intensity. By introducing into the interior of the helix a cylindrical magnet, he obtained a deviation in the galvanometer; a deviation which was sensibly more powerful, but always in the same direction, when he had suppressed the communication of the helix of iron wire with the galvanometer wire; a proof that the current before this suppression was the difference between the current induced in the copper wire and the current induced in the iron wire, and that the former was much more powerful than the latter. Wires of iron, zinc, tin, lead, and copper, all drawn to the same diameter, were compared two and two in the same manner; only instead of introducing a magnet into the double helices, Faraday placed a soft iron cylinder, which he magnetised by means of a powerful horse-shoe magnet, that produced more marked effects, and amounted to the same thing, as far as the mode of experimenting is concerned. As the result of these comparisons, the metals were found to be ranged in the following order: copper, zinc, iron, tin, and lead. This is exactly their order of conducting power for electricity; this is exactly, also, the order of their power of magnetic rotation according to the experiments of Babbage and Herschel. Those of Harris, also, give similar results. Iron alone forms an exception. This is because, in the phenomena of magnetism by rotation, it acts not only by the currents of induction, but also in virtue of its own magnetic properties. It is this circumstance, also, that explains the difference discovered by M. de Haldat between the effect of a steel disc and that of an iron one; the former, with a very inconsiderable velocity of rotation, exercising an effect almost null; and the latter, on the contrary, acting very powerfully. In fact, the poles of the magnetised needle readily determine, upon the parts of the iron or steel discs, opposite poles, which draw them along by virtue of ordinary attraction; but these poles, which aid for a moment the rotatory motion, being drawn further onward by the rotation itself, act upon the needle in a contrary direction. If they last for a brief space of time, as in soft iron, the rotatory movement, far from finding in them an opposition, receives from them a favourable impulse; if they last longer, as upon steel, they retard the needle, and act in opposition to the rotation. Thus the coercitive force does not, as M. de Haldat thought, influence in a direct manner the dragging force, but it acts simply by retarding in steel the destruction of the ordinary magnetism.

With regard to the action of a very inferior order, and scarcely sensible, that discs made of non-conducting substances exercise upon the needle, it is evident that it cannot be explained in the same manner as that of the metallic discs, since currents of induction cannot be established in them; it is due to another order of phenomena, recently discovered by

Mr. Faraday, and which form the subject of the last Chapter of this Third Part.

### *Magneto-electric Machines.*

We have just seen that magneto-electric induction is a remarkable source of dynamic electricity. We may therefore take advantage of this in order to produce electric currents, as we use friction in the electrical machine for developing static electricity.

The first magneto-electric machine was constructed by Faraday. It consists of a copper disc movable in a vertical plane around a horizontal axis, and made to rotate between the two opposite poles of a magnet (*Fig.* 144.). We have seen that, if we make the two ends of the galvanometer wire communicate, one with the axis of the disc, and the other with a point of its circumference, the deviation of the needle, that occurs in one direction or the other according to the direction of the rotation, indicates the liberation of a constant current in the disc. But this current has very little intensity; it is incapable of producing chemical decomposition, shocks, &c. It is the same with the currents of induction to which terrestrial magnetism gives rise in metal discs or globes set in rotation under its influence.

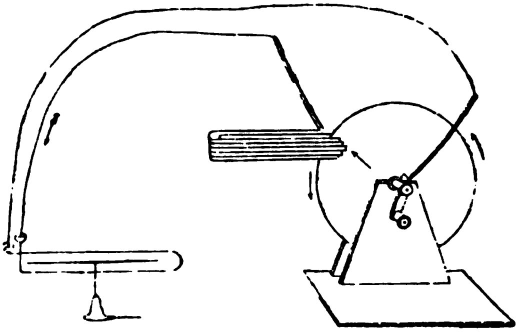

*Fig.* 144.

In order to obtain induced currents of a somewhat decided intensity, we must develope them in tolerably long wires in such a manner, that the conductor by which the ends of these wires are connected is sufficiently good, or at least is not much less good, than the wires themselves. It follows from this, that the current may traverse them instead of retrograding by the wire itself in which the induction occurs. The first artist who constructed a machine on this principle is M. Pixii. A large horse-shoe magnet was set in rotation beneath a similar armature of soft iron, the two branches of which were surrounded by a silk-covered wire. Every time the poles of the magnet arrived under the armature and quitted it, there were induced currents developed in the wires; and these currents were made manifest by the conductors that connected the two ends of these two wires. M. Pixii succeeded in producing, by means of his apparatus, chemical decompositions, shocks, the spark; and he even succeeded, by insulating the ends of the wire instead of uniting them, in charging a Leyden jar and the gold leaves of an electroscope by means of the electricity accumulated in each of them.

This ingenious machine, which was rather inconvenient in actual use, was soon replaced by the much more portable apparatus of Saxton, modified and afterwards perfected by Clarke. Saxton's apparatus (*Fig.* 145.) consists of a powerful

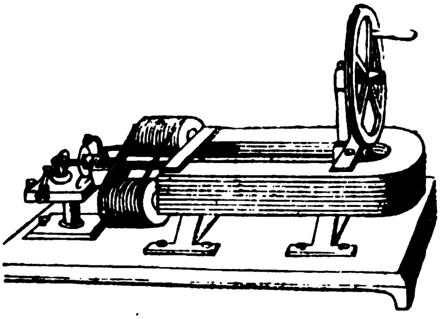

*Fig.* 145.

horse-shoe magnet fixed horizontally; an armature of soft iron having the form of a horse-shoe, and each branch of which is surrounded by a wire covered with silk, is set in rotation before the magnetic poles by means of a horizontal axis passing between the branches of the magnet, and which is itself moved by means of a wheel. An endless cord, passing at once round the circumference of the wheel and the groove of a pulley fixed on the axis by its centre, serves to communicate motion. The two branches of the armature, which is fixed transversely to the extremity of the axis, are, for each turn of the wheel, both made to pass successively before the two poles of the magnet. At each passage there is magnetisation and demagnetisation, and consequently a development in the ambient wire of two induced currents in contrary directions. Hence it follows, that in all there are four currents in each of the two wires for one complete rotation of the wheel. If we compare each induced current in one of the wires with the current induced in the other at the same instant, that is to say, at the instant of magnetisation or at the instant of demagnetisation, we shall remark that these currents must be moving in contrary directions; because the poles of the magnet, to whose influence they are owing, are of a contrary name. In order that they may add to instead of neutralise each other, we must connect together the two ends of each of the wires whence the current seems to come out, and the two ends at which it seems at the same time to enter. These four ends, thus united two and two, present now only two extremities, which are like species of poles, and which are to be united by the body destined to be placed in the route of the induced currents. We may also unite together one of the extremities of one wire with the corresponding extremity of the other; so that the two wires shall form but a single one, traversed entirely by each of the induced currents developed in both wires. It is necessary that, in the same instant, the two currents simultaneously induced should have the same direction; which is obtained by properly selecting the two extremities that are put in communication, and which we have called, in order to express this idea, *correspondent*. The two other extremities, that are not united together, form in this case the two poles. The difference presented by these two arrangements consists in that, in the former, there are two parallel circuits, the effects of which are added together; and that, in the latter, we have but a single circuit of a double length, which propagates a double current of induction. The second circuit is evidently much less a conductor than the first, since it is composed of a single wire of a double length, instead of two wires of half the length; on which account it is preferable, when the currents of induction are intended to traverse imperfect conductors: the first is preferable in cases where the bodies that are placed in the course of these currents have a good conducting power. It is easy, with the same machine, to connect together the ends of the two wires according to one or other mode, and thus to be able, with one and the same apparatus, to obtain the various effects that would require two, one of which would be with a short and thick wire, and the other with a long and thin.

In order to establish communication between the two extremities of the wires or poles, one is made to terminate in a stem fixed on the prolongation of the axis, in the middle of the armature, and which moves with it, and the other in a small vertical metal disc, fixed by its centre to the same stem, which traverses it, but from which it is well insulated by means of a glass tube enveloping the stem. The disc constantly plunges by its lower part into a small mercury bath, which also receives successively the two points of a small brass needle, adjusted to the extremity of the stem, and communicating metallically with it. The mercury thus establishes every time that, by the effect of the rotatory movement, one of the points plunges into it, a metallic communication between the two extremities or poles of the inductive wire. If care is taken so to arrange the needle that each of its points plunges into the mercury at the moment when the armature arrives before the poles of the magnet, it follows that the first current of induction occurs at the instant of immersion, and the second at the instant of the emersion of the needle. Thus this immersion and emersion are each accompanied by a spark produced by these two currents, and there are consequently manifested a series of brilliant sparks, forming as it were a continuous light so long as the rotatory movement is given to the armature.

When we wish to pass the series of induced currents through a conductor, we suppress the needle fixed transversely to the extremity of the axis of rotation, and we press against this extremity, which is cut hollow, the end terminating in a point of a small metal stem, firmly attached to one of the pieces of the apparatus, and the other end of which plunges into a cup filled with mercury. We place this cup, and the mercury into which the small disc constantly plunges, in communication by means of a conductor; and it consequently follows that the latter serves for the passage of the series of induced currents. We must take care to amalgamate the bottom of the small hollow cavity at the extremity of the axis, in order that the communication, established between the bottom and the point against which it rubs in turning, may be entirely metallic, and consequently conducting.

The effects of the induced currents are, with some few differences, the same as those of voltaic currents. Thus these currents heat, and even render incandescent, a very fine platinum wire placed in their course; they decompose the acidulated water of a voltameter; they produce very violent shocks, and sometimes even very painful ones, to the person whose hands clasp the conductors, connected one with the mercury of the small cup, the other with the mercury in which the disc is plunged. In order that this effect may be very sensible, it is necessary that the part of the two conductors that is held in the hands should be in the form of a handle, and be slightly moistened with salt water.

The currents that are obtained by means of the magneto-electrical machine differ from the ordinary currents of voltaic electricity in two respects: the first is that they are discontinuous; the second, that they move alternately in opposite directions. It is to the former of these two circumstances, and not to the latter, that the remarkable intensity of the physiological effects are due; for we may obtain the same result by rendering an ordinary voltaic current discontinuous by means of a rheotome, which produces a series of discontinuous currents, it is true, like the currents of induction, but all moving in the same direction. The influence of the second circumstance is felt in chemical decompositions. Since the currents are moving alternately in one direction and in the other, and since consequently each wire serves alternately as the positive and as the negative pole, it follows that the gases collected around each of the platinum wires of the voltameter in the decomposition of the water are a mixture of hydrogen and oxygen. It even happens that, if the surface of the platinum in contact with the liquid is considerable, a great part of the hydrogen and oxygen that are transported there alternately by the effect of electro-chemical decomposition, combine together to form water. This phenomenon is especially manifested when the currents of induction succeed each other very rapidly, so that the appearance of the oxygen and that of the hydrogen, or each of the two platinum wires or plates, is almost simultaneous. This recomposition causes that the quantity of gas manifested in the voltameter is sometimes very trifling; it may even become null if the recomposition is complete, even though the currents possess great power. This power is then made evident by interposing in the circuit one of the calorific galvanometers that we have described in the First Part of this work. A magnetic galvanometer would not give any indication, because, being traversed by equal currents alternately contrary, which succeed each other very rapidly, there is no reason for the needle deviating in one direction more than in another.

In Clarke's apparatus (*Fig.* 146.), the magnet is vertical instead of being horizontal, and the apparatus is so arranged that we can do without the mercury bath; a small spring, constantly pressing upon a metal cylinder put in place of the vertical disc, serves to establish the communication; this cylinder is itself traversed by the axis from which it is insulated by means of a glass tube, or simply by an envelope of wood: with regard to the axis, it terminates in a cylinder, serving as a commutator or break-piece, and which, to this end, is hollowed out so as to present solutions of continuity upon its surface, or, which is still better, possesses a surface alternately of metal or of wood. It follows that a second spring

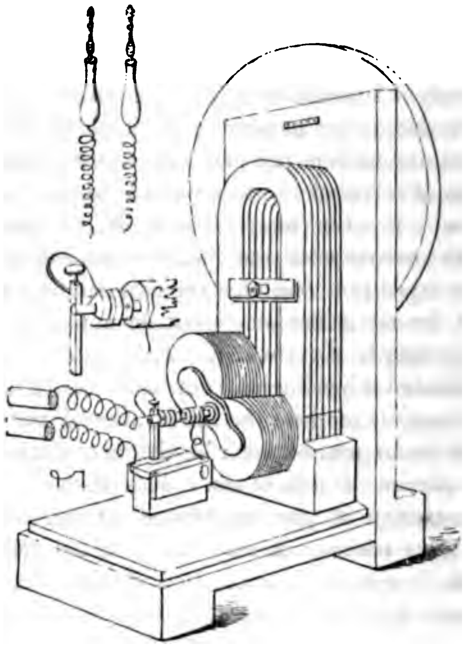

*Fig.* 146.

constantly resting against this piece, is found by the rotation to be in contact sometimes with the metal, at other times with the wood of the surface of the cylinder, which causes it to be sometimes in communication, and at other times not in communication with one of the extremities of the induced wire, whilst the former spring, by pressing against the metallic cylinder which is in place of the disc, and the surface of which is continuous, is always in communication with the other extremity of the wire. The arrangement that we have just been describing possesses the advantage of enabling the experimenter to obtain induced currents all moving in the same direction: it is sufficient for this to combine the interruptions of the communication between the extremity of the axis and the spring that rests against it, so that they shall occur at the moment when the armature approaches the magnet, or else at the moment when it is receding from it. In the former case, it is the currents induced by the magnetisation of the armature that are excluded, and those that occur at the moment of demagnetisation are collected; in the latter case, it is the reverse. A series of induced currents, all moving in the same direction, such as may be procured by the apparatus we have been describing, produce exactly the same effects as the currents of a voltaic pile, especially when they succeed each other with great rapidity. The longer and finer the wire is in which the induction is produced, the more do the currents that are developed in it resemble the currents of piles of high tension. It however happens that, at a certain degree of fineness and length of wire, these induced currents cease to have the power of producing, not only calorific, but even chemical effects. On the other hand, they give rise to physiological effects of much higher intensity. This influence of length and diameter is due to the conductibility of the circuit which depends upon it, being greatly concerned, independently of the producing cause of the electricity, in the greater or less degree of the intensity of the effects of the electric current. This is a point upon which we shall treat in the Fourth Part of this work.

MM. Palmieri and Linari succeeded, in magneto-electric machines, in substituting terrestrial magnetism for the horseshoe magnet. They had at first constructed their machines by arranging on the same horizontal axis several soft iron cylinders surrounded by silk-covered wires wound in helices, and then, placing the axis in a direction perpendicular to the magnetic meridian, they gave it a rotatory movement, whence there resulted, in the cylinders of iron, by the effect of terrestrial magnetism, a magnetisation alternately in one direction and the other, and consequently the production in the ambient wires of a series of currents of induction, exactly similar, except in intensity, with those that are obtained in Saxton's and Clarke's machines, by making the soft iron armatures pass in front of the poles of the magnet. An arrangement of the same kind, as those that we have described when speaking of these machines, serves to collect the induced currents in MM. Palmieri and Linari's apparatus, and to separate them at pleasure. The two philosophers succeeded, in a second machine, in developing directly, and without the intervention of the soft iron, induced currents in copper wires, by the immediate action of terrestrial magnetism. After various attempts, they found that the best method of obtaining this result consisted in taking a thick copper wire, about $\frac{1}{5}$ in. in diameter, and several yards in length, and winding it around an elliptical frame, $39\frac{1}{4}$ in. in diameter, in the direction of its larger axis. A rotatory movement is given to this frame around its axis, taking care to place the axis in a direction almost perpendicular to that of the magnetic meridian; they obtained currents of induction which give a powerful spark, and produce all the calorific, chemical, and physiological effects of the ordinary magneto-electric machines. In this apparatus, MM. Palmieri and Linari, in order to collect the induced currents, made one of the extremities of the wire communicate with a simple small metal wheel, plunging into a mercury bath by its lower part, and the other extremity with an axis traversing the entire wheel, but at the same time insulated from it. The conductor by which the extremity of the axis and the mercury bath were connected, was traversed by the currents. It is exactly the same arrangement as in Saxton's apparatus, that we have described above. However, up to the present time, notwithstanding the persevering efforts of M. Palmieri, the magneto-electric machines founded upon the employment of terrestrial magnetism have not been able advantageously to replace those in which the magnetic influence emanates from magnets.

But of all magneto-electrical machines, the most powerful are those in which we make use of a temporary magnet or electro-magnet. Their mode of construction differs essentially from that of the machines in which the action is derived from an ordinary magnet. In fact, it is not necessary to have an armature and an electro-magnet, nor consequently to give one a movement in respect to the other. It is enough to have a single piece of soft iron (in the form of a cylinder, for example), around which we coil two wires covered with silk: we pass a voltaic current through one of these wires, taking the precaution to render it discontinuous by means of a rheotome, and we obtain, in the other, a series of induced currents moving alternately in contrary directions, and corresponding to the passage and to the interruption of the inducing current. The wire that conducts the inducing current ought not to be either too long or too fine, seeing that the current arises generally from a single pair, and that it is necessary, in order that the magnetism of the soft iron be powerful, that the resistance of the conductor be inconsiderable. With regard to the wire in which the induced current is developed, its dimensions depend, as in the machines that we have been describing, upon the nature of the effects that we desire to produce. With a wire about 30 or 40 yards in length, and of great fineness, and by passing the current of only one pair of Daniell's, having a surface of 4 or 5 in. square, through an ordinary wire, we are able to obtain induced currents of such an intensity, that a very strong man cannot with impunity endure for a minute or two the shocks to which they give rise.

For all other chemical or calorific effects, we generally employ for receiving the induced current a similar wire to that which conducts the inducing current. The two wires are coiled either together, or one over the other, around the bobbin, in the interior of which is placed the soft iron. The latter may be indifferently a solid or a hollow cylinder. There has even been found some advantage in supplying the place of the cylinder by a bundle of wires, or, better still, of soft iron bars, insulated from each other by a layer of varnish. This circumstance does not permit of the establishment of currents of induction circulating, as in the case of a single cylindrical bar, over the exterior surface of the cylinder, currents which diminish the inducing powers exercised upon the wires themselves. It is for the same reason that we must avoid placing in the interior of the bobbin a hollow cylinder of brass or copper; it would be better that the magnetic bundle should be in immediate contact with the wood. However, these precautions are not indispensable; they are not really necessary, except in certain cases in which we are engaged upon particular effects, as we shall see further on.

One of the most important parts of soft iron magneto-electric machines is the rheotome. The most simple is a toothed wheel, moved by the hand by means of a small handle, and communicating by its axis with one of the poles of the pile, whilst the other pole is in communication, by means of the inducing wire, with an elastic plate resting against the teeth of the wheel. Every time the plate, in consequence of the rotatory movement, leaps from one tooth to another, there is an interruption and a completion of the circuit in the inducing wire, and consequently a production of two induced currents successively in opposite directions in the induced wire. When the two ends of the induced wire are not united by a conductor, the currents give rise to a spark that escapes between the plate and the tooth, and which arises from the current induced in the inducing wire itself, which is only manifested so long as the former is not manifested.

The rheotome that gives rise to the most powerful current of induction is the mercury rheotome that is described (*Fig.* 130.). We require only two needles, which close the circuit when they are plunged into the mercury, and interrupt it when they come out: they are fixed transversely to an axis that is itself moved by a clock movement, the velocity of which is regulated by means of fans, to which is added the effect of the resistance of the mercury. The only inconvenience presented by this system is that the mercury is projected, and is very rapidly oxidised. It is then covered with small black globules, that interfere with the perfect contact of the needles with the liquid metal, and, as they rise above its surface, frequently make the two compartments communicate together in a permanent manner; and they ought not to have any other communication than what is established, at intervals, by the two needles that plunge into it. The apparatus annexed (*Fig.* 147.), constructed by M. Bonijol, represents an induction machine, in which the two rheotomes may be indifferently employed. The two cups, A and B, are intended to receive two poles of the pile (generally a single pair).

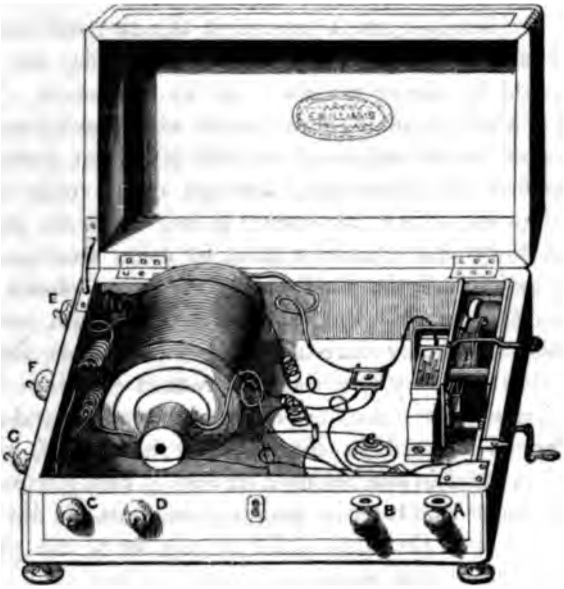

*Fig.* 147.

From the cup B there proceed two conductors, one of which is attached to the toothed wheel, the other to one of the compartments of the mercury rheotome. From the other compartment of this rheotome, as well as from the elastic plate that rests against the toothed wheel, comes a conducting wire; and these two wires arrive at the other extremity of the inducing wire. If we wish to employ the mercury rheotome, we set the clock movement in motion, and the needles immediately execute their immersion and their emersion: we take care at the same time to raise the elastic plate, so that it shall have no point of contact with the toothed wheel, and that the current can only be established by the mercury rheotome. If we desire to employ the toothed wheel, we make it rotate by means of the handle, after having put the elastic plate again in contact with it; we at the same time take care that the needles of the other rheotome, which are no longer in motion, are arranged in their state of rest, so as not to plunge into the mercury, and consequently not to permit the current to circulate by this path.

The two knobs C and D represent the two extremities of the induced wire; any conductor by which they are united is traversed by the succession of induced currents. To the two other knobs, E and F, arrive metal wires, each proceeding from one of the extremities of the inducing wire: these knobs are intended for transmitting through every conductor, by which they are united, the currents induced in the inducing wire itself, in such a manner that, by using alternately the knobs C and D, and the knobs E and F, we can obtain either the one or the others; but we cannot make them act at the same time, the former currents existing only when the latter are not liberated, as we have already remarked. It is, indeed, a very remarkable thing to see this mutual dependence of the currents induced in the inducing wire itself, and the currents induced in another parallel wire. This circumstance is a good proof that the two species of currents are due to the same cause, and that they differ merely as to the place in which they are propagated.

The chemical and calorific effects that may be produced by means of these induced currents, as well by means of one as of the others, are very energetic. We can ignite a platinum wire, and can even obtain a small luminous arc between two points of coke. With regard to the chemical effects, they are very decided at the first instants: but the two gasses liberated alternately at the two wires of the voltameter very soon recombine, and the chemical power seems in appearance diminished.

A fifth knob, G, placed after E and F, communicates with a wire which comes to the cup B. It is employed for the following purpose; or, what amounts to the same thing, the following is what occurs, when it is united by a conductor to the knob E. The current induced in the inducing wire, which is liberated at the moment of the breaking of the circuit, is found by this combination compelled to traverse a circuit formed of the inducing wire, of the conductor interposed between E and G, of the wire that goes from G to the cup B, of the voltaic apparatus that connects the cup B with the cup A, and of the wire that goes from the cup A to the inducing wire. The induced current is moving in the same direction as the inducing current, namely, as the current of the voltaic apparatus, so that the conductor placed between G and E is traversed at once by two currents, namely, the induced current and the voltaic current. There results from this an effect which is more than the sum of the effects of the two currents when separate; for it appears that the passage of the induced current through the voltaic apparatus notably increases the powers of this apparatus. This augmentation is especially sensible, when the voltaic apparatus consists of a single pair, and the conductor interposed between G and E is a voltameter. We then see the current of one pair, incapable of itself to decompose water, produce, with the addition of its own induced current, a very energetic chemical decomposition. This reinforcement of the current by itself, which I discovered in 1843, led me to give the name of *electro-chemical condenser* to the apparatus, by means of which I succeeded in obtaining it.

This apparatus (*Fig.* 148.) presents a peculiarity of some interest; it is, that in place of a toothed wheel, or a clock-movement with needles and mercury, it contains, for rendering the current discontinuous, a simple elastic metal stem, provided with a small piece of iron, placed very near to the

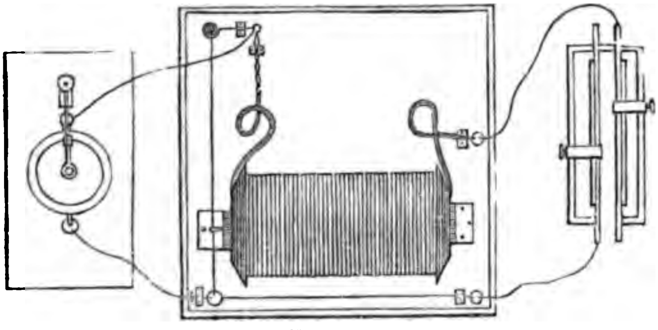

*Fig.* 148.

soft iron of the bobbin. When this soft iron is magnetised, the small piece of iron is attracted, and the elastic stem to which it is connected is raised; this occasions the breaking of the inducing circuit, which, in order to arrive at the wire of the bobbin, must traverse the stem, and pass into a small metal cup filled with mercury, or simply amalgamated, on the bottom on which the extremity of the stem rested. This rupture of the circuit destroys the magnetisation of the soft iron of the bobbin; the small piece being no longer attracted, the elastic stem immediately falls back, so that its extremity rests again on the bottom of the cup, and the circuit is made again. It follows from this that the current is interrupted a greater number of times, according as it is more intense; the rapidity with which the interruptions succeed each other depending on the power of the magnet.

Instead of having a distinct apparatus, we may adapt this kind of rheotome to the same case that already possesses the two others, as may be seen by *Fig.* 147. A small capsule, placed beneath G, and communicating with one of the ends of the inducing wire, receives the bended extremity of an elastic stem, that arrives at the cup A, and, passing near the soft iron of the bobbin, is furnished, in the part nearest to this iron, with the small piece, which is also of iron, and which, by the attraction that it obeys, raises the stem, and so interrupts the circuit.

Another more simple apparatus, also constructed by M. Bonijol (*Fig.* 149.), presents, under another form, the same system of rheotome. We interpose in the circuit of the inducing wire, a bent but fixed stem, A B, and an elastic plate, C D. The plate, by virtue of its elasticity, naturally places itself in contact with the extremity of the stem: the two surfaces in contact are covered with a platinum disc, in order to avoid oxidation and the rapid destruction of the metal. It is therefore between the two platinum discs that the contact occurs, and from which the spark darts, if there is one. The elastic plate is traversed in E by a stem that may be raised or lowered, so as to bring its extremity, which is a horizontal iron disc, at a proper distance from the soft iron of the bobbin. It follows from this, that the attraction exercised by this iron, when magnetised, upon the soft iron disc, compels the plate to separate itself from the fixed stem A B, and so interrupts the circuit, which is immediately re-established, the magnetisation ceasing as soon as it is broken. The second wire which arrives at F and at G, as well as every conductor interposed between F and G, receives the induced current. The poles of the voltaic apparatus are to communicate, one with one of the extremities of the inducing wire, the other with the extremity C of the elastic plate; the fixed stem A B being placed in direct communication at K, by means of a conductor, with the second extremity of the inducing wire. In this manner, the circuit is closed so long as the stem and the plate remain in contact at D B; it is open as soon as magnetism has separated them.

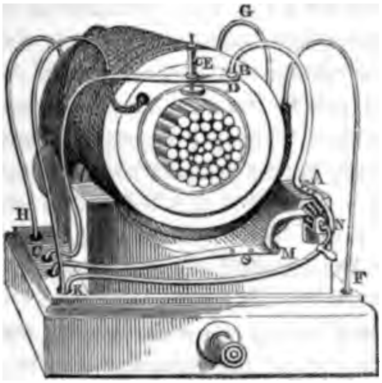

*Fig.* 149.

With this apparatus, as well as with the preceding ones, we are able to obtain the induced current in the inducing wire itself by placing H and K in direct communication by the intervention of the conductor, in which we desire to transmit this induced current. We may, in like manner, cause the induced currents to pass through the voltaic apparatus itself by placing the interposed conductor, which is, for example, a voltameter, as C and K are placed. In fact, the current induced in the wire H K is obliged, in order to accomplish its circuit at the moment when the communication is interrupted in B D, to traverse the pair from H to C, in order to arrive through the interposed conductor from C to K, where it finds the second end of the wire H K.

The same apparatus is also provided at H and N with a rheotome with an elastic plate and a toothed wheel, that may be employed for certain experiments in which the self-acting rheotome could not be set in action, or would not be conveniently applicable. This, for example, would be the case when the inducing current should be acting without the intervention of the soft iron of the bobbin, in order to produce an induced current. It is evident that we must here have a rheotome that has its mode of action independent of magnetisation.

It is necessary, when we make use of this rheotome, to transfer to I the end of the inducing wire that was formerly at K; because it is at I that the conductor arrives which comes from the elastic plate intended for interrupting the circuit, by leaping from one tooth to the other of the wheel N set in motion by the handle. There are in H, in C, and I, and in K, small cavities hollowed in the wood and filled with mercury, in order to facilitate communication.

The soft iron placed in the interior of the bobbin is not a single cylinder, but a bundle of small cylinders covered with an insulating varnish of wax.

Such are the principal magneto-electric machines that are generally employed. If the former are of more easy and of more economical employment, since they require only an ordinary magnet, the latter, which require at least the voltaic current of a single pair in order to magnetise the soft iron, possess the indisputable advantage of being much more powerful. We shall see that each of them may confer great services on electricity, either under purely scientific relations, or in relation to practical applications.

Before terminating this subject, let us add, that the principle of the self-acting rheotome may be demonstrated by a very simple apparatus. This apparatus possesses the additional advantage of being applicable to any electro-magnet, so as to obtain from it the current of induction produced in the inducing wire itself (which is indispensable in this case; for there is only one wire around the electro-magnet). This current, being obliged to traverse the pair that produces the magnetisation, becomes capable of developing electrical effects which, without this mode of the intervention of the electro-magnet, would require the employment of several pairs. The apparatus (*Fig.* 150.) consists of a horizontal rod movable around a transverse axis; the rod carries at one of its extremities a soft iron disc, which, when it is in equilibrio, is only about the tenth or twentieth of an inch at most from the polar surface of the electro-magnet; the other extremity is in contact, by its bent point, with the bottom of an amalgamated capsule. This rod, being maintained in equilibrio by a counterpoise, is traversed by the current that circulates around the electro-magnet. Immediately this circulation occurs, the electro-magnet is magnetised, and, the iron disc being attracted, the rod loses its horizontality; whence it follows, that the circuit is interrupted at the point where there was contact between the capsule and the bent extremity. This interruption causing the magnetisation to cease, the rod recovers its horizontal position, the current immediately begins to circulate again, and so on. According to the arrangement of the conductors, the current may be brought to traverse the voltaic pair itself, or to be transmitted directly through any body placed in its route. The figure represents it traversing the voltaic pair. A very curious fact is, that if the small soft iron disc is placed over the central part of the polar surface of the electro-magnet, there is no attraction, however powerful the electro-magnet may be. In order that

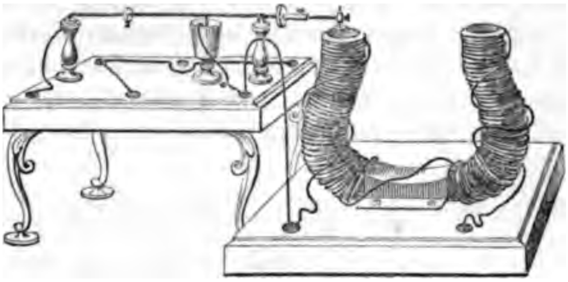

*Fig.* 150.

attraction may take place, and, consequently, in order that the instrument may work, it is necessary that the disc be near the edges of the polar surface. It would not be the same if the soft iron disc, instead of being very thin, had a thickness of a ninth or tenth of an inch or more. This negative result is therefore evidently due to the fact, that, when it is very thin and is placed symmetrically in respect to the magnetic forces, namely, in the centre of the polar surface, a small plate of soft iron acquires on its two faces two equal and contrary polarities, which neutralise all exterior action, however powerful it may be.

### *Electro-Static Effects of Electro-Dynamic Induction.*

After having explained the mode of producing currents of induction and their principal properties, and having described the machines, by means of which they may be developed in a powerful and continuous manner, it remains for us to study various remarkable phenomena presented by electro-dynamic induction. Hitherto we have confined ourselves to establishing this fundamental principle,—that closed currents or magnets develope in a closed circuit two instantaneous induced currents: the first, moving in a direction contrary to the inducing current, is disengaged at the moment when the inducing and the induced circuits are brought near to each other; the second, moving in the same direction as the inducing current, is disengaged at the moment when the two circuits are removed away from each other. We have described the different methods of making the inducing current or the magnet act; we have demonstrated that motion is an essential condition of this kind of action; and we have seen how, by varying the mode of motion as well as the form of the induced conductor, we are able to obtain discontinuous currents all moving in the same direction, or discontinuous currents moving alternately in contrary directions. Finally, in the production of induced currents, we have found an explanation of magnetism by rotation. This first general glance at induction has been sufficient to enable us to comprehend the description and the theory of magneto-electric machines. But it remains for us now to examine several points relative to induction itself, which we have barely glanced at, or have not even touched upon. Thus, induction by currents and magnets not only gives rise to dynamic electricity, but produces the electro-statical effects of tension: thus induced currents may themselves also become inducing currents, and so give rise to induced currents of another order; so, also, electric discharges, such as those of a Leyden jar, are able to produce induced discharges. Finally, many circumstances,—length, form, the nature of the induced circuits, the interposition between them of certain bodies, exercise an important influence over the results of induction. The properties of induced currents may themselves vary with these circumstances, and with others also; such, in particular, as the introduction into or the absence from the interior of bodies that are employed for the induction, of pieces of iron of different forms and qualities, and of other different substances. There are many different points of view under which it remains for us to regard the very rich subject of electro-dynamic induction. Under the impossibility in which we are placed, of giving a complete idea of the labours of all the philosophers that have been engaged with it, as Masson, Breguet, Henry, Abria, Matteucci, Marianini, Wartmann, Knockenhauer, Riess, Verdet, Dove, Weber, &c., we shall confine ourselves to stating summarily, and without confining ourselves to chronological order, the principal results of their researches.

*A current of magnetic induction is able to produce sparks at a distance in the air, and powerfully to charge a condenser: consequently, a current of induction can be entirely transformed into static electricity.*

This is the important principle which Faraday had already glanced at, but which MM. Masson and Breguet have verified and established by experiments made upon a very large scale, and which are the more conclusive, as the source electricity, of which they employed for producing the induction, was a current or a magnet, and not the electricity of tension. Two wires, each 711 yards long, and well insulated, were coiled round a bobbin, so as to be in juxtaposition to each other. One of the wires was placed in the circuit of a pile; the other communicated, by its two extremities, with the plates of a condensing electroscope. Every time the inducing circuit was interrupted by means of a rheotome, powerful charges of electricity were given to the condenser, the sign of which was in accordance with the direction of the current that would have been obtained in a galvanometer. We are also able to draw sparks from the plates of the condenser, but only when it is charged with the induced current at the moment of the interruption; for the one that is induced at the moment of the establishment of the circuit does not give sparks, and charges the condenser but feebly.

In order to obtain the signs of electric tension, it is not necessary to employ the two ends of the same helix. If we have two helices, one of 1422 yards, traversed by the inducing current, and insulated upon a cake of resin; the other, of 711 yards, placed over and very near to the former, and suspended by a silk thread so as to be well insulated, we experience a smart shock on seizing the extremity of the wire of the former helix, and the contrary extremity (namely, that which is charged with a contrary electricity) of the second. This experiment proves that the two wires are, at the moment of the interruption of the circuit, under the same conditions as are two charged Leyden jars. The length of the wire produces almost the same effect of insulation as a glass plate; and the tension observed in the inducing wire arises from the extra-current, or the current induced by itself. This extra-current may also of itself alone give, with the 1422-yard helix, effects as powerful as the induced current. It has even produced very bright sparks in vacuo between two brass balls, placed at a distance of, at first, nearly $\frac{1}{10}$th of an inch apart, and then brought to $\frac{3}{4}$ inch, without the light ceasing to disappear. In this experiment the ball and all the rod forming the positive pole of the extra-current are surrounded by a violet atmosphere; the negative ball is entirely bare; but between the two balls there is a kind of reddish flame, of which the negative ball is the base; and from time to time there are perceptible on this same ball a multitude of small brilliant points. The pile by which the inducing current was produced was simply eight pairs of Daniell's. With the induced current in a different helix from that in which the inducing current circulates, we obtain luminous effects quite as decided; which proves that we can induce a current in an open wire, provided, however, that its two extremities are connected by a conductor, a position here filled by the vacuum. Furthermore, the properties of the electric light that is obtained by means of the currents of induction, entirely resemble those of the light, that is liberated in electric discharges.

In all these experiments, MM. Masson and Breguet made use of a toothed-wheel rheotome (*Fig.* 131.). M. Abria, by means of an almost similar rheotome, and of which we give the description further on, obtained luminous effects, which were also very decided; but he remarked that the negative ball or point is surrounded with a violet atmosphere, whilst the positive point gives out a reddish flame, which elongates in proportion as the point is made to recede from the ball, but without reaching to this latter, so that there exists an obscure interval between the point and the upper part of this flame. This reddish light only traverses the distance between the ball and the point, which is about $\frac{1}{5}$ or $\frac{1}{6}$ of an inch.

### *Induction by induced Currents.*

Mr. Henry, of Princetown, discovered and carefully studied the induction of a current upon itself, and he contrived to construct a spiral plate, *a* (*Fig.* 151.), composed of a metal ribbon covered with silk, which, when interposed in the circuit of a very feeble current,—one incapable of producing the slightest spark of itself, gives a very brilliant one at the moment when the circuit is broken; an effect that is due to the current induced in the spiral itself, which conducts the inducing current. This same spiral, *a*, produces by induction in another, *b*, which is placed over it, a current that has the power of producing powerful shocks (*Fig.* 151.). But the point which the American philosopher most particularly studied, is the development of currents of induction by the induced currents themselves. With this view, he made use of several flat spirals (*Fig.* 152.) above and very near to the former one, *a*, which conducts the current of a pile, or of the *first order*, he placed a second and similar one *b*, the two extremities of which are connected to those of a third, *c*, placed at a certain distance; above the latter, and very near to it, is a fourth, *d*, the extremities of which are in like manner connected with those of a fifth, *e*, and so on. At the moment when we interrupt the circuit of the first order, which is circulating in *a*, there is in *b* an induced current of the second order, moving in the same direction as the current of *a*; the current of *b* traverses *c*, and determines in *d* a current of the third order, moving in a contrary direction, and which, traversing *e*, determines in the spiral placed beneath it a current of the fourth order, still moving in a contrary direction to its own. With the exception of the first induced current, which is due to the immediate action of the current of the piles, all the other induced currents, arising from the action of the induced currents themselves, are moving in a

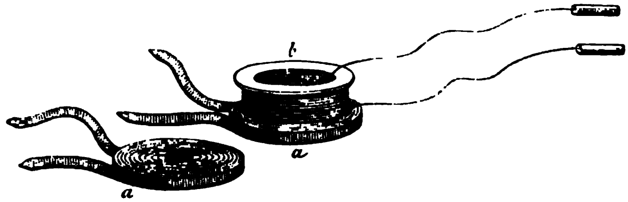

*Fig.* 151.

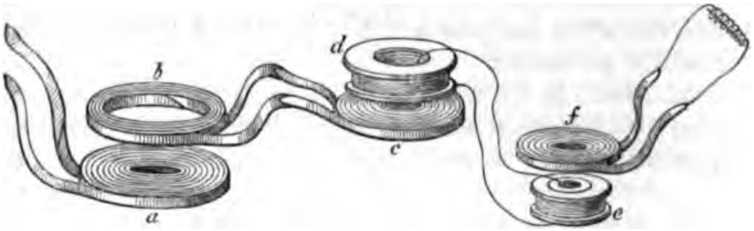

*Fig.* 152.

contrary direction to their inducing currents. This difference arises from the fact that, as an induced current is instantaneous, it must, when it acts as an inducer, determine two induced currents almost at the same time, one in the opposite direction to its own at the moment when it is established, the other in the same direction at the moment when it ceases. We see that it is the former that overcomes the latter in the present case. Moreover, the direction of these different induced currents is determined by the interposition in their circuit either of a galvanometer-multiplier or of the chemical voltameter. However, the process employed in preference by Mr. Henry is the employment of a magnetising spiral placed in the induced circuit of any order. *Fig.* 152. represents one placed in the circuit of the current of the fourth order. This spiral indicates the direction of the induced currents by the direction of the magnetisation imparted to a small steel needle placed in its interior.

M. Abria, in a very remarkable work on induction, has completed Henry's researches, principally in as far as concerns induced currents of different orders, and the influence of several circumstances upon the intensity and the direction of induced currents in general. By employing the method of the magnetisation of steel needles, and by extending the experiments as far as currents of the seventh order, he first verified that for the succession of different induced currents, there is the following series, when the induction is produced by breaking the circuit. The current of the first order is the voltaic current itself at the moment when it is broken; and the change of sign indicates the change in the direction of the current.

| | |
|---|---|
| Current of the pile, or of the first order - - | + |
| Current induced by the rupture of the preceding, or of the second order - - - - | + |
| Current induced by the rupture of the preceding, or of the third order - - - - | — |
| Current induced by the rupture of the preceding, or of the fourth order - - - - | + |

Current induced by the rupture of the preceding, or of the fifth order - - - - −

The same phenomena occur at the moment when the voltaic circuit is formed, instead of being opened; but as the current of the second order is then in an opposite direction to that of the inducing current, the changes of sign occur, setting out from the current of the second order, and we have the following series: —

Current of the pile, or of the first order - - +
Current induced at the moment when the preceding is established, or of the second order - - −
Current induced at the moment when the preceding is established, or of the third order - - +
Current induced at the moment when the preceding is established, or of the fourth order - - −
Current induced at the moment when the preceding is established, or of the fifth order - - +

We have distinguished the induced currents of different orders of the two series, by saying that each of those of the former is produced by the *rupture* of the preceding one, and each of the latter by its *establishment.* But these currents, except that of the first order, being all instantaneous, it is in fact impossible to distinguish their establishment from their rupture, or, to speak more correctly, we should confine ourselves to saying that instantaneous currents develope by induction currents also instantaneous in a contrary direction to their own; whilst currents that have a sensible duration develope currents, whose direction is contrary to their own, at the moment when the action commences, and is the same when it ceases.

The production of these induced currents of different orders, very well explains the diminution experienced by induction when a closed spiral, namely, one in which the two ends are metallically united, is brought near to the inducing spiral. We must merely consider that we have then two closed spirals placed in the vicinity of the same inducing spiral, namely, the spiral primarily subjected to experiment, and the new spiral that is brought near to it. The currents induced in each of them, by the direct action of the inducing spiral, are in the same direction; but each determines in the other a current of the third order, and we thus perceive, as experiment demonstrates, why the effect of induction is less than if the additional spiral did not exist; for this current of the third order has a contrary direction to that of the second order, and consequently diminishes in each spiral the intensity of this current.

M. Abria occupied himself greatly in the study of the mutual reaction that spirals thus exercise over each other; and he also discovered that the diminution produced in each induced spiral, by the inducing effect of the current of the other, depends not only upon the intensity of this latter, but also on other circumstances, such as their position either in relation to the inducing system or in relation to each other. But, of all the results obtained by M. Abria, the most important, inasmuch as we are able to deduce from it the explanation of the alternate direction of the currents of different orders, and that of the variable effects of the additional spirals, is the difference that he succeeded in establishing between the direct and the inverse induced currents with regard to their faculty of being transmitted through a given circuit, notwithstanding that these currents are equal. With this view, he studied the currents of induction, not only with the galvanometer, but by means of their physiological, their calorific, and their chemical effects. For these last two kinds of effects, and, in certain cases also, for galvanometric effects, he made use of an apparatus which could give him a series of induced currents, either direct, that is to say, corresponding to the rupture of the voltaic circuit, or inverse, that is to say, which are developed when forming this same circuit.

This apparatus is composed of two toothed wheels, with brass and wooden teeth, and mounted upon the same axis, but insulated. The central part of each wheel communicates with a steel spring, and the surface with a brass spring. The two wheels are able to turn tightly and independently of each other upon a common axis; they are, moreover, perfectly equal; and we can understand that, if the steel and the brass springs of one of them are made to communicate with the extremities of the induced circuit, it is easy to arrange the two wheels so that the brass spring of the second falls upon a wooden tooth at the establishment of the voltaic current, and upon a metal one at its rupture. We then obtain in the induced circuit a series of currents all in the same direction, developed by the rupture of the voltaic current. We can also arrange the two wheels so as to obtain in the secondary circuit a series of induced currents, all in the same direction, developed by the establishment of the principal current. I have described (*Fig.* 130.) an apparatus which, by means of two systems of two needles, each one of which forms part of the inducing circuit, and the other of the induced circuit, can produce the same effect, if we take care so to arrange it that the two needles of the induced circuit do not plunge into the mercury when those of the inducing current come out of the mercury, and consequently thus occasion the rupture of this current. We have then a series of direct currents. We can also procure a series of inverse currents by arranging the needles so as to collect the induced currents that occur at the moment of establishing the inducing circuit, and avoiding those that occur at its rupture.

*Fig.* 153. represents a commutator, founded upon a principle analogous to that of M. Abria, only it possesses the

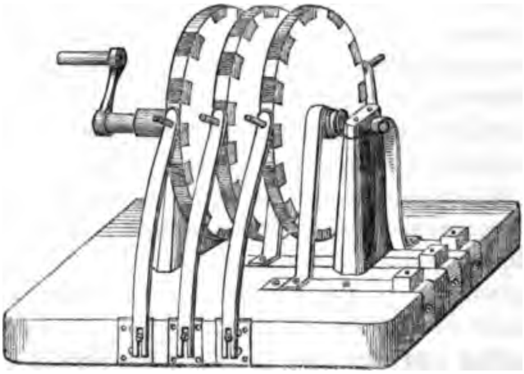

*Fig.* 153.

advantage of being applicable to a greater number of possible combinations. M. Wartmann was the first who constructed it. It is composed of three metal wheels, which present at their circumference twelve hollows filled by inlayings of hard wood. They are placed upon the same brass axis, which rotates easily. A spring, that constantly rests upon this axis, communicates by this means with the most distant wheel; the other two wheels do not communicate metallically with the axis from which they are separated by an ivory ring, covered exteriorly with a brass cylinder against which a spring rests, so that there are three springs pressing against the axis, of which one alone communicates metallically with one of the wheels: these three springs can be placed in metallic communication with each other. Finally, six springs made of hard copper plate, and fixed by screws to the stand of the instrument, rest by their free extremity against the circumference of each of the wheels. We can at pleasure reduce the apparatus to two wheels when we desire to have but one of the induced currents, and to one alone when we desire to confine ourselves to rendering a voltaic current intermittent. We must be able to change the place of the contact of the springs that rest against the circumferences of the wheels, and to change the position of one of the wheels upon the axis in respect to the others. We have also the power of collecting either of the induced currents, and even, by employing the first wheel, to render the current intermittent, and each of the other two to collect each of the two induced currents, we may succeed in procuring the series of induced currents, all travelling in the same direction. For this purpose, we have merely suitably to arrange the conductors that serve to unite together the different elastic plates, that are resting against the circumferences of the wheels, and the springs that press against the axis.

It follows from all the observations made by M. Abria with a series of induced currents, that the consequences to which he had arrived by studying the currents of induction by the method of magnetisation are found to be verified, in as far as the general order of the results are concerned, by the study of their calorific, their chemical, or their physiological effects. Were we indeed able to measure accurately these latter effects, it is probable that we should obtain concordant values with those that are furnished by the other methods.

With regard to the galvanometric effects, they differ from the others in that they are equal in a secondary circuit, whether they correspond to the rupture or to the establishment of the circuit; whilst it is not the same with the other different effects, which are, on the contrary, unequal under the same circumstances. In like manner, these latter are influenced by the action of metal spirals or plates, whilst the former are not so. Finally, the deviations of the needle are scarcely sensible when the galvanometer forms part of a circuit of a superior order to the second. But, if we pass through the galvanometer, the two series of induced currents, moving alternately in contrary directions by means of the toothed wheel, and no longer, so that the circuit is constantly closed, the needle generally indicates by the direction of its deviation, a single series of currents, that of direct currents. However, we see plainly, by the occasionally uncertain movements of the needle, that the inverse currents also traverse, alternately with the direct ones, the wires of the galvanometer; but these currents experience an unequal resistance in passing from the springs to the brass wheel, and the galvanometer indicates the series of currents that have undergone the least reduction, or which have the highest tension. Sometimes the inverse currents have the mastery, but, after a few moments, the needle of the galvanometer passes to the other side, and indicates the presence of the direct current. It follows from this, that the two successive currents that are manifested in an induced circuit of the second order are really equal, as indeed experiment shows, when the circuit is uniform; but, as soon as it ceases to be completely uniform, the direct current predominates, being better able to traverse a non-uniform circuit, than is the inverse current. Now this is what occurs in physiological, calorific, and chemical effects, and even with the galvanometer, but only in the case when the toothed wheel is in the circuit.

With regard to currents of higher orders, it is very probable by analogy that they consist, the third of two contrary currents corresponding to a current of the second order, the fourth of four currents corresponding to the two of the third order, and so on; since each current must always induce two others in opposite directions in a neighbouring conductor. All these currents have a very brief duration; those of the first order must be equal to each other, but must differ, as do those of the second, by their facility of being transmitted in a circuit not perfectly continuous. In fact, if we place a galvanometer in a continuous circuit of the third order, and allow only direct secondary currents to act upon the spiral, by placing the toothed-wheel in the secondary circuit, we obtain a series of tertiary currents − +; − +; − +; the needle of the galvanometer indicates the equality of these opposite currents, by placing itself indifferently on the right or on the left of zero, or at zero itself. It is the same when we act with inverse secondary currents. But if we place the toothed-wheel in the tertiary circuit, the galvanometer detects the presence of a single current only, instead of indicating that of two contrary currents, as in the preceding case. When, for example, we collect the tertiary currents developed by the *rupture* of the primary circuit, the needle indicates the series of currents − − −; the series of currents + + + being more reduced than the other, in passing from the spring to the wheel. It is the reverse when we collect the tertiary currents developed by the *establishment* of the primary circuit.

To sum up:—a primary current developes two induced secondary currents in contrary directions, one at its establishment, the other at its rupture: these two currents may be separated by an interval of time; they are equal, but have not the same tension, that is to say, the same facility of traversing imperfect or discontinuous conductors. Each secondary current is able to determine two opposite tertiary currents, but separated by an interval of time of inappreciable duration, seeing that the secondary current is itself instantaneous. These two tertiary currents are equal, but they likewise have not the same tension. Each tertiary current is in like manner able to determine two equal quarternary currents, but also of different tensions; at each secondary current, namely, at the rupture or establishment of the primary current, there correspond therefore four quarternary currents, produced by the two tertiary ones. If all these induced currents, that are separated by infinitely short intervals of time, had the same tension as well as being equal; or, rather, if they had to traverse only perfectly uniform circuits, they would all mutually neutralise each other, and no effect would be manifested. But this is not the case, on which account it is that there is a production of phenomena, due to the superiority of tension of the currents moving in one direction over those moving in the other.

This is the most plausible explanation that can be given of the currents of different orders: we shall see that it is found to be confirmed by the study of the phenomena of induction, produced not merely by the currents themselves, but by the electrical discharges, to which we are about to turn our attention. But first, I ought again to mention certain laws relative to induced currents, discovered by M. Wartmann, who has been much engaged upon this subject. This philosopher has shown that, *for lengths of additional wire increasing in geometric progression, the intensities of the induced current measured by the galvanometer diminish in arithmetical progression, as well when the induced circuit is opened, as when it is closed.* It follows, as a matter of course, that the length of the induced wire was constant, and it was that of the inducing wire that was variable. M. Wartmann multiplied the experiments by subjecting a constant wire to the action of two inducing wires, both variable or constant, or one variable and the other constant: he obtained results in relation with the preceding, and to which we shall return when we are engaged on electric conductibility, upon which they essentially depend. The same philosopher further showed, that the presence of a voltaic current in the induced wire in no way modifies the effect of induction, any more than does the absence of atmospheric pressure.

### *Electro-dynamic Induction produced by Electric Discharges.*

Electro-dynamic induction was not at first obtained, except by employing electric currents. But on seeing that instantaneous currents might themselves produce induced currents, Henry conceived that electric discharges, such as that from a Leyden jar, might also develope them. He succeeded indeed, but it was by taking many precautions, to insulate the wires of the spirals from each other, by means of silk and gum-lac, and to separate the induced spiral from the inducing spiral by means of glass. Moreover, by operating with spirals, arranged as in the experiments made with voltaic currents, he obtained induced currents of different orders, and having the same direction in respect to each other as they have when it is the current of the pile that produces the primitive induction. In the case of induction produced by means of discharges, there occurs a fact that we have already pointed out in the induction produced by induced currents: it is the influence exercised by a conducting plate on a closed spiral interposed between the inducing and the induced spiral. The current induced in this plate or spiral being of the second order, developes in the spiral subjected to induction an induced current of the third order, and consequently contrary to that which is determined in it by the direct action of the inducing current; there occurs, therefore, to the latter either its annihilation or a great reduction. This important observation explains how it was that M. Savary modified or even sometimes entirely annihilated the magnetising power of discharges, by placing the needles, upon which they were exercised, within envelopes, or in the vicinity of metal plates that become the seat of currents of induction, the action of which tended to annihilate or at least greatly to diminish the direct action of the principal discharge. M. Abria, by employing currents instead of discharges for producing magnetisation, had found on the contrary that the influence of metal envelopes was altogether null; an observation entirely in accordance with that of Henry, who remarked that, when currents are employed instead of discharges for producing induction, the envelopes are without influence; at least when not referring to induction produced by induced currents themselves, which then conduct themselves like discharges, as we have seen above: but it is not with currents of this kind, but with ordinary voltaic currents, that M. Abria was operating.

But, without stopping at these details, we must enter in a more direct manner into the study of the phenomena that occur in induction produced by electric discharges. The question that presents itself is the same as the one we have already entered upon, when engaged in induction produced by electric currents: it is to know what the nature is of the electric motion that constitutes the induced discharge. Is it a simple movement, analogous to that which constitutes the inducing discharge itself? Is it rather the succession of two discharges induced in opposite directions, one occurring when the inducing charge commences, the other when it ceases, and separated consequently by an interval of an inappreciable duration? It is clear that, under the supposition that we have already enunciated, when we were explaining the induced currents of different orders, it is necessary, in order that the effect shall not be null, that the two induced discharges should not be of the same intensity; for, but for this, they would neutralise each other. The solution of this question is not easy; and we are about to study it, by passing rapidly over the works of different philosophers upon this subject.

M. Aimé was one of the first to perceive the existence of the induced discharge, by fixing on the two faces of a glass plate several bands of tin-foil, so as to form two parallel and discontinuous metallic circuits. At the moment when he made the discharge of a Leyden jar pass through one of these circuits, sparks passed in all the solutions of continuity of the second circuit. Mr. Henry, by operating also with two parallel bands of tin-foil, had perceived, by means of the magnetisation of steel needles, the induced discharge change in direction,— an effect that he had at first attributed to the difference of distance between the inducing and the induced circuit; but which he endeavoured to explain more recently, by admitting that an electric discharge determines several induced discharges in contrary directions, the differences of whose intensity vary with the absolute intensity of the inducing discharge. He observed on this occasion a remarkable fact, which is, that a simple spark, about an inch in length, coming from the prime conductor of a machine, and received at the extremity of a metal circuit placed in a room, may produce a sufficiently powerful induction to magnetise needles, placed near a circuit parallel to the first, situated in a cellar at thirty feet distance. However, neither of the two philosophers that we have named have solved the question that we have laid down.

M. Marianini had endeavoured to solve it by means of the magnetisation of soft iron, substituted for the magnetisation of steel needles. He made use of the following apparatus. A sewing needle feebly magnetised is suspended to a very fine silk thread, so as to remain horizontal. Beneath it, and upon a horizontal wooden plane, is fixed a small cylinder of iron, about three quarters of an inch longer than the needle, and surrounded along its whole length by a helix of copper wire, covered with silk. This cylinder is arranged perpendicularly to the needle, when the latter is in equilibrium. From this arrangement it is evident that if, by any cause, and in particular by a current circulating through the wire, the cylinder should acquire magnetic polarities, the needle, being urged by forces all acting in the same direction, will be deviated more or less from its normal position, according to the energy of the acting cause. Many experiments having proved to Marianini that his instrument might also be employed to render sensible electro-magnetic currents, and currents produced by ordinary electricity, he called it a *re-electrometer*. After a detailed study of induction produced by means of electric discharges, which he termed Leydo-electric induction, M. Marianini arrived at results, some of which, such as those relating to induction of different orders, had already been obtained by Henry; and of which others belong to him exclusively. The following are the most important:—

In general, the induced discharge has the same direction as the inducing discharge, every time the Leyden jar is of tolerable capacity and is well charged; but, if the tension of the discharge diminishes, the dimensions of the jar remaining the same, or if the dimensions increase, the tension not changing, then the induced discharge has an opposite direction to that of the inducing discharge. We may also, with the same Leyden jar, produce the same change that is brought about by the diminution of the dimension of the jar, or that of its charge, by altering the conducting property of the inducing circuit; an alteration that is produced, either by greatly elongating the wire of which this circuit is formed, or by interposing in it liquid conductors. The learned Italian endeavoured to explain these results by distinguishing the induced current arising from the invasion of the discharge of the jar, from that arising from the cessation of this discharge; and by admitting that the definitive induction is always the result of the difference between the effect that would be produced by the invasion alone, and that which would be produced by the cessation of the current alone. But why do the dimensions of the jar, its degree of tension, the greater or less degree of conductibility of the inducing circuit, determine a greater rapidity for the invasion or for the cessation? In other words, why do these circumstances cause that the induction, brought about by the commencing discharge, shall outmeasure that brought about by the finishing discharge? This is the important point, which does not appear to us to be sufficiently cleared up by the researches of M. Marianini. We merely see that the causes that tend to diminish the rapidity of the discharge, tend to render predominant the inverse induction that occurs at the moment of its cessation.

M. Matteucci, after having at first employed the magnetisation of steel needles, as Henry did, afterwards made use of the galvanometer; and he found, contrary to what he had at first believed, that the distance between the inducing circuit and the induced circuit in no degree influences the effect of the induction, but merely its intensity. He had seen that this intensity depends, not only upon the distance, but upon the charge of the battery; and that the direction of the induced discharge is always the same as that of the inducing discharge, if at least the induced circuit is continuous; for if it is interrupted, and a spark passes at the place where there is a rupture, the induced discharge is then the inverse of the inducing. M. Matteucci also arranged several spirals, one after the other, in order to have inductive currents of different orders. He constantly found that, when the induced discharge becomes inducing, the discharge that it produces is the inverse of its own. But things change also if there is production of a spark in one or other of the circuits. In order, in this case, to determine properly the direction of the discharge, which is indicated but indifferently by the galvanometer, as it is itself but little influenced, M. Matteucci employed a process founded upon the experiment of the pierced card, in which the hole made by the spark on a piece of paper or a card is always near the point by which the negative electricity arrives: it is necessary that the two metal points be on different sides of the paper, and at a certain distance from each other, which distance, in the experiments in question, was about $\frac{1}{14}$ in. By means of this process, combined with the employment of the galvanometer, M. Matteucci found that induction by the discharge of the jar is subject to the following law, namely, that when the inducing circuit and the induced circuit are both closed, the induced discharge is determined in a direction contrary to that of the inducing; that the same is the case if they are both open, so that there is a spark; but, if one of the two circuits, no matter which, whether the inducing or the induced, is closed, and the other opened, so that there is a spark, the induced discharge is constantly determined in the same direction as the inducing. The direction of the discharges or the instantaneous currents is indicated, when the circuit is open, by the position of the hole made by the spark in the paper; and when it is closed, by the movement of the galvanometer.

M. Riess employed the condenser to determine the direction of the induced discharge by putting the extremities of the conductor, in which the induction is brought about, in communication one with the upper, and the other with the lower plate. But, in order thoroughly to study the mode of propagation of the induced discharge, M. Riess put in place of the conductor a metal disc covered with a thin coat of resin upon its two faces; the two extremities of the induced wire arrived at two metal points, between which was placed the disc, on the surfaces of which the two electricities were diffused. The mixture of powdered sulphur and minium that is employed for producing the Lichtenberg figures is then projected successively upon each surface; and, after numerous and varied trials, we succeed in recognising a very constant relation between the arrangement and the form of the spots left by the sulphur and red lead, and the direction of the induced discharge; a direction which the German philosopher found to be altogether independent of the intensity of the inducing discharge, of the distance of the induced wire from the inducing wire, and of the conductibility of either of the circuits. After having satisfactorily determined the *constancy* of the direction from the arrangement assumed by the mixture of the two powders, it was necessary to determine its *direction*. For this purpose, the employment of the condenser became necessary, and it was found that this direction was the same as that of the inducing discharge. However, M. Riess afterwards discovered, by fresh experiments, that his conclusion was too absolute, and that, although the arrangement of the spots indicates well enough that the nature of the electric movement, of which the induced wire is the seat, remains constantly the same, it does not always happen, atthough it is by far the most frequent case, that this movement produces the same effects as a single discharge would produce, sent in the same direction as the inducing discharge.

We shall not detain ourselves with M. Knockenhauer's method, founded upon the employment of the calorific galvanometer, namely, upon the heating brought about by the induced discharge in the platinum wire of an electric thermometer, through which it is transmitted. M. Riess had already employed an analogous method; and he had deduced from it the calorific power of the induced discharges, and the influence of different causes upon this power; a subject to which we shall return when studying in the Fourth Part the calorific effects in general of electricity. But this method, proper enough for measuring the intensity of the induction, could furnish no data as to its direction, although M. Knockenhauer had thought he was able, as we shall see in a moment, to deduce from it that the induced discharge has a direction which is constantly the reverse of that of the inducing discharge.

It follows, from the rapid exposition that we have been making, that neither the magnetisation of steel, nor that of soft iron, nor the employment of the galvanometer, nor even that of the condenser, may be regarded as perfectly sure methods of determining the direction of the induced discharge. In fact, magnetisation, even that of soft iron, as M. Marianini remarked, depends not only upon the direction, but also upon the intensity of the magnetising discharge; the galvanometer is of difficult employment for the appreciation of instantaneous currents such as those in question; and we have just seen that Riess did not find the indications of the condenser always irreproachable. The pierced card that M. Matteucci employed can only serve in the particular case in which the induced discharge gives a spark; and the calorific effects are powerless for giving the direction of a current. However, the results obtained by these more or less imperfect methods present a great degree of scientific interest; for they are well-observed facts, which, independently of the importance they possess of themselves, may put philosophers on the most proper road towards the solution of the question.

This road seems to us to be that which M. Verdet, a French philosopher, has followed. His method depends upon the phenomenon known under the name of *polarisation of electrodes*. It is well proved by Mr. Wollaston's experiments, and by those of Faraday, that an electric discharge of feeble tension is able to produce chemical decompositions; but other researches have further shown that a similar discharge, transmitted through a decomposable liquid by means of two wires or plates of gold or platinum, renders them capable of then producing of themselves an electric current sensible to the galvanometer. This phenomenon, which also occurs when it is a current instead of a discharge that has produced the chemical decomposition, is called polarisation of the electrodes. The direction of this current, which we shall call *secondary*, varies with the direction of the discharge, as it does with that of the current: the wire by which the positive electricity has penetrated, called on this account the positive electrode, behaves as the negative metal of the new pair; and that by which the negative electricity has penetrated, namely, the negative electrode, behaves as the positive metal. The current that is produced by this pair, so formed of these two similar metals, but which have served to transmit the discharge, is stronger as the discharge itself has been more considerable; but when very energetic currents are in question, it is not only the greater or less deviation which they impress upon the needle of the galvanometer, but the duration of the deviation, which varies with the intensity of the primitive discharge. However, for currents such as those at present under consideration, we may content ourselves with observing the galvanometric deviations, and deducing from their directions and their amplitude the direction and intensity of the secondary current, and, consequently, of the discharge that has produced this current, calling to mind that the direction of the secondary current and that of the discharge are always inverse, and that their intensities are proportional to each other.

M. Verdet, in his experiments, made use of flat spirals, the wires of which were insulated from each other with great care by silk and by a layer of gum-lac varnish. The spiral intended for receiving the inducing discharge was made with copper wire $\frac{3}{5}$ in. in diameter and $91\frac{3}{4}$ ft. in length, forming twenty-four spirals. The spirals intended for receiving the induced current, to the number of three, were made of wire $\frac{1}{50}$ in. in diameter and $157\frac{1}{2}$ ft. in length, forming ninety-five spirals. All the spirals were about $9\frac{4}{5}$ in. in diameter. The battery consisted of nine jars $10\frac{3}{5}$ in. in height by 6 in. in diameter. The battery was charged until a spark passed between two balls, the distance of which, measured by an adjusting screw to $\frac{1}{500}$ in., served to measure the intensity of the discharge.

M. Verdet's experiments led him to recognise that, when the induced circuit is entirely continuous, no traces of polarisation are obtained except by excessively powerful discharges; the galvanometric deviations are only from 2° to 3°; and they indicate that the induced discharge has the same direction as the inducing. If, on the contrary, the induced circuit is interrupted in any place, so that there is a spark, the current of polarisation becomes very sensible, but the phenomena at first appear very irregular. Nevertheless, we easily recognise that the length of interval, traversed by the inductive spark, exercises a great influence upon the direction and the intensity of the induced current. In order to appreciate this influence, M. Verdet made the inductive sparks pass between the lower extremity of a micrometer-screw terminated in a point, and the surface of a small mass of mercury insulated in a glass capsule. He observed that, when the direction of the induced current is such that the positive electricity comes out by the point, and consequently the negative arrives at the mercury, the direction of this current does not change, whatever be the distance of the point from the mercury; and its intensity increases with this distance. Moreover, the direction, in this case, of the induced charge, is similar to that of the inducing charge. When it is the point that is the negative pole, and the mercury the positive, the induced current varies irregularly in direction and in intensity; but setting out from a certain distance between the point and the mercury, the direction of the induced discharge becomes constant, and always identical with that of the inducing discharge.

These results are very well explained, if we take care not to lose sight of the fact, that there are two induced discharges, the one *inverse*, the other *direct;* and that, if they are perfectly equal, we should obtain no effect. This is what occurs, or nearly so, when the induced current is entirely continuous. But if, by any circumstance, one of the discharges becomes more feeble than the other, we then obtain an effect the more considerable as the difference is greater, even when the total induction is much less. This happens if the induced circuit presents a solution of continuity. Why does this solution of continuity favour the direct in preference to the inverse discharge, especially if the apparatus is arranged so that it is the positive electricity of the direct that passes out by the point? It is probable that this is due to the property, possessed by positive electricity, of escaping more easily by points than negative does,—a property of which we shall see several more examples in the Fourth Part. It is true that, when it is the positive electricity of the inverse charge that is to come out by the point, it does not always, although it does sometimes, get the advantage over the direct. I imagine that this anomaly is due to another property, which we shall also study when engaged upon the propagation of electricity,—namely, that a current or a discharge passes more easily between two electrodes, after these electrodes have transmitted a discharge or a current the inverse of that which is about to pass. Now, the direct induced discharge is always preceded by the inverse discharge. It ought therefore, in general, to be transmitted more easily, viz., in a greater proportion, and, consequently, should surpass the other in intensity. When the two favourable circumstances are united, it always is the superior; when the latter alone exists, it is the superior or not, according to the relative preponderance of the two influential causes.

M. Verdet, when studying the induced discharges produced by induced discharges themselves, arrived at similar results. The direction of the polarisation of the electrodes is constant; it always indicates the superiority of the induced direct discharges; but they do not become sensible, except as the induced circuit is interrupted. If it is continuous, there is no trace of polarisation. In fact, in this case, all the induced currents, which are here to the number of four, because they are due to the inducing action of the two induced discharges themselves, are equal; and as they are inverse, they mutually destroy each other. But if there is a solution of continuity, this causing the last direct current to predominate, there is then an effect.

We see that, in respect to discharges, we arrive at conclusions very similar to those to which M. Abria arrived when studying the induction produced by voltaic currents,—

namely, that the direction of the induction produced, either by instantaneous currents, such as the induced currents of superior orders, or by simple electric discharges, always depends upon the relative superiority of the induced currents or discharges; the one set inverse, the other set direct; which leads us to recognise that, in these cases, the observed effect is not an absolute effect, but the difference between 2, 4, or a greater number of almost simultaneous, induced currents.

M. Knockenhauer, on the contrary, arrived, by a different method to that of M. Verdet, to conclusions completely opposite. The method employed by this philosopher consisted in making the inducing discharge and the induced discharge pass simultaneously through the platinum wire of an electric thermometer, by arranging the communication in two successive experiments, so that one of the discharges should traverse the platinum wire in the two opposite directions, the direction of the other remaining constant. The elevation of temperature indicated by the thermometer was not the same under both circumstances; and, if we admit that the greater elevation corresponds to the case in which the two discharges pass in the same direction through the thermometer, the smaller to the case in which they pass in contrary directions, the experiments would assign to the induced discharge, contrary to M. Verdet's results, a direction the contrary to that of the inducing discharge.

In order that this conclusion may be accurate, it would be necessary that experiment should have demonstrated the accuracy of the principle upon which it rests; for nothing proves *à priori* that two equal currents, circulating in the same wire in opposite directions, produce a null calorific effect. Furthermore, M. Matteucci, by combining the current of a pile with the discharge of a Leyden jar, showed on the contrary that the calorific effects of these two modes of producing dynamic electricity are always added together, whatever be the relative direction of the current and of the discharge.

M. Knockenhauer's researches, which are remarkable moreover by the great number of the experiments, had led him to consider the phenomena of electro-dynamic induction as simple effects of induction due to static electricity; but, when the subject is more closely studied, it is impossible to confound these two orders of facts. The free electricity of the battery cannot be the cause of the induced discharge, which is simply due to the inducing effect of the electricity in motion; but it may, it is true, give rise to another electric movement that in no manner depends upon the direction of the principal discharge. This movement, to which the name of *lateral discharge* has been given, is an instantaneous decomposition of the natural electricity of the neighbouring conductors, in virtue of which the electricity that is contrary to the free electricity of the battery is attracted towards the inducing wire, and the similar electricity is repelled from it. A conductor, when subjected to induction, and consequently placed in the neighbourhood of the conductor of a discharge, is always the seat of a lateral discharge that may, in certain cases, take the form of a true induced discharge. We have the proof that, notwithstanding the appearance, there is no identity between these two discharges in the spark that may be drawn from the induced current, as well when it is opened as when it is closed, by an insulated conductor that is brought near at the moment when the principal discharge takes place. We then find the conductor charged with a similar electricity to the free electricity of the battery, conformably to the laws of the induction of static electricity. The direction of the induced discharge has no influence over this class of effects, which moreover are the more sensible as the tension of the electricity of the battery is stronger.

These phenomena are due to the fact that the two surfaces of the battery which are made to communicate with each other by means of the conducting wire of a discharge, are almost always charged with very unequal quantities of electricity. It hence follows that, at the moment of the discharge, there is on each point of the conducting wire an excess of free electricity acting by induction upon the neighbouring bodies. It is probable that to this excess of free electricity the luminous appearance is due, which, as M. Poggendorff has observed, is presented by a wire that is transmitting the discharge of a battery. It appears illuminated along its whole length, and gives sparks perpendicular to this length. If the wire is bent into two parallel parts very near to each other, the outer side alone is luminous; if it is in a helix, it is also the exterior of the helix, a further proof that the phenomenon is a phenomenon of static electricity.

We now understand the nature of the errors of which the discharge may be the cause, in experiments upon induction, especially when the condenser is employed; but M. Verdet satisfied himself that it has no influence over the polarisation of electrodes, and that, consequently, it does not involve in any inaccuracy the results obtained upon induced currents by this mode of investigation. In fact, the induced circuit being open, one of its extremities has been placed in communication with one of the platinum wires of the decomposition apparatus, the other communicating with the ground; and, however powerful the charge of the battery may be, there is no sensible polarisation where the discharge is made, although there is a powerful lateral discharge. This lateral discharge, which, as we shall see, plays a most important part,—a phenomenon known by the name of *return-shock*, and especially in lightning-strokes, has been the object of study to several philosophers, and in particular to M. Riess, who found it intimately connected, in respect to its range, that is, in respect to the distance at which it occurs, and in general in respect to all the circumstances that accompany it, with the tension of the electricity in the battery, and the velocity with which this electricity escapes. M. Matteucci, on his part, considers that many of the phenomena attributed to the lateral discharge are due to a veritable induction brought about in the surrounding bodies, and he quotes some curious facts tending to prove that even insulating bodies are susceptible of experiencing it. He found that plates of mica, interposed between several successive steel needles, diminish the magnetism that they acquire, in comparison with that produced from the same discharge in perfectly similar needles, arranged in the same manner, except that there is not any mica between them. This effect of the presence of mica varies with regard to its absolute intensity with the distance of the needle from the wire that conveys the discharge. Whatever may be the case, it seems to be proved that, in the presence of an electric discharge, there is produced in the induced ambient body, and immediately afterwards destroyed, electric discharges that succeed each other in contrary directions, in very brief intervals. We shall return to this subject when we are studying, in a special manner, the mode of propagation in different media of dynamic electricity, either instantaneous or continuous. For the present we shall confine ourselves to explain further, and in a few words, the interesting results to which M. Riess arrived, in regard to the influence exercised by induction in the phenomenon of heating fine metal wires traversed by an electric discharge. He found in fact, that if, parallel to and near this wire, there is placed a second similar wire, the two ends of which are put into communication, the current induced in this second wire generally diminishes the calorific effect of the direct discharge upon the first,—a diminution that appears to be due to the retardation in velocity experienced by this discharge, and consequently in its heating power, which depends essentially on the promptitude of the electric escape. This influence of the induced current is modified by the length of the circuit that it traverses, having for a determinate length a maximum that cannot be exceeded. In fact, the prolongation of the secondary circuit produces a double result: in the first place of retarding the current that is developed by the discharge, and of thus increasing its reaction upon the principal wire; in the second place, of enfeebling this current, and on the contrary diminishing this same reaction. At first the former effect predominates, and the reaction is seen to increase; but soon the secondary current is so enfeebled that its influence ceases more and more, until it becomes null beyond a certain length, which is equivalent to a complete interruption of the circuit.

M. Riess did not confine himself to determining the reaction of the induced discharge upon the direct discharge; but he also made, as we have already said, a very special study of the induced discharges themselves, employing for the purpose of measuring their intensity the heat produced in the very fine platinum wire of an electric thermometer, through which they are transmitted. This mode of operating could not give M. Riess the direction of the induced discharge; but he found, by the magnetisation of a steel needle, that this direction is the same as that of the inducing discharge. However, he recognised that the duration of the magnetisation impressed upon a needle by a secondary discharge may vary with circumstances independent of the direction of this discharge, as occurs in Savary's experiments for direct discharges. Furthermore, with regard to the intensity of the induced discharge, measured by the calorific effect, it is proportional to that of the inducing discharge, and to the efficacious length of the wire by which this discharge is conducted; but it is in inverse ratio to the distance of the two wires, and independent of the conductibility of the induced wire. The influence of interposed conductors upon the calorific effect of the induced current is very sensible, whether this conductor is a metal wire, the two ends of which are connected, or a plate, that is a very good conductor, either by its nature or its thickness. The interposition of a copper disc, 16 inches in diameter and $\frac{1}{23}$ in. in thickness, completely annihilated the effect of heating in the induced wire, although the inducing discharge was produced by four highly charged jars. Riess found that in general the intensity of the current in the secondary wire is the more diminished as the thickness of the interposed plate is greater.

To sum up, it follows from all the numerous researches made upon induced discharges, that this is a very complex phenomenon, and is influenced, in all the circumstances essential to its existence, by the very mode that is employed for determining it; on which account this determination is very difficult. However, we may reduce it to this very simple form, namely, that a discharge determines in a conductor that is near to the one by which it is transmitted, two induced discharges, having the first a contrary direction, and the second a similar direction to that of the inducing discharge; — that these two opposite discharges succeed each other in an interval of time of inappreciable duration; — that they nearly neutralise each other if the induced circuit presents no resistance, but that if the circuit is interrupted either by a fine wire that is heated, or by an interval that gives rise to a spark, then one of the discharges surpasses the other, and it is generally the latter, namely, the one that travels in the same direction as the inducing discharge. The cause of this superiority is essentially due to the conditions of the circuit, which more facilitate the transmission of electricity in one direction than in the other; it is also due to the fact that the direct discharge being the second, the causes that retard in general the propagation of electricity, must act proportionately with less force upon it than upon the former. However, we must not disguise that this manner of explaining the phenomena of the induction, produced by discharges or instantaneous currents, is not that adopted by several German philosophers, and in particular M. Dove. This philosopher, and others also, especially M. Weber, hold different views of this order of phenomena, and do not think that they can be reduced to such simple laws. Probably they are not altogether wrong. Further, we may judge of this by the explanation, unfortunately but a brief one, that we are about to give of their researches.

### *Influence that is exercised upon Induction by metal Masses, principally magnetic, placed in the Interior of Bobbins.*

It remains for us, in terminating this Chapter, to study for a few moments a point that we have merely alluded to, namely, the influence that is exercised upon discharges, as well as upon induced currents, by the nature and arrangement of the metal masses that are introduced into the interior of the helices, intended for the production of induction. This influence is manifested by the modification that it exercises over the properties of induced currents. It is further manifested, and is explained by the production of induced currents occurring on the surface itself of these masses, when they are continuous, and not formed of isolated pieces, in a greater or less number, and particularly on the surface of magnets.

M. Dove made a very special study of this subject. With this view, he successively employed currents and discharges to produce induction, and arrived at perfectly concordant results. Laying down the position that, in a current, namely, in the neutralisation of two contrary electricities, we must distinguish two elements, the original intensity of these two electricities, and the time that their neutralising lasts; or, which comes to the same thing, the force of the current and its duration, he succeeded in recognising that, according to the nature of the effects produced, one of these elements exercises a greater influence than the other. If the magnetic, chemical, physiological, and calorific effects of an electric current depended equally on its force and on its duration, the equality recognised between currents for one of these classes of effects would have equally occurred for the three others. But things do not occur in this way. The differences that are observed between the effects of two currents, arising from the neutralisation of equal quantities of electricity, must therefore be attributed to a difference in the duration of this neutralisation. These differences are especially sensible when the galvanometric and chemical effects, that are proportional to each other, are compared with the physiological effect. Now this latter is by no means proportional to the deviation of the needle nor to the quantities of gas given by the voltameter; it is not, like the two others, a product of the duration by the force; it only depends on this latter, and increases consequently with the rapidity of the neutralisation. Thus it is that the same discharge of a Leyden jar, which violently shakes the body, and does not cause the needle to deviate, may, if it is slowly drawn off by a point, affect a galvanometer, the coils of which are well insulated, and not produce any shock upon the human body placed in its route. It is, however, the same quantity of electricity in both cases. The property possessed by the electric current, of magnetising tempered steel, is of the same order as its physiological effect. If, therefore, there are two currents developed in the same conductor,—and that these currents produce the same deviation in the galvanometer, and that one determines a more powerful physiological effect and more vivid sparks than the other, and communicates more powerful magnetisation to steel, we must conclude from this that the same quantity of electricity is moved in less time in the former than in the latter; and reciprocally, when the physiological and magnetising effects of the two currents shall be the same, that one of the currents whose effect shall be the least upon the galvanometer will merely have existed for a shorter space of time, still being however of the same intensity.

These differences, which distinguish in a striking manner the phenomena of the electricity of common friction machines from those of voltaic electricity, are no less sensible when we compare inductive currents one with the other, and when, without making any change in the induced circuit, we confine ourselves to modifying the nature and the mechanical aggregation of the metal masses that are placed in the helix; a modification that is sufficient to produce a considerable one in the properties of the induced currents themselves.

We have already remarked that, in magnetising bundles of iron wire by the electric current traversing the wire of a helix, we obtain much more powerful shocks than when we use a cylinder of solid iron. M. Dove, in order to establish an exact comparison between the physiological action and the galvanometric action, in respect to the influence that is exercised upon each of them by the nature and the state of the iron that is employed, made use of two perfectly similar helices made with thick copper wire, and traversed successively by the same voltaic current. These helices acted, by induction, upon a helix superposed on each of them. These new helices, made with a much finer wire, communicated together by one of their extremities; so that the direction of the inductive current in the one was opposed to that of this current in the other. The two free extremities of the system of two helices were furnished with handles, which permitted of completing the circuit by the intervention of the body or by that of the galvanometer. In both cases, the two inductive currents being inverse, neutralised each other. It was no longer the same when wires or masses of iron were introduced into the interior of each helix. M. Dove, after having successively introduced into one of the helices cylinders made of forged iron, of different kinds of cast iron, of tempered steel, placed at the same time in the other the number of wires necessary for rendering null either the galvanometric or the physiological effect. He thus determined the number of wires necessary for establishing the compensation or the equilibrium between the induced current for the bundle of wires. This number was different according as the current was appreciated by its effect upon the galvanometer, or by its effect upon sensation. Thus, with forged iron, 110 wires were not sufficient to establish galvanometric equilibrium; 15 were sufficient to establish it for sensation; with tempered steel, 28 were required in the former case, 7 in the latter; with grey cold blast iron, 27 and 11. Analogous results were obtained with a differential galvanometer, the two wires of which were traversed each by one of the inductive currents. The latter having been rendered equal with regard to their action upon the galvanometer, they were not so with regard to physiological action; the superiority for this latter kind of effect belonged to the one that came from the helix in which were the iron wires. With regard to the different kinds of iron, experiment shows that, if we class them according to their galvanometric effect, we obtain a different series from that to which we arrive in classing them according to their physiological effect. Thus this latter effect depends, not only upon the discontinuity of the mass, but also upon the nature itself of the iron. Thus, by combining the two causes, we arrive at finding soft iron wires of a certain diameter capable of compensating the action of a cylinder of a certain kind of iron as well in relation to the galvanometer as in relation to sensation.

This double result was obtained, for example, with twelve wires of about $\frac{1}{4}$ in. in diameter, and a cylinder of grey smelted cast iron. Furthermore, the influence of the nature of the iron is itself probably due to some difference in the molecular constitution of the mass. Thus, grey rough cast iron is of all kinds of iron the one that approaches the nearest to bundles of wires with regard to the effect of induction, its physiological action being relatively greater than might be expected from the intensity of the current developed in the galvanometer. This result would seem to indicate that, in this cast iron, the part of the iron susceptible of magnetisation does not form a continuous mass, which accords with M. Karsten's chemical researches.

The experiments made by means of the magnetisation of steel, and by comparing the vividness of the sparks, have confirmed the preceding results, and have also demonstrated, in a general manner, that in an inductive current, developed by employing a bundle of wires, the same quantity of electricity moves in less time than when it is the result of induction produced by a solid cylinder. Tubes, substituted for the iron, act like forged cylinders, and completely nullify the effect of wires placed in their interior, except in the case where they are traversed by a longitudinal slit; for, in that case, the introduction of a certain number of iron wires increases the physiological effect, but in no way modifies the action upon the galvanometer, which in consequence appears to arise only from the iron envelope. In the experiments in question, the tubes were hollow cylinders of the dimensions of a gun-barrel: the results are not the same when tubes of thin sheet iron are employed. The wires act through these tubes, quite closed as they are, so as to increase the galvanometric effect, and even proportionately more than the physiological effect. But if the thin tube is slit longitudinally, the result is the inverse, and the introduction of the wires causes a greater increase in the physiological effect than if they were placed in a closed tube.

Closed or unclosed conducting envelopes, such as an insulated wire, wound to a helix around a tube of card in which the iron is placed, and the two ends of which are connected or insulated, such again as a tube of brass closed or slit lengthwise, produce effects that are perfectly in accordance with those that we obtained when employing iron wires or solid cylinders. The closed helix and the continuous brass tube diminish the action of a bundle of iron wires which they surround, so as to render this action similar to that of a solid iron cylinder, and even inferior to it, although it was very far superior before the wires were thus enveloped. The tube split lengthwise produces thus a less reduction of force than the closed tube, but a little more considerable than a helix, the extremities of which are not united. By closing the circuit of the split tube by means of the wire of a galvanometer, we may prove the existence of the induced current. These experiments show that the difference we found to exist between the action of a bundle of iron wires and that of a solid cylinder is essentially due to the currents of induction being enabled to be set up on the surface of the cylinder.

From all the facts that we have described, it follows that the diversity of effects manifested by the currents of induction is due to a difference in their *duration*, and not to a difference in their *energy*. The metal envelope that surrounds a bundle of wires or the continuous surface of a solid iron cylinder *does not enfeeble* the action of induction, but *retards* it. This retardation has no influence on the galvanometer needle, upon which the effects of the current are accumulated, an operation for which duration is of no importance; but it greatly diminishes the physiological effect and the magnetising action. It is to the same cause we must attribute the fact, that the sparks and shocks produced by the extra current, namely, by the current induced upon itself in a helix, the axis of which is occupied by a bundle of iron wires or by pieces of solid iron, disappear almost entirely when the wires or pieces of iron are placed in a closed brass tube. But it is not the same if the brass tube is opened. The end of a gun-barrel produces the same results, when closed and open, as does the brass tube; only with the closed gun-barrel there is still a feeble shock.

A very important remark made by M. Dove, and the accuracy of which I have often had the opportunity of proving, is, that the effects are greatly increased, all other circumstances remaining the same, by reversing the polarity of the iron, whatever it may be that is in the interior of the helices, by means of a change in the direction of the current. This result is due to the fact, that iron, even the softest, always preserves a certain amount of magnetic polarity, even when the magnetisation has ceased, if at least it has been prolonged for a short time. It follows that the inductive current, produced by the rupture of the circuit, is less powerful than if the magnetisation at this moment ceased entirely. But, by reversing the polarity, we necessarily obtain this result. In general, the most powerful effect of induction belongs to the metal whose magnetic state experiences the greatest change. The indications of the galvanometer are, in this case, analogous to those resulting from sensation. Many examples show that, if we did not take into account this principle of the increase of energy by the reversal of polarity, it would be impossible to compare together different sorts of iron. Thus soft steel and tempered steel, when their polarity is reversed, surpass all kinds of cast iron; and these in their turn, when their polarity is reversed, have all a greater energy than soft steel and tempered steel. It is the same with the different species of cast iron in respect to each other, and with bundles of iron wire.

After having employed electric currents, M. Dove employed discharges for producing induction, with a view of determining the influences that may be exercised upon induced discharges by the introduction of all kinds of metals. The apparatus that he employed, and which he termed the *differential inductor*, consisted of two helices made of two thick copper wires, and wound upon two glass tubes 13 in. long by 1 in. in diameter. The spirals of these wires were insulated with great care by means of a thick coat of gum-lac. Two other larger helices, but perfectly similar to each other, wound in the same direction around a tube of card, and consisting of the same number of convolutions, received in their interior the first-named helices. The latter transmitted the discharge of a battery of Leyden jars, which traversed successively the two wires. There resulted from this an induced discharge in the two enveloping helices. Of the four ends of these helices, two, belonging each to a different helix, were placed in communication by a conductor, and the two others served to transmit the induced discharge through the human body, the wire of a galvanometer, a magnetic spiral, or a voltameter. By the arrangement of the apparatus, we could at pleasure introduce into the interior of the helices solid cylinders or bundles of wire. This apparatus, although essentially intended for induction produced by discharges of common electricity, may serve equally in the cases where voltaic currents are employed instead of discharges (*Fig.* 154.).

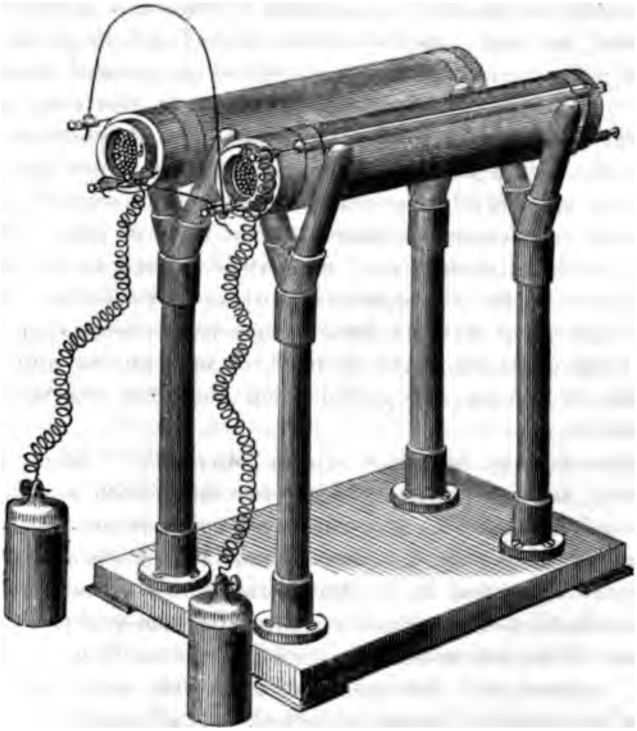

*Fig.* 154.

The helices of the induced circuit may be united, so that the two induced discharges travel in the same direction, or so that they travel in the contrary direction. In the latter case, they completely neutralise each other, so that if the introduction of any substance in the interior of one of the helices modifies in any way the induction brought about in that helix, it is immediately perceived, because the neutralisation no longer occurs, and one of the induced discharges surpasses the other. Unfortunately, the galvanometer, the chemical voltameter, and the magnetisation of soft iron, are in no degree influenced by the instantaneous current of the induced discharge, so that we must have recourse to other means for estimating it, namely, to the shock, and to the magnetisation of steel needles. M. Dove made use of the physiological shock, which, by its degree of intensity, indicates by how much one of the instantaneous currents is superior to the other; but, in order to obtain the definitive direction of the current, and to discover which of the two helices gives a superior current to the other, he employed M. Riess's method, namely, a condenser and figures traced by the two electricities upon cakes of resin, placed between the two extremities of the induced wire. By operating thus, he found that the physiological effect of the inductive current, developed by the discharge of the jar, is enfeebled by the introduction into the bobbin of non-magnetic metals, and the more so as they are better conductors. This diminution, therefore, is much less for *antimony*, *bismuth*, and *lead*, than it is for *copper*. The effect of these cylinders is the same as that of helices whose two ends are united; it is then the result of the reaction exercised upon the secondary circuit, by the instantaneous currents developed upon their surface. Thus, tubes cleft longitudinally, and bundles of wires, diminish much less the effects of induction than do continuous cylinders. *Forged iron*, *tempered* and *untempered steel*, *grey* or *white cast iron*, equally diminish the physiological effect by their introduction: but it is not the same with bundles of insulated *iron wire;* there is then, on the contrary, an augmentation. The condenser in this case indicates that the instantaneous current has travelled in the inverse direction to the preceding case,—a proof that the introduction of the wires *does not weaken*, but increases the effect of the induction. If the bundle of iron wires is enveloped by a continuous surface of copper, it then acts as a solid cylinder and diminishes the action. It is the same if it is surrounded by a wire, coiled as a helix, and having its two ends united; but it is necessary that the wire be a good conductor. A solid mass of *nickel* increases the induction, and acts like a bundle of iron wire: this is probably due to its feeble degree of electric conductibility, joined to its great magnetic virtue.

What we have been saying is sufficient to establish satisfactorily the difference existing between induction produced by discharges, and that produced by continuous electric currents, at the moment when they cease to pass. The physiological effects, far from *diminishing*, actually *increase*, by the introduction into a helix of a piece of iron of any kind; it is true that they increase more, if the mass of iron presents solutions of continuity parallel to the axis. With regard to the galvanometric effects that are appreciable in this case, we may remember that they are more sensible with solid cylinders than with bundles of wires; and that solutions of continuity in the cylinders or an envelope around the wires, in no degree modify their action: nor does the introduction of non-magnetic metals into the interior of the helices produce in this case any effect.

If, instead of employing the physiological effects for studying the induction produced by discharges, we employ the magnetisation of steel needles, we find that, far from weakening the action, the introduction of a mass of any kind of iron into the interior of a helix sensibly augments it: but the more so, it is true, as this mass is the more divided parallel to its axis; this is exactly what is found with currents. Thus, when referring to the magnetisation of steel needles, the continuous current and the discharges of batteries present phenomena altogether similar, which is not the case with physiological effects. Calorific effects are, like these latter, diminished by the introduction of iron, whatever be its form;

it is the reverse of this when the induction is produced by a continuous current, instead of being by a discharge.

To sum up, when we operate with *ordinary electric discharges*, the introduction of a solid of iron into one of the helices of the differential inductors *enfeebles* the physiological, the calorific, and the tension or electroscopic action of the discharge, but *increases* its effect of magnetisation.

It *increases* all the effects, without distinction, when *voltaic currents* are employed.

The introduction of the bundle of iron wires acts like the solid mass with voltaic currents. It also *increases*, in the case of electric discharges, all the effects save the calorific, which it *diminishes*.

Finally, when, in order to magnetise iron, instead of employing currents or discharges circulating in a helix, we bring a magnet near to it, we do not increase the current of induction by dividing the iron into wires; neither do we see it diminish, when these wires are surrounded by a conducting envelope. This is because magnetisation by the magnet does not, like that by the helix, determine inductive currents around the surface of the magnet or the envelope, and as it consists only in producing magnetic poles.

M. Dove concludes, therefore, from all his experiments, that we must distinguish, in all effects relating to the influence exercised upon induction by the introduction of masses of metal into the interior of the helices, two distinct phenomena:

1. Those that are due to the magnetic polarity acquired by these masses when they are susceptible of becoming magnetised.

2. Those that are due to induced currents developed around their surface more or less easily according to their degree of conductibility, and their greater or less continuity.

Magnetic polarity is not developed instantaneously; but, when the primitive current is of a continuous nature, the magnetism has all this time to attain its maximum, and its inducing action easily surpasses the contrary action exercised by the currents that are induced by the rupture of the primitive circuit around the surface of the iron. Every thing that can prevent the development of these currents increases still more the effect that is due to the magnetism. On the contrary, when the inducing current is only instantaneous, like the discharge of a battery, the magnetism not having time to develope itself entirely, the direct induced currents that occur at the moment when the discharge ceases, get the advantage over the contrary action due to the magnetism that is disappearing. We can here understand also that, by preventing the formation of the currents either by the employment of metals of very feeble conducting powers, as nickel, or by reducing them into wires of very small diameter, we may entirely invert the phenomenon by making the effect due to polarity predominate over the effect that has become null or almost null, arising from induced currents. But these contrary actions are not in equilibrio at the same time, for all the kinds of effects, because these effects are each a different function of the quantity of electricity set in motion in the induced current, and of the duration of this current, which itself depends on the retardation produced by the current induced around the surface of the interior metal.

M. Dove conceived the idea that, by preventing the induced currents from forming around other metal masses, besides masses of non-magnetic iron, by dividing them with this view into very fine wires, he might probably make them perform in induction a part analogous to that of iron wire approaching it in intensity, and thus discover among them traces of magnetism, if any existed in them. Antimony, lead, bizmuth, tin, zinc, and mercury gave some, as did also brass, but it was necessary to make it into very fine and well-varnished wires: the current came from the helix in which was placed a packet of them, the other containing nothing. We may find a certain diameter of the wires such that they compensate each other, namely, for which the effect of the induced current, circulating around the surface, neutralises the effect of the magnetic polarity of the wire. The mercury was placed in very fine glass tubes, closed with wax, and sealed at the two ends. All the other wires were covered with a coat of gum-lac varnish, so as to be insulated from each other. We should add that, except for the copper, zinc, and mercury, it was not perfectly certain that the metals contained no iron. Moreover, we shall see in the following Chapter proofs of another kind that magnetic power is much more general than it was for a long time suspected, and that all bodies possess it in different degrees.

It still remains for us to speak of the special study made by M. Dove on inductive currents, that occur at the commencement and at the end of a primary current, in the conductor itself that transmits the current; he termed these currents *counter currents*, to distinguish them from *juxta-currents*, that occur in circuits parallel to the inducing circuit. With this view he employed a magneto-electric machine, analogous to that of Saxton, in order to produce the primary currents, which were naturally instantaneous. A small helix, the spirals of which, by reacting upon each other, produced counter-currents, was placed in the circuit. The apparatus was so arranged that the circuit might be closed in four modes: 1. So as to seize the primary current without the helix being in the circuit; 2. So as to seize it, the helix being in the circuit, consequently with the two counter-currents, the initial and the final, opposed; 3. So as, having the helix alone in the circuit, to obtain only the final counter-current; 4. So as, the helix being in the circuit, to obtain only the primary current and the initial counter-current. Calling $p$ the primary current, A the initial counter-current, and E the final counter-current, we obtain, in the first case, $p$; in the second, $p - A + E$ (the second counter-current being in the same direction as the primary); in the third case, E alone; and in the fourth, $p - A$. In all these cases, experiment showed that the counter-currents were subjected to the same influences by the effect of the introduction of metal masses, whether magnetic or not, whether divided or not, as are juxta-currents or ordinary inductive currents. The circumstances that cause A and E to vary were carefully studied, by the aid of physiological effects, of the galvanometer, and of the chemical voltameter, so as to be able thoroughly to learn the action of $p - \mathrm{A}$, and the more complex action of $p - \mathrm{A} + \mathrm{E}$. Now, the most interesting result of this work is, that the circumstances that cause A to vary are not always the same as those that make E vary; so that A and E, although counter-currents arising from the same primary current, are not generally equal. This explains why, in the phenomena of induction, produced with ordinary electricity, A and E are not completely neutralised, as the short duration of the primary current $p$ might have induced us to believe.

The phenomena discovered by M. Dove seem, in general, to be but little favourable to Ampère's hypothesis of the nature of magnetism; in fact, if a magnet is composed of an assemblage of electric currents, circulating around its surface, how comes it that induction, by exciting similar currents on the surface of an iron cylinder, counteracts the effect that the magnetic virtue of this same cylinder tends to produce? For this, there must needs be opposition between these two kinds of action: whence it follows that one cannot be the cause of the other; the electric current and magnetic polarity, developed in iron by electricity in motion, are therefore two distinct agents, capable, sometimes the one, sometimes the other, of becoming superior; being able exactly to produce equilibrium under certain circumstances, but always counteracting each other. It is true that Ampère supposes that the currents, to which the polarity is due, are molecular, which establishes a great difference between them and the finite currents that are produced by induction around the surface of magnets. In this case, a bundle of wire, magnetised by the current that traverses the helix, approaches the nearest possible to Ampère's solenoid. But, in order to represent a magnet, the conducting envelope would be necessary, the absence of which establishes so great a difference between the action of a bundle and that of a solid mass of iron. In other respects, theory and experiment have proved that, whether molecular or not, the currents of which a magnet is constituted behave like an assemblage of closed circuits, circulating around its surface. How, then, can it happen that these currents, instead of favouring, oppose the effect of similar currents produced by induction?

In order to resolve this difficulty, we must, in fact, admit that there is a very great difference between Ampère's molecular currents that produce magnetisation, and the finite currents that traverse a conducting surface. This difference consists essentially, as we think, in that the molecular currents pre-exist in the particles of the magnetic body, even before it is magnetised; and that magnetisation only displaces the particles, so that all these currents have the same direction,—the given direction, according to the laws of electro-dynamics. This displacement of molecules is analogous to that of a movable conductor traversed by a current, and upon which an exterior attractive force is acting. We have already seen that all circumstances, and especially the calorific and mechanical actions, that favour magnetisation, whatever be the cause producing it, are favourable to this opinion. But the inductive current is quite another thing; it is a current that, by the effect of an exterior cause, circulates instantaneously upon a surface, as would any other current to which it might serve as a conductor, and this without displacing the particles. The mode of the establishment, as well as the duration of these two species of currents, must be very different. We may, therefore, very well conceive how the primitive discharge, by acting directly upon the iron, compels the molecular currents to arrange themselves parallel to its direction, and in the same direction with it; and how this same discharge produces a secondary current in the exterior helix, and finally, by induction, an instantaneous current upon the surface of the iron. This current reacts upon that of the induced helix, by developing in it one moving in a contrary direction to that which is traversing it; it diminishes, therefore, the power of this latter, as experiment proves, but it diminishes it only for effects that require a great velocity in the circulation of the discharge. With regard to the molecular currents that constitute magnetisation, they must tend, not to diminish, but to augment, the effects of induction in all cases, since they augment only the first effect of the primitive discharge, seeing that they do not disappear sufficiently quickly to produce a second inductive current opposed to the first. It is easy now to understand why, on making the superficial currents disappear by the mechanical division of the mass, still, however, preserving the molecular currents that constitute magnetisation, we in all cases add force to the inductive current, the cause tending to diminish it being no longer there. There is but a single exception; it is relative to the calorific effects, and is due, probably, to the fact, that, as magnetisation is not brought about instantaneously, it prolongs the duration of the induced discharge, still, however, increasing its intensity;—a double contrary action, the result of which is to diminish the calorific power, upon which, as we shall see, the velocity of the discharge has an influence proportionately greater than its intensity has.

### *General Considerations on Induction.*

We shall not terminate the Chapter on Induction without speaking of the works of the two German philosophers, MM. Weber and Neumann, who have taken up this subject in a general manner in endeavouring, both by means of experiment as well as by calculation, to connect the phenomena of induced currents with the laws by which electro-dynamic actions in general are governed. M. Weber, in an important work*, has treated this question in a very profound manner; and in particular has made some interesting approximations between the effects of induction, resulting from the relative movement of a conductor and a magnet, and the mutual action of a magnet and a current. We shall quote, as an example, the following experiment, which is a modification of one of Faraday's:—

The English philosopher, as the result of a series of experiments, had been led to observe that an induced current

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* Electro-dynamische Maasbestimmungen; von W. Weber. Leipsig, 1846.

may be developed in the metal substance of the very magnet, that is employed for producing the induction. He first fixed a copper disc to the extremity of a magnet, separating it from the metal by paper interposed; the magnet and the disc were set in rotation together, and the ends of the galvanometer come, one to the centre, the other to the circumference, of the disc. The direction and intensity of the current were the same as if the disc alone had been made to rotate, the magnet remaining stationary. By enveloping the magnet towards one of its extremities with a cylinder of brass, which covered it nearly to the middle of its length, but which, by means of interposed paper, had no metal contact with it, still remaining solidly fixed to it, the same effects were obtained as with the disc, namely, the same as if the cylinder alone had rotated, and the magnet had remained at rest. Finally, by plunging the magnet itself vertically in mercury to about the half of its length, and making it rotate rapidly upon its axis, a current was obtained, when one of the ends of the galvanometer was introduced into the mercury, and the summit of the magnet was touched with the other, by means of a small cavity, filled with mercury, that is formed in the centre of its upper surface, and into which the extremity of the galvanometric wire penetrates. The current has still the same direction; a proof that the surface itself of the magnet here plays the same part as was played, in the preceding experiment, by the brass cap with which it was covered. However, we may to a certain point attribute the effect observed to the induction exercised by the central parts of the magnet upon the surface of the ambient mercury.

M. Weber's experiment differs from those of Faraday in that the magnet, being arranged so as to rotate on its horizontal axis, carries a metal disc, through which it passes tightly, and which can be slipped so as to be placed upon different sections of the magnet. This disc is plunged by its lower part in a cup full of mercury, into which is inserted one of the ends of the galvanometer wire, whilst the other communicates with the axis of the magnet itself (*Fig.* 155.). On making the magnet rotate upon its axis, a continuous current is obtained, the direction of which depends upon that of the rotation, and the intensity of which varies proportionately with the velocity of this rotation. But the intensity depends also essentially upon the power of the magnet, and especially upon the distribution assumed by the magnetism in it: for it greatly changes, according as the magnet that serves for the operation is subjected or not, at its two extremities, to the action of the contrary poles of two powerful auxiliary magnets that are brought near to it. The length of the space on the surface of the magnet, and parallel to its axis, has no sensible influence over the force of the current. For this force is the same when, the brass disc being fixed at one or other of the two extremities of the magnet, the end of the galvanometer not in communication with the disc is placed in contact with the north end and with the south end, that is to say, with that which is nearest to, or with that which is most distant from, the disc. However, the absolute effect is less considerable in this case, than it is when the brass disc is in the middle of the magnet.

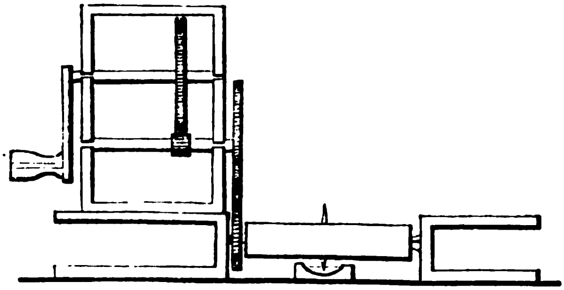

*Fig.* 155.

It is difficult for us to admit, with Weber and Faraday, that the induction currents, which are produced in the preceding experiment, are upon the surface of the magnet in rotation; there can, in fact, be no induction by the influence of the magnet that is rotating upon points of its own surface, which all preserve during the motion the same relative position in respect to the axis, and especially in respect to the magnetic poles. In the same manner as, in the experiment of the rotation of the magnet on its axis, under the influence of electric currents, that are traversing it, the cause of the motion rests solely (p. 259.) in the action of the portion of the circuit which is independent of the magnet, and consequently immovable; so likewise in the present instance the induced current can be produced in that part alone of the conductor which does not participate in the motion of the magnet. The fact that the direction of the current depends alone on that of the rotation, and that it is independent, as well as the intensity is, of the part of the surface which is in communication with one of the extremities of the fixed conductor, whose other extremity is at the end of the axis, shows clearly that the effect observed is the result of the inductive action exercised upon the conductor by the collection of currents, of which, according to Ampère's theory, the magnet is constituted; a phenomenon altogether analogous to what occurs, according to Faraday and Nobili, in a metal disc, above or beneath which a magnet is made to rotate.

Further: M. Weber himself, in including under a self-same theory the phenomenon of static electricity and those of dynamic electricity and of induction, has endeavoured to show that the latter were the consequence of the movement of translation of the electric particles, which give rise to four forces (two attractive and two repulsive) in the case of two conductors each traversed by a current, itself composed, according to M. Weber, of elementary currents, the one of positive, the other of negative electricity. In considering the electro-dynamic action of two elements as the resultant of four forces, he was led by this idea, which had already been put forth in a very ingenious manner by Professor Prevost of Geneva*, to the same formula that Ampère had found for expressing the mutual action of the two elements of the current. In order to explain induction, M. Weber supposes that an element of the conductor without a current is moved in presence of a fixed conductor, traversed by a current. The same four forces are in this case in action, only the

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* Bibliothèque Universelle de Génève, t. xxi. p. 178. (1822.)

velocity of the electricities in the induced conductor, instead of being that of a current, is that of the conductor itself; it is thus the same, and occurs in the same direction, for the two electric fluids, instead of being in a contrary direction, as in the inducing wire. In this case the formula gives for the electro-dynamic action a null result, which ought to be the case, for there is no production of mechanical movement; but, if we calculate the energy with which the inducing element tends to separate the two electricities in the induced, we find that it is expressed by the difference between the two equal and contrary forces, to which each of the elements of the induced are subjected on the part of the inducing current,—forces, whose sum or resultant is null, as we have just seen, but whose difference is $2f$, by calling one $+f$, and the other $-f$. If we decompose this force $2f$ into two others, the one perpendicular, the other parallel to the induced wire, the former is destroyed: the latter, which M. Weber calls *electro-motive force*, produces a current, which lasts as long as the motion of the wire continues; this is the inductive current. M. Weber has also observed and verified several experimental laws, and perfectly agrees with Neumann as far as concerns the induction exercised by a closed circuit; the only one, moreover, that can be obtained directly.

Neumann succeeded in calculating this latter action, setting out from a less theoretical point of view than Weber; to wit, simply that electro-dynamic action and inductive action are sufficiently connected with each other, both in respect to their value and in respect to their direction, that we may suppose that the electro-motive force produced by the motion of an induced element is proportional to the electro-dynamic action that it would receive from the inducer, decomposed according to the direction of its velocity, and multiplied by this latter. It is very remarkable that Weber had arrived at the same result by an entirely different train of ideas; and we may hence deduce the following, which is no longer a simple empirical, but rather a mathematical law; namely, that whatever be the cause of the electro-dynamic action of two currents, if to explain the induction experienced by a conductor when in motion, it is considered as a current in which both the electricities travel in the same direction, it is evidently natural to suppose that the electro-motive force is then proportional to the electro-dynamic force exercised by the inducer upon a current having this same direction.

There exists, as we have just seen, as well in the theoretical view as the experimental relation, a remarkable analogy between electro-dynamic actions and the phenomena of induction, an analogy which consists essentially in this reciprocity, namely, that the former produce a mechanical movement, and that the latter are engendered by a movement. From this difference there results, in the consideration of induced currents, an important element that has no existence in the others; it is the velocity of the movement necessary for their production, an element that has essentially served as a basis to the calculations of Weber and Neumann. Experiment had already proved its importance, by showing that the intensity of an induced current is the more considerable as the velocity of the induced conductor is greater.

As far back as 1847, I had studied (*Mém. de la Soc. de Phys. et de l'Hist. Nat. de Génève*, t. ix. p. 191.) this influence of velocity with one of Saxton's machines (*Fig.* 145.), which gives the two induced currents, the inverse and the direct; and I discovered that the rapidity of the rotation increases the energy of the action, either because there is in the same time production of a greater number of currents, or because each of them is individually more intense. Thus, when there were 28 currents per second, it required only 462 in order to liberate in the voltameter the same quantity of gases, which would have required 1050, when there were only 14 per second. By placing the helix of a Breguet's thermometer in the circuit (*Fig.* 21., p. 33.), it indicated successively 7°, 55°, 100°, and 133°, for velocities of rotation, such that there were first 2, then 10, then 20, and then 40 currents per second. However, I remarked that this influence of velocity is not the same for every kind of effects and of conductors; and that, in certain cases, there are limits beyond which it tends to diminish, rather than to increase, the intensity of the action.

M. Lenz observed, in 1841, that there is in fact a maximum in the intensity of the current, which is not simply a function of the velocity of the rotation of the magneto-electric machine. He found, as I had also observed, that the manner in which the conducting wires are placed in respect to each other, and the resistance of the system that is to be traversed by the current, determine the maximum of induction for very different velocities. If, for example, we connect with each other the wires of six bobbins, so that their total length is traversed by the induced current, a moderate velocity is sufficient to obtain the maximum induction; it is not the same if the six bobbins are separated, so that each of them is traversed by only a sixth part of the current which is distributed among them. We then, by greatly increasing the rapidity of the rotation, succeed in obtaining a current which has a force six times greater than in the former case. According to M. Lenz, this maximum is due to the secondary magnetisation which the induced currents impress upon the same masses of iron to which they owe their origin, by the effect of the momentary magnetism that they acquire in passing before the poles of the magnet. This reaction of the permanent magnetism upon itself is, in fact, often felt, and it is especially sensible in machines, in which the inducing magnetism is produced by an electric current (*Fig.* 147.). However, by suitably arranging the commutator, we may protect ourselves from its effects; and, in this respect, M. Lenz gives some practical rules, which each experimentalist may establish for his own apparatus.

A circumstance which must play a great part in the influence that is exercised by the velocity of rotation over the intensity of the induced currents, is the time of greater or less duration, and never null, that soft iron requires for being magnetised and demagnetised. In this, also, is the cause of the *finite*, although very short duration of currents induced in this manner. In fact, although we have said that the inductive currents were instantaneous, they are not completely so, at least not always; and we must distinguish those which are really so from those which we might call *temporary,* because they last for a very short time it is true, but still an appreciable time. We may easily distinguish them, in that the former cannot act like the latter upon the magnetised needle of the galvanometer, on account of its inertia, and in that they are manifested essentially by the physiological shock and by the spark. Among the causes that determine one or other kind of currents, besides those which are due to their origin, we may point out the influence of the nature of the circuit that is to be traversed by them, which may cause an originally temporary current to become an instantaneous one. In fact, if the circuit contains an imperfect conductor, such as the human body, the induced current, instead of passing away in proportion as it is produced, will not be projected onward until the instant when it shall have acquired the intensity necessary for traversing the imperfect conductor; and consequently it will be altogether *instantaneous.* We further refer to M. Dove's experiments, which we have already given in detail (p. 419. *et seq.*).

# CHAP. VI.

## ACTION OF MAGNETISM UPON ALL BODIES.

### *Notions relative to an Action of the Magnet upon all Bodies other than that arising from Induction.*

ONE of the circumstances that have constantly been the greatest characteristics of magnetism is its speciality; namely, the small number of bodies capable of being magnetised or influenced by the magnet. Iron and steel, and then more recently nickel and cobalt, have for a long time been considered as the only substances susceptible of acquiring and of manifesting magnetic properties. The discovery of magnetism by rotation seemed at first to be about to change this opinion; but the fact that motion was necessary in order to there being action of any body upon a magnet is sufficient to show that a veritable magnetic action was not in operation in this case, since the body, when at rest, exercised no effect. Moreover, the explanation of the phenomena by the production of inductive currents soon connected it with another order of facts.

The universality of magnetism, that is to say, the disposition of all bodies, as well as iron, cobalt, and nickel, to obey the influence of a magnet, in order to be demonstrated, must be manifested directly by an action of some kind exercised, by a magnet at rest, upon a body in like manner at rest. Otherwise, we may always fear that the actions we take for magnetic phenomena may be simply the effects of induction.

Induction, or, to speak more correctly, induced currents, may in fact give rise to motions. Thus, for example, if I place above, but between the poles of a powerful electro-magnet, the two branches of which are vertical, a copper ring from 4 to 6 inches in diameter, made from a very thin plate, and less than half an inch wide, consequently very light and delicately suspended, I can excite in it inductive currents by magnetising and demagnetising the electro-magnet by means of a voltaic current; and I have the proof of the existence of these currents by the movements this ring executes under the influence of the magnetic poles. These movements become still more sensible if the ring is surrounded by a belt of very powerful voltaic currents transmitted through a copper wire covered with silk, and making several circular convolutions. We then see it obey the action of these currents, as if it formed itself a part of the electric circuit; a proof that, under the influence of the electro-magnet, it is traversed by an inductive current, which its own movement renews at each instant. In order to satisfy ourselves that we must attribute the effect observed to this cause, we may cut the ring anywhere in its circuit, and join the two ends by an insulating substance. There is no longer any action, because the current can no longer circulate, and consequently cannot be established; but immediately the two ends touch each other, by communicating together by a good conductor, the action recommences.

Furthermore, a French philosopher, M. Lallemand, succeeded in demonstrating in a direct manner that the instantaneous currents produced by induction attract or repel each other as do continuous currents; and, according to the same laws, he even observed that tertiary currents, which produce no appreciable deviations in the galvanometer, act very powerfully upon each other either by attraction or repulsion. The action of the inducing upon the induced current presents some remarkable peculiarities, which I have also had occasion to verify in the experiments with the electro-magnet that I have reported above. The movable circuit is energetically repelled, although it is traversed by the two direct and inverse induced currents. It would seem to result from this, that the inducing current acts by repulsion equally upon both the induced currents. But the experiment made with the two induced currents separately shows that there is still repulsion when the inverse current is passing, and attraction when the direct current is passing, as ought to occur, according to Ampère's laws; only the repulsion is more energetic than the attraction, which explains the result of the preceding experiment. This difference in the effect of the same inducing current upon the two induced currents that are really equal, arises from this, — that the inducing current, whilst it is acting upon the inverse current, gradually increases its intensity; whilst, when it is acting upon the direct current, it in like manner gradually diminishes it; the former action occurring at the establishment of the circuit, and the latter at its rupture. It necessarily follows from this, that the former must be more powerful than the latter; for the inducing current acts upon the inverse induced current during the whole time of its duration, which does not occur to the direct one, which lasts only for a few instants after the inducing current has ceased. Moreover, the action of a current upon one or other of its induced currents is proportional to its intensity, which furnishes a confirmation of the law demonstrated by M. Abria, that there is a constant relation between the intensity of the inducing and that of the induced current.

We see, from the preceding remarks, that we must not employ the method of oscillations in order to prove whether a non-magnetic body is or is not susceptible of being influenced by a magnet; for, as soon as there is motion, there may be production of induced currents; and the effect observed is of quite another nature.

Coulomb, who was one of the first that endeavoured to discover traces of magnetism in non-magnetic bodies, found that, by giving to these bodies the forms of small bars, two or three-tenths of an inch long, and $\frac{1}{100}$th of an inch in thickness, and by suspending them to a silk thread without torsion between the opposite poles of two powerful magnets, they all placed themselves in the direction of these magnets; and that, if they were turned aside, they were always brought back after a certain number of oscillations. This effect was probably due to excessively small quantities of iron diffused indistinctly in the bodies, and not to a particular property. Such, at least, was Coulomb's opinion; who found, for example, that in a small silver needle submitted to experiment, $\frac{1}{133119}$ of iron was sufficient for it to experience the influence of magnets. It is probable that this same was the cause of the phenomena observed by Coulomb, although, however, there actually is a proper action exercised by magnets upon all bodies; but this action does not produce the same effects upon all, — a proof that, in what we have just related, it was indeed the presence of iron that was the predominant cause of the phenomenon.

M. Becquerel obtained, long after Coulomb, but a short time before Oersted's discovery, some curious results by submitting different substances to the action of very energetic electric currents, or very powerful magnets. Having observed that a soft iron needle freely suspended in the interior of a galvanometer, places itself, as might have been suspected, perpendicularly to the coils of the wire, by virtue of the magnetisation that it acquires, he put in place of it a small cartridge filled with very fine filings of cast iron, which conducted itself in like manner. But, having filled the cartridge with deutoxide of iron, he found that things were widely altered. This cartridge, about $\frac{1}{100}$ in. in diameter, being conveniently suspended, and subjected to the influence of the current, was rapidly attracted in the plane of the apparatus; and, after a few oscillations, placed itself in a direction parallel to the coils of the wire. If the pole of a magnet were presented to the cartridge of deutoxide of iron whilst it is under the influence of the current of the galvanometer, the pole is seen to act in the same manner on all the points that are situated on the same side of the galvanometer. The pole of the magnet being changed, the effect is inverted. Thus, all the north magnetism of the cartridge is on one longitudinal side of its axis, and all the south magnetism on the other; a distribution of magnetism the reverse of that which commonly occurs in magnetic bodies. Needles of copper, wood, and gum-lac appeared to experience, on the part of the current, the same kind of action as cartridges filled with deutoxide of iron, only in a much less degree. But the effect is so slightly marked, and the experiment so delicate, that its results may seem dubious.

By submitting various substances to the action of powerful magnets, M. Becquerel observed analogous effects: namely, he found that in bodies, such as steel and soft iron, the distribution of magnetism always occurs in the direction of their length; whilst in others, such as deutoxide and tritoxide of iron, wood, gum-lac, it most frequently occurs in the direction of their width. The following is a curious experiment. A wooden needle 1½ in. in length is placed between the two opposite poles of two powerful magnets, the extremities of which are about $\frac{1}{10}$ in. apart, and its point of suspension is as near as possible to the interval by which they are separated. The needle then places itself perpendicularly to the line that joins the poles, instead of placing itself in the same direction, as did a cartridge, containing a mixture of deutoxide and tritoxide of iron, or deutoxide alone. But if the poles of the bar are drawn apart, the wooden needle finally places itself in the same line as the poles. A gum-lac needle presents the same phenomenon, but in a less degree. It is impossible to recognise the transverse polarity with these different substances as it was recognised in the cartridge of deutoxide of iron, or in that containing a mixture of deutoxide and tritoxide.

Another remarkable form under which the mutual influence of magnetism and non-magnetic bodies may be manifested, is that which M. Arago observed, when making a horizontal magnetised needle oscillate above different substances that are non-conductors of electricity; and in which, consequently, the inductive currents could not be set up. Thus, over a plane of ice, a magnetised needle, in order that its deviation should be reduced from 53° to 43°, made

| | | | | |
|---|---|---|---|---|
| 26 | oscillations at | ·0275 | inches | distance. |
| 34 | „ | ·0496 | „ | „ |
| 56 | „ | 12·7850 | „ | „ |
| 60 | „ | 20·1140 | „ | „ |

Over a plane of crown glass, another needle, in order to reduce its deviation from 91° to 41°, made

| | | | | |
|---|---|---|---|---|
| 122 | oscillations at | ·0358 | in. | distance. |
| 180 | „ | ·0389 | „ | „ |

208 oscillations at ·1196 in. distance.
220 „ ·1578 „ „

These great differences in the number of oscillations made by the same needle under the same circumstances, but at different distances from the plane of ice or glass, evidently prove the mutual influence of each of these substances upon the magnetised needle.

Finally, an important fact is the repulsion, first observed by Brugmanns, and then more recently by Lebaillif, exercised by bismuth and antimony upon the pole of a magnetised needle. Endeavours were made to connect this fact with a general law; namely, with a mutual repulsion exercised between bodies by the effect of any radiation, such as calorific radiation; but carefully conducted experiment has shown that the necessary condition of the phenomenon was that the needle should be magnetised, and that, consequently, it depended upon magnetism, and not upon causes foreign to this agent.

### *Distinction of Bodies into magnetic and diamagnetic.*

The facts, that we have been relating, would seem to prove that the magnet exercises upon the different bodies in nature an action that is neither analogous to that which it exercises upon magnetic bodies, nor is it an action due to induction. But these were isolated facts, and did not appear subject to any laws; and it is to Faraday that we are indebted for having established them in a positive manner, and at the same time for having brought them under one general principle.

The learned English philosopher, as the result of researches relating to the influence exercised by magnetism over a polarised ray of light, transmitted through certain transparent substances placed under the action of a powerful electro-magnet, researches of which we shall speak further on, endeavoured to submit to the directive action of the electro-magnet the same transparent substances; and he thus arrived at a remarkable discovery. The transparent substance that he principally employed, and which is most suited to the manifestation of phenomena of this kind, is a particular glass of a yellowish colour, prepared by Mr. Faraday himself with a view to optical purposes, and which he named *heavy glass* on account of its great density; it is a boro-silicate of lead. A prism of this glass two inches in length, with a section of one-fifth of an inch, is suspended horizontally, by means of a waxed silk thread, above and very near to the two poles of a powerful electro-magnet, so arranged that its two branches are vertical. At the moment when the electric current traverses the wire of the electro-magnet, the glass prism is seen to put itself in motion, and, after a certain number of oscillations, to place itself perpendicularly to the line that joins the two poles; a position which Mr. Faraday termed *equatorial*, in opposition to that assumed by magnetic bodies, which place themselves in the line of the poles, and which he called *axial*. If it is deranged from its equatorial position, the glass prism tends to return to it, at least so long as the electro-magnet is magnetised. When, in its oscillations between the two poles, it approaches the edge of one or other of the two polar surfaces, it is seen to stop, and to be sharply repelled by this edge.

If the branches of the electro-magnet are too far apart for the action of the poles to be made sufficiently manifest upon the substance suspended between them, pieces of soft iron are placed upon each polar surface, either prismatic or cut into points, at the two parts facing each other; and, before magnetising the electro-magnet, these pieces or armatures are put at such a distance from each other that the body suspended between them shall be as near to them as possible, without, however, being inconvenienced in its rotatory movements around its suspension wire. The directive action, that we have described and designated under the name of equatorial, is then manifested in the most decided manner. But it is not only heavy glass that obeys it; all organic and inorganic substances are equally subjected to it, providing they are not magnetic or do not contain a certain portion of magnetic elements; and they do not assume the *axial* direction. Thus *rock crystal*, various non-metallic salts and chemical compounds, *iodide of phosphorus, sulphur, resin, cooked* or *raw meat, blood, a feather, a piece of apple* or *pear*, acquire the equatorial direction between the poles of the electro-magnet.

Mr. Faraday obtained the same results by employing a powerful ordinary horse-shoe magnet, instead of an electro-magnet, but the phenomena are less decided. Care must be taken, when attaching the bodies that are to be submitted to the influence of magnetism to the suspension thread, to make use of copper or brass wires only, and such as are in no degree magnetic.

When we examine the phenomenon more closely, by studying it upon a substance, such as heavy glass, which manifests it in a high degree, we are surprised by seeing the repulsion that is also exercised upon the substance by both the magnetic poles. Thus, if the prism of heavy glass is suspended, so that its centre of suspension, although situated upon the axial line, is nearer to one of the poles than it is to the other, the action of the electro-magnet always makes it assume the equatorial position; but, at the same time, it is repelled parallel to itself by the pole to which it is nearest.

We see this repulsion manifested in its highest degree when, in its oscillatory movement between the poles, the prism is near the edge of one or the other of the two polar surfaces. Further: whatever may be the form of the piece of heavy glass, as well when it is cubical or spherical as when it is prismatic, it is repelled in like manner by either of the poles; but, in order that it shall experience a directive action which shall give to it its equatorial position, it is necessary that the length shall exceed the other dimensions. Repulsion would seem, therefore, to be the phenomenon in its greatest simplicity; and the equatorial direction would be nothing but the result of the tendency of each of the particles of the body to move itself to the place where the repulsion is the least, and where consequently the magnetic action is the most feeble.

Continuing to submit substances of various natures to the action of electro-magnets, Faraday examined very closely the different metals under this relation. He distinguished those that place themselves axially, or which by being attracted by each of the two poles must be considered as *magnetic*, from those that assume an equatorial position, and being repelled by the poles, are, as Mr. Faraday called them, *diamagnetic*. These latter are essentially *bismuth*, *antimony*, *zinc*, *tin*, *cadmium*, *mercury*, *silver*, and *copper*. The force with which the new action is exercised varies with these different metals; bismuth and antimony manifest it in a high degree; a small bar of bismuth, about one-fifth of an inch wide, is, of all substances subjected to experiment, the one that best makes this phenomenon manifest in its various details. Moreover, in the enumeration that we have just been making, the metals have been classed in the order of the degree of intensity with which they manifest the kind of action in question.

Mr. Faraday employed bismuth for studying certain parts of the phenomenon that would have escaped observation with less sensible substances. He thus proved that two bars of bismuth, delicately suspended and submitted at the same time to the action of magnets, did not act upon each other, which seems to banish all idea of polar antagonism in the bars. He also saw that fine powder of bismuth, when projected upon paper, placed on one of the poles of the electro-magnet, assumes a regular arrangement; the particles distribute themselves without and within upon a circular line, which is just the edge of the soft iron cylinder. This line remains perfectly distinct, which shows the tendency of the particles of bismuth to be repelled at once in all directions, a result in accordance with the remark that we made upon the more active repulsion exercised by the edges of the polar surface upon the suspended bars. M. Pouillet obtained similar results by mixing sesquichloride of chromium, which is magnetic, with bismuth, both of them being very finely powdered; he obtained a violet circle, formed by the chloride, above the edge of the pole of the electro-magnet, which attracts it, between two very distinct circles formed by the bismuth powder, which is itself repelled by the edge.

Some of the metals, and especially copper, undergo a motion of a very peculiar kind at the moment when, being suspended between the poles of the electro-magnet, the latter is magnetised: this movement, which is very distinct from that which the bar obeys, in order to place itself in the equatorial direction, and which occurs even when it is already naturally in that direction, is equally manifested at the moment when the magnetisation of the electro-magnet ceases. It is evidently due to the production, upon the surface of the metal, of currents induced by the electro-magnet. We may satisfy ourselves of this by varying the form, the dimensions, and the primitive position of the metal that is submitted to experiment. Besides, these movements are not at all observed in heavy glass; they are scarcely sensible in bismuth, and are less decided as the metal is a worse conductor of electricity. The following is the order in which the different metals may be placed in this respect: *copper, silver, gold, zinc, cadmium, tin, platinum, palladium, lead, antimony*, and *bismuth*. This order is the same as that which M. Arago and Messrs. Herschel and Babbage had assigned to the metals with regard to their faculty of drawing on the magnetised needle in the phenomena of magnetism by rotation, and, consequently, of giving rise, upon their surfaces, to inductive currents; a proof that it is indeed to this latter kind of action, which must not be confounded with that whereon we are now engaged, that the particular movements observed by Faraday are due.

The metals that, instead of placing themselves equatorially, place themselves axially, are magnetic, as we have remarked. Mr. Faraday found a great number of them besides those that were already known, as iron, nickel, cobalt, to be endowed with this faculty. He further observed, that the greater part of compound bodies, and among them the salts of magnetic metals, are also such; and it is even from the magnetism of their compounds that he concluded for several, such as manganese, cerium, chromium, &c., the magnetism proper to them. These compounds are magnetic as well when they are dissolved in water as in the solid state. The numerous compounds into which iron enters were the subject of a special study, and they all placed themselves axially between the poles of the electro-magnet, and were attracted by these poles. The presence of a very small quantity of iron is sufficient to render a substance magnetic. Thus, green bottle glass and crown glass are magnetic; paper and fine cardboard are also so, probably because they have been in contact with iron in the act of fabrication; for organic substances are in general diamagnetic. However, the yellow crystals of ferro-cyanuret of potassium, as well as the red, assume the equatorial direction, which would seem to prove that they are not magnetic. This anomaly is probably due to the crystalline state of the substance, which, as we shall see further on, exercises a great influence over this order of phenomena.

The very marked influence that is exercised by the presence of a minute quantity of iron, shows with what precaution we must operate, in order to draw conclusions from a substance acquiring an axial position, that it is magnetic. It is sufficient, for example, to have cut a piece of wood with a knife, in order that it shall place itself axially, whilst wood always affects the equatorial direction, being eminently diamagnetic. Thus, when we submit solutions and liquids in general to experiment, we take care to place them in glass tubes whose substance is as thin as possible, and to select white and consequently non-magnetic glass. It is true that the tube is then diamagnetic; but as this property is never so decided as the other, the diamagnetism of the glass does not prevent the magnetism of the internal liquid from being manifested.

We can, moreover, test liquids, not only by placing them in small cylindrical glass vases suspended horizontally, but also by placing in them different substances upon which the action of the electro-magnet is no longer the same when they are surrounded by liquid. Thus it is that, by mixing in proper proportions protosulphate of iron, which is magnetic, and water, which is diamagnetic, we can procure a solution that is neither repelled nor directed by the electro-magnet, at least in air; but which, when surrounded by water, assumes the axial direction. In like manner, by reducing the proportion of iron, we may impress upon it in air an equatorial direction, whilst it acquires in water an axial direction. The experiment shows us that it is possible, by a suitable mixture of two bodies, each taken in one of the classes, to procure a substance that is intermediate between them with regard to the magnetic and diamagnetic properties, at least if no change is made in the ambient medium; if, for example, it is always air. On the other hand, Mr. Faraday was not able to find any body, either solid or liquid, except the artificial mixtures of which we have been speaking, that is neutral; namely, that is not magnetic or diamagnetic.

We shall not pause at the essays Faraday made, in order to determine the place that gases and vapours should occupy in the class of diamagnetic bodies. This subject, taken up subsequently by this clever philosopher according to another method, having led him to results, if not in opposition to, at least different from those he had obtained, we shall, in another place, devote a special section to the study of the magnetic and diamagnetic properties of electric fluids. We shall confine ourselves for the present to remarking that, by his first researches, Faraday was led to place air and vacuum in the middle of the table containing the list of substances ranged in the order of their magnetic power, and inverse to their diamagnetic power. The following is this table, in which the magnetism goes on decreasing from iron to air and vacuum, which are designated by 0°; and diamagnetism increasing from air and vacuum to bismuth: —

Iron.
Nickel.
Cobalt.
Manganese.
Chromium.
Cerium.
Titanium.
Paladium.
Crown glass.
Platinum.
Osmium.
0° Air and Vacuum.

0° Air and Vacuum.
Arsenic.
Ether.
Alcohol.
Gold.
Copper.
Silver.
Lead.
Water.
Mercury.
Sodium.
Flint glass.

Cadmium.
Tin.
Zinc.
Heavy glass.
Antimony.
Phosphorus.
Bismuth.

Faraday's experiments, that we have just been describing, were scarcely known, when MM. Becquerel, father and son, endeavoured to show that they were included in those that M. Becquerel, Sen., had made in 1827 on the transverse magnetism of bodies, and of which we have spoken above. They attributed the longitudinal, and the transverse or oblique direction, that is assumed by a substance between the poles of a powerful magnet, to the form of the substance, which, combined with its degree of magnetism, determines the resultant of its magnetic forces, and consequently the position that is the consequence of it. MM. Becquerel rested their opinion principally upon experiments made with peroxide of iron, which is magnetic, and which frequently, however, conducts itself like a diamagnetic body.

Mr. Faraday, indeed, recognised that this substance does actually assume very various positions between the poles of magnets; but it is not the less always attracted by the magnet, as are all magnetic bodies. Moreover, when a tube filled with peroxide of iron assumes a direction transverse to the line of the poles, it is a position of unstable equilibrium; and, if it is but slightly removed from it, it is attracted by the poles. With diamagnetic bodies, such as bismuth, phosphorus, &c., the transverse position is that of stable equilibrium. If the substance abandons it, it returns to it after a series of oscillations, and the centre of gravity of the mass is constantly *repelled* and not *attracted* by the magnet. The simple and fundamental fact, that distinguishes diamagnetic from magnetic bodies, is, that the former are repelled, while the latter are attracted by the magnet. Direction is a phenomenon that is a consequence of the fundamental fact, but which may be modified by different circumstances. The distribution of magnetism is not, therefore, made in a transverse direction. It only happens sometimes, as with a cartridge of peroxide of iron, that the state of disaggregation of the mass which opposes the transmission of magnetism by induction from particle to particle, joined to the absolute length of the cartridge, determines the creation at different distances and in different directions of magnetic poles, that may be considered as independent of each other. It is easy, therefore, to understand why the cartridge, when placed transversely to the line of the poles of the magnet, remains there by the effect of all the magnetic poles of contrary names that are found on each of its faces; and why, when one of its extremities approaches excessively near to the magnet, it is attracted by it, and is consequently deranged from its equatorial position. In proof that it actually is the particular distribution of the magnetic poles resulting from the state of disaggregation of the substance, and not, as MM. Becquerel supposed, its feeble degree of magnetism that determines the direction assumed by a cartridge of peroxide of iron, Faraday quotes the fact, that substances much less powerfully magnetic than the peroxide, but which do not present the same state of disaggregation, such as very diluted solutions of the protosulphate of iron, solution of the salts of nickel and of platinum, conduct themselves exactly, except in respect to intensity, as do all other magnetic bodies, and not as does the peroxide.

M. Edmond Becquerel has more recently taken up the same question; and, by operating with an enormous electro-magnet upon all substances cut into small bars, while he renounced the idea of a transverse magnetism, thought he ought to persist in his opinion, namely, that all bodies are magnetised under the influence of a magnet just as soft iron itself is; but to a more or less marked degree, according to their nature. The direction that they assume depended, then, simply on the difference existing between the action that is exercised upon them, and the action that is exercised upon the medium by which they are surrounded. A substance would be attracted by a magnetic centre with the difference of the actions exercised upon this substance and upon the volume of the medium that is displaced; whence it follows, that a body is attracted by a magnetic centre or is repelled from it, according as it is plunged in a medium more magnetic or less magnetic than itself; like as a balloon falls upon the surface of the ground, or rises in the atmosphere, according as the gas with which it is filled is more or less dense than the air. This principle would be analogous to that of Archimedes for gravity, with the difference, that the latter is applicable to the mass of the body, whilst the magnetic intensity developed by induction in a substance does not depend upon it, but is probably connected with the manner in which the subtile medium, or ether, of which a certain modification produces magnetism, is distributed in the body.

It would result from this, that the attractions and repulsions, exercised by the poles of the magnet upon different bodies, would depend on the same cause, and not upon two different orders of facts. Experiment, in fact, indicates that they follow the same laws, and vary in the same manner, proportionately to the square of the magnetic intensity. For obtaining these results, M. Becquerel employed the torsion-balance, taking care always to bring the substances back to the same position in respect to the poles of the electro-magnet, and only measuring, in each case, the angles of torsion. By this method, he obtained the same proportional numbers for the same substances, by making the intensity of the magnetic action vary. He also proved, in the same manner, the influence of ambient media. Thus, common glass, which in air is attracted by the poles of a magnet, is powerfully repelled by these same poles in solutions of iron and of nickel; sulphur and white wax, which are repelled by the centres of magnetic action in air, are, on the contrary, attracted when they are plunged in concentrated solutions of chloride of calcium or of chloride of magnesium.

From this theory it would seem that all bodies ought to be attracted by magnets in vacuo; since attraction is the general fact, that is modified only by the presence of the ambient medium. Now, several substances, such as bismuth, phosphorus, sulphur, are, on the contrary, more repelled in vacuo than in air. In order to explain this anomaly, M. Becquerel is compelled to admit that an empty space, like a full one, behaves itself more magnetically than the substance that is repelled; in other words, that vacuum, or rather the etherial medium by the aid of which the magnetic actions are transmitted, is itself magnetic; and that it is more so than certain bodies, and less so than others. But this conclusion appears to us contrary to all the received notions of magnetism; a property that is essentially connected with matter, and which seems to be inseparable from it. Thus M. Plucker, although he arrived at results similar to those of M. E. Becquerel, did not deduce from them the same conclusion.

We shall terminate this section by making known the results which M. Plucker obtained, by seeking to determine for each body the intensity of its magnetic or diamagnetic properties, or what might more properly be termed its specific magnetism or diamagnetism; Mr. Faraday having confined himself to giving the order in which substances ought to be ranged according to the energy of their magnetic or diamagnetic properties. In order to arrive at this determination, M. Plucker employed the balance,—the most certain and most direct means of measuring with weights the force with which each substance is attracted or repelled by a magnetic pole. He placed the substance in a watch-glass, covered with a rough and very flat glass that fitted exactly upon the edges of the watch-glass. In this manner, he gave to each substance submitted to experiment a volume always similar and of the same form. The whole is placed upon a thin brass ring suspended by three silk threads 7·87 in. long from a balance that turned with the sixtieth of a grain. Then, by means of a current of a constant force, the electro-magnet is magnetised; and one of its poles attracts or repels the substance always arranged in the same manner in respect to this pole.

Laying down as a principle, that the proper magnetism or diamagnetism of each substance is proportional to its mass,—a principle that M. Plucker endeavoured to verify directly by mixing, in greater or less quantity, fine iron filings with wax, so as that the total volume was always the same,—the magnetism or diamagnetism of the bodies was obtained by dividing by their weights the force, also expressed in weight, with which an equal volume of each of them is attracted or repelled. We thus obtain the element sought, for equal weights. Solid substances in these experiments are reduced into as impalpable a powder as possible.

It was found by this method that, expressing the intensity of the magnetism of iron by 100,000, this intensity for loadstone is 40,227, for micaceous iron-ore 533, and for the brown peroxide 71. Of all the solid or liquid compounds into which iron enters, this latter is the one that has given the most feeble result. The following, however, is the detailed table of the results, upon which we shall confine ourselves to remarking that the combination of acids with oxides, in order to form salts, does not enfeeble the original magnetism of the latter,—that the water of hydration sometimes adds force to the magnetism, as is the case with the hydrate of protoxide of nickel, which is three times more magnetic than the protoxide itself,—that, finally, all the compounds of manganese, which were submitted to experiment, were found to be magnetic.

| | | |
|---|---|---|
| 1. | Iron | 100,000 |
| 2. | Loadstone | 40,227 |
| 3. | Oxide of iron, No. 1. | 500 |
| 4. | „ „ No. 2. | 286 |
| 5. | Red ochre | 134 |
| 6. | Micaceous iron-ore | 533 |
| 7. | Hydrated peroxide of iron | 156 |
| 8. | Brown peroxide of iron | 71 |
| 9. | Artificial hœmatite | 151 |
| 10. | Dry sulphate of oxide of iron | 111 |
| 11. | Green vitriol | 78 |
| 12. | Saturated solution of nitrate of oxide of iron | 34 |
| 13. | „ „ hydrochlorate | 98 |
| 14. | „ „ sulphate of iron | 58 |
| 15. | „ „ hydrochlorate of potass | 84 |
| 16. | Green vitriol in solution | 126 |
| 17. | Sulphate of protoxide, dissolved in vitriol | 142 |
| 18. | Nitrate of oxide in solution | 95 |
| 19. | Hydrochlorate of oxide of iron | 224 |
| 20. | Sulphate of oxide of iron | 133 |
| 21. | Hydrochlorate of protoxide of iron | 190 |
| 22. | Sulphate of protoxide of iron | 219 |
| 23. | Deutochloride of iron in solution | 254 |
| 24. | Protochloride „ „ | 216 |
| 25. | Iron pyrites | 150 |
| 26. | Protoxide of iron in hydrochloric solution | 381 |
| 27. | „ „ sulphuric solution | 462 |
| 28. | Peroxide of iron in the hydrate | 206 |

| | | |
|---|---|---|
| 29. | Peroxide of iron in hæmatite | 168 |
| 30. | „ „ nitric solution | 287 |
| 31. | „ „ hydrochloric solution | 516 |
| 32. | „ „ sulphuric solution | 332 |
| 33. | Iron in the loadstone | 55,552 |
| 34. | „ oxide, No. 1. | 714 |
| 35. | „ „ No. 2. | 409 |
| 36. | „ red ochre | 191 |
| 37. | „ micaceous iron-ore | 761 |
| 38. | „ hydrated oxide | 296 |
| 39. | „ hæmatite | 240 |
| 40. | „ pyrites | 321 |
| 41. | „ sulphate of oxide | 349 |
| 42. | „ green vitriol | 385 |
| 43. | „ solution of nitrate of oxide | 410 |
| 44. | „ „ hydrochlorate | 737 |
| 45. | „ „ sulphate | 474 |
| 46. | „ „ hydrochlorate of protoxide | 490 |
| 47. | „ „ sulphate of protoxide | 594 |
| 48. | Protoxide of nickel | 35 |
| 49. | Hydrate of protoxide of nickel | 106 |
| 50. | Nitrate of protoxide of nickel, in solution | 65 |
| 51. | Sulphate „ „ „ | 100 |
| 52. | Chloride of nickel in the preceding solution | 111 |
| 53. | Protoxide of nickel in hydrate | 142 |
| 54. | „ „ nitric solution | 164 |
| 55. | „ „ hydrochloric | 171 |
| 56. | Nickel in oxidule | 45 |
| 57. | „ hydrate of protoxide | 180 |
| 58. | „ nitric solution | 208 |
| 59. | „ hydrochloric solution | 217 |
| 60. | Hydrate of manganic oxide | 70 |
| 61. | Manganous oxide | 167 |
| 62. | Manganic oxide in hydrate | 78 |
| 63. | Manganous in hydrate of oxide | 112 |
| 64. | „ „ oxidule | 322 |

### *Theories of Diamagnetism, and Diamagnetic Polarity.*

Before pursuing further the study of diamagnetic phenomena, it is necessary to acquire an idea of the theories that have been put forth in explanation of them. Mr. Faraday, who discovered, and who so carefully analysed, the phenomena of diamagnetism, was content with putting forth the law with which experiment had furnished him, namely, that diamagnetic substances are those which, in the field of magnetic forces, direct themselves from the places where these forces have the greatest intensity, towards those where they have the least; and that the converse is the case for magnetic bodies. We must not forget that Mr. Faraday distinguishes, by *field of magnetic forces*, the larger or smaller space within which the poles of an electro-magnet cause their influence to be felt, and which is traversed in all directions by forces of variable intensities and directions, of which the curves marked out by iron filings give, to a certain degree, a very exact idea.

We have already spoken of M. E. Becquerel's theory, based upon the principle that all bodies are magnetic in the same manner, only in different degrees, and that the repulsions, exercised by the two poles of magnets, upon certain substances, are only apparent, and arise from these substances being plunged in a medium more magnetic than themselves; a medium which, by reaction, gives rise to the effects that are observed. We have not been able to attach ourselves to this theory, on account of the consequence to which it irresistibly leads, namely, that vacuum itself is magnetic like bodies, more so than some, less so than others.

M. Plucker, although inclining, in respect to the laws by which the phenomena are regulated, to those of M. E. Becquerel, does not deduce from them the same consequences in respect to the magnetism of vacuum. He arrives, by his researches, to the following laws, which are no other than the principle of Archimedes extended, and in which the force of magnetism supplies the place of gravity. If a magnet acts by attraction or by repulsion upon the molecules of a body or of a fluid by which it is surrounded, the effect of the magnet upon the immersed body is the same as upon the body in vacuum, minus the effect produced upon the volume of the liquid, whose place is supplied by the body. These laws explain why an areometer, that is very little affected by the magnet, rises in a magnetic liquid, and descends in a diamagnetic liquid when it is placed above the poles, and presents contrary effects when placed below. They show, also, why a magnetic solid, when plunged into a liquid more magnetic than itself, comports itself diamagnetically, whilst a diamagnetic body shows itself magnetic in a liquid more diamagnetic than itself. Thus is explained the extraordinary force with which bismuth, and even glass that is slightly magnetic, direct themselves equatorially in a saturated solution of sulphate of iron, notwithstanding the resistance of the medium.

We see that M. Plucker admits with Mr. Faraday, and contrary to M. E. Becquerel, that the magnetism and the diamagnetism of bodies are two distinct and opposite properties; but he considers that they have a similar origin, and he is disposed to adopt, in this respect, the ideas of Poggendorff, of Reich, and of Weber, who consider diamagnetic phenomena as arising, equally with magnetic phenomena, from a polarity induced by the action of the magnet in the substances submitted to its influence, with this difference, however, that the poles in diamagnetic bodies are of the same nature as the nearer poles of the magnet, contrary to what occurs in magnetic bodies, in which they are of a contrary nature. Thus, in like manner as the pole of a magnet gives rise to an attractive pole in the extremity of the iron bar, it determines a repulsive one in the extremity of the bismuth bar; or, what comes to the same thing, the currents which Ampère supposes to be excited in iron by the influence of the magnet, have an opposite direction to that which they present in bismuth. We now come to examine and discuss the facts upon which this hypothesis is founded.

Poggendorff had found that if, to a bar of bismuth, antimony, or phosphorus, arranged equatorially between the poles of an electro-magnet, we approach the extremity of a small needle, magnetised too feebly to induce in itself a sensible magnetism, this extremity attracts the bar on the same side where it would have repelled it, had it been of iron; a proof that the electro-magnet determines, in diamagnetic substances, poles of the same name as those which act upon them. The same philosopher had also observed that, if a bar of bismuth, suspended equatorially between the poles of an electro-magnet, is surrounded by a helix, traversed by an electric current, this bar moves in the interior of the helix in a direction which seems to indicate that it has acquired a polarity, similar for each of its parts to that of the nearer pole. M. Reich, on his part, had remarked that when the opposite poles of two magnets are made to act simultaneously upon the same face of a bar of bismuth, the repulsion engendered is equal to the difference, and not to the sum of the forces possessed by each pole, when acting alone; in such sort that, if the two perfectly equal poles of an electro-magnet are employed, the effect is altogether null, there is neither attraction nor repulsion.

These experiments, and others of the same kind, although apparently favourable to the idea of magnetic polarity, are far from being conclusive; and this follows from the examination of them that was made by Mr. Faraday, who himself, at first, inclined towards this opinion, and by Professor Thomson of Glasgow. These two philosophers consider that all these effects arise from a modification that is produced in the field of the magnetic forces, by the introduction of a new magnet, or of an electro-dynamic helix, for the purpose of demonstrating the polarity of the substance that is in this field. Thus, for example, M. Plucker, in order to support the idea of polarity, had quoted the fact, that if a cylinder of soft iron is placed equatorially between the poles of an electro-magnet, a little below the plane, in which a similar cylinder of bismuth moves, the force with which this latter tends to place itself equatorially is much augmented; whence he concluded, that the two extremities of the bismuth had acquired, under the influence of the electro-magnet, contrary poles to those acquired by the two extremities of the iron under the same influence. Mr. Faraday has shown that this result arises solely from the alteration produced in the lines of magnetic force by the presence of the bar of iron; in fact, this presence must increase the force existing between the two poles of the electro-magnet on the line which joins them, and diminish the intensity of that existing on the equatorial line, the iron which is below of necessity partly neutralising it, so that the bismuth is driven from the axial to the equatorial position, with a much greater difference of force than it would manifest had there been no soft iron.

Mr. Thomson, on his part, through modifying the direction and the intensity of the forces in the magnetic field, by various positions given to the magnets, succeeded in impressing upon magnetic bodies, such as a ball of soft iron, motions analogous to those presented by diamagnetic bodies under the same circumstances. Thus, a ball of soft iron, of very small volume, and very delicately suspended from a long horizontal lever, under the influence of two contrary poles of unequal force, placed on the same side in respect to it, but at different distances, may be held in equilibrium at a certain distance from them both. So also the same ball, when submitted to the action of two poles, equal in force, but of the same name, will have, not only a position of unstable equilibrium in the middle of the line that joins these poles, but also two positions of stable equilibrium at the two extremities of a right line, drawn perpendicularly to the middle of the former, and of a length depending upon the force of the magnetic poles. All these effects, and others also of the same kind, may be obtained in a much less decided manner, it is true, but still sensible, by supplying the place of the soft iron by bodies that are very slightly magnetic, and even by diamagnetic bodies. In proof of the identity of the action exercised upon these latter substances, as well as upon magnetic bodies, Mr. Thomson quotes the fact that, according to his view, for one class as well as for the other, the effect exercised by the magnet is proportional to its force; a result opposed to those by which M. Plucker thought he had been able to establish that diamagnetism decreases more rapidly than magnetism, with the diminution of the force of the electro-magnet, or with the increase of distance. He had found that, if a quantity of mercury or bismuth is placed upon a watch-glass, which is slightly magnetic, at a certain distance from the poles, diamagnetism obtains the pre-eminence, and repulsion takes place; at a greater distance magnetism is in the ascendancy, and there is attraction. Mr. Thomson thinks that the changes of effects, due to the increase of distance, arise from the influence of the second pole of the electro-magnet, which, becoming more sensible in proportion as the body is removed from the pole that acts directly upon the substances submitted to experiment, brings about a modification in the distribution of the lines of magnetic force. He was equally satisfied that this distribution is altered in a very decided manner by a change in the intensity of the absolute force of the electro-magnet, which would equally explain why substances such as carbon, whose magnetism and diamagnetism are both very undecided, place themselves, as M. Plucker observed, sometimes axially, at other times equatorially, according as the force is more or less considerable. We see, therefore, that an attentive observation of the phenomena is not favourable to the idea of a polarity in diamagnetic bodies; however, in favour of this opinion, have been argued another class of facts, discovered by Weber, and which are deserving of a serious examination.

It was by placing a diamagnetic metal instead of soft iron, within a bobbin intended for producing induction, that Weber thought he discovered the proof of the acquisition by this metal, when under the influence of a powerful electro-magnet, of poles of a contrary nature to those acquired by soft iron under the same circumstances. The bobbin is surrounded by a copper wire covered with silk 984 ft. in length, and $\frac{1}{40}$th in. in diameter, the two extremities of which communicate with those of a very sensible galvanometer, and it is placed vertically upon the polar surface of an electro-magnet. Cylinders made of different metals are introduced successively into the bobbin, and a commutator, placed in the circuit, of which the galvanometer forms a part, is combined so as to be able to form this circuit, either at the moment when the metal cylinder is introduced, or when it is withdrawn. The galvanometer sometimes indicates the presence of an instantaneous current; and, as care has been taken to maintain the magnetism of the electro-magnet at the same degree of force, the current observed can only be an inductive current, arising from the introduction into the bobbin of a metal, upon which a magnetic pole acts. But this current, when produced by a bar of bismuth, for example, has a direction contrary to what it possesses when it derives its origin from a bar of soft iron; whence M. Weber concludes, that the bar of bismuth acquires at its two extremities poles of a contrary nature to those which the bar of soft iron acquires under the same influence.

On repeating Weber's experiments in February, 1850*, I obtained results analogous to his, save that I did not find that the intensity of the effect obtained bore any relation to the degree of diamagnetism of the substance: thus the introduction of a cylinder of zinc into the bobbin gave a more powerful current than what was derived from the introduction of the cylinder of bismuth, although zinc is much less diamagnetic than bismuth; and antimony and lead, the one very diamagnetic, and the other but little so, each gave rise to a current that was barely perceptible. After a long and detailed study of these phenomena, Faraday succeeded in discovering that they were not due to diamagnetism, but to the greater or less degree of conductibility of the metals, upon the surface of which, when they are introduced into the bobbin, there are established inductive currents, analogous to those which were observed by Dove, and of which we have spoken in the preceding Chapter.†

Faraday's apparatus consisted of a helix three inches in length, and two inches interior diameter, fixed horizontally at the extremity of a cylinder of soft iron, which enters it one inch: this soft iron cylinder is itself the extremity of one of the branches of a powerful electro-magnet. A system of suspension, constructed with great care, enabled him to give a movement, to and fro, of about two inches in extent, in a horizontal direction, to a wooden lever two feet in length, at one of the extremities of which are fixed successively cylinders of different metals 5½ in. in length and ¾ in. in diameter; the apparatus is so arranged that these cylinders may penetrate into the helix, and come out of it six times in a second, without in the least degree shaking either the helix or the

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* Arch. des Scien. Phys. et Nat. de la Bibliothèque Univ. t. xiii. p. 115. (Feb. 1850.)

† The Memoir in which Faraday describes the results that he obtained, was communicated to the Royal Society, March 13. 1850; and appeared in the 1st part of the "Philosophical Transactions of 1850."

electro-magnet, which is essential. The two ends of the helix communicate with those of the galvanometer, and a commutator, whose movement is connected with that of the lever by which the metal cylinder is sustained, enabled him to appreciate only one of the currents — that which is developed at the moment of the introduction, or that which occurs at the moment when one of these cylinders leaves the helix. The following are the results: —

Cylinders made of very magnetic metals, such as iron and nickel, determine a very powerful induced current, the direction of which indicates that it is due to the polarity acquired by these metals at the moment in which they approach the electro-magnet, and which disappears at the moment when they are withdrawn from it; however, this method of detecting the existence of magnetic polarity is not very sensible; for substances that are powerfully magnetic like iron, as a solution of proto-sulphate of iron, or crystals of sulphate of iron, do not produce any effect. It is not the same when diamagnetic metals are employed. A deviation is produced in a contrary direction to what obtains when magnetic metals are employed; but the intensity of this deviation is not proportional to that of the diamagnetism. Thus, it is considerable with cylinders of gold, silver, and copper; for it is maintained in a very permanent manner to 66° or 70°, whilst it is very slightly sensible with platinum and lead, and nothing with antimony. The energy of the effect appears, therefore, to depend exclusively upon the degree of conductibility of the substance; and, consequently, upon the facility with which inductive currents may be established upon its surface. The following are some further proofs in support of this mode of explaining the production of the currents that are determined in the wire of the helix by the introduction of a diamagnetic metal.

We may, without diminishing the intensity of the effect, diminish the length of the diamagnetic cylinder, and reduce it even to an inch; this is because the inductive currents that are circulating round its surface are only developed in the part that is nearest to the pole of the electro-magnet; whilst a similar diminution in length, when made on the magnetic cylinder, brings about a great reduction of the current, which in this case is due to the polarity that has been acquired by the metal under the influence of the magnet, and the effect of which has its full force only when the cylinder is as long as the helix.

The division of the metal cylinder into wires of the same length, but of a very small diameter, has altogether an opposite effect: it notably increases the power of magnetic metals; it entirely annihilates that of diamagnetic metals: this double contrary effect is due to the same cause, namely, to the obstruction which the division opposes to the establishment of inductive currents around the surface of the metal, which is the only cause of the currents, indicated by the galvanometer in diamagnetic metals, and which, on the contrary, is the cause of the weakening of these currents in the case of magnetic metals. This observation had been already made by Dove, as we remarked in our Chapter on Induction, p. 425. If, for a bundle of copper, gold, or silver wires, whose effect is null, we substitute a cylinder of the same diameter, but formed by the superposition of discs of these same metals, a current of 25° or 30° is obtained, because the inductive currents may be established around the edges of the discs.

To these very conclusive proofs Faraday adds others, drawn from the fact that the velocity with which the metal cylinder is introduced into the helix, exercises a very different influence over the intensity of the induced currents, according as the metal is magnetic or diamagnetic; and that the commutator must act in one case at a very different moment from that in which it should act in the other case, in order to give the maximum effect.

The conclusions to which Faraday arrives have been further confirmed by the recent researches of M. Verdet. This philosopher had employed in his experiments a horseshoe magnet, before the poles of which a metal plate rotates; the branches of the magnet are placed in the axis of two bobbins of long wire, which is placed in communication with a sensible galvanometer. In operating with slightly magnetic substances, such as sulphate of iron, very appreciable induced currents are obtained, which shows the sensibility of the apparatus; with regard to non-magnetic metals, the intensity of the currents induced during the movement, when the plate is very near to the line of the poles, shows that the effects depend only on the conductibility of the metals, and not at all on their diamagnetic power. M. Verdet, in order to analyse the phenomenon in its details, added to the machine a commutator, which allowed the current to reach the galvanometer only during the second part of a rotation of the plate; he thus recognised, as Faraday had done, *the influence of time* upon the induction, which explains why the induced currents are not distributed in a symmetrical manner, during the period when the plate is withdrawing from the line of the poles, and during the period when it is approaching it; — a dissymetry, which is the more marked in proportion as the velocity is greater.

We see, therefore, that we must renounce the idea of a diamagnetic polarity, analogous, but of a contrary name to magnetic polarity; — that it is in like manner impossible to admit the existence in diamagnetic bodies of a polarity similar in all respects, save in regard to its intensity, to that of magnetic bodies. It therefore appears to us probable that the force which impels substances when they are suspended freely in the field of magnetic forces, to pass from the more powerful to the more feeble points, is of a very different nature from magnetism; moreover, that it is general, and that, if magnetic bodies do not obey it, it is, that in them it is counteracted by that very special property with which they are endowed, and which we term *magnetism.* We have, in fact, seen that Mr. Thomson succeeded in impressing upon magnetic bodies, by a special arrangement, which neutralised the effect of their magnetism, a position similar to that acquired by diamagnetic bodies under the same circumstances. The point, in our opinion, upon which the attention of the philosopher should be directed, should therefore be a careful study of the magnetic field, and, consequently, a minute analysis of the forces by which it is traversed, and of the circumstances that may make these forces vary, in order, if possible, to arrive by these means at the discovery of the cause which leads them to act upon bodies.

Let us add, further, that it would be important to study, better than has hitherto been done, the conditions arising from the very constitution of bodies, in regard to the form, the molecular arrangement, and the chemical constitution which renders the action exercised upon them by these forces more or less energetic. The influence of temperature would be valuable to know; M. Plucker has already proved that a mass of bismuth weighing 2223 grains Troy, required at the ordinary temperature a weight of 25·78 grains Troy to counterbalance the effect of diamagnetic repulsion; whilst it required no more than 4·32 grains Troy, when the temperature was raised to the point of the fusion of the metal. The solid or liquid state exercises no change over this property; ice, according to the observations of M. Brunner, Jun., is as diamagnetic as water, whether in a state of liquid or of vapour. These facts, and others also, are neither sufficiently numerous, nor sufficiently in accordance, to enable us to draw from them any general consequence; it is possible we may arrive at some such, when they shall have been more multiplied.

### *Influence of Magnetism upon Flames and Gases, and upon Liquids.*

Mr. Faraday had thought he was able to conclude from his first experiments that air and the different gases do not differ from each other in regard to their magnetic or diamagnetic properties, and that they ought, in this respect, to be placed, as well as vacuum, almost in the middle of the scale, that is to say, between magnetic and diamagnetic bodies. I was induced to remark that the results obtained by Mr. Faraday were perhaps only apparent, and that they simply depended upon the material of the tube in the interior of which the vacuum or the gas was placed, as well as upon the influence of the surrounding medium. A curious experiment made at Genoa by Father Bancalari had demonstrated that elastic fluids are not so indifferent as might have been supposed to magnetic action. M. Bancalari found that the poles of an electro-magnet have a decided repulsive action upon the flame of a lamp, upon smoke, as well as upon the vapour of water and of alcohol. M. Zantedeschi, in repeating and confirming these experiments, proved that flame is repelled equally by each of the poles:—that the effect is not due to currents of air, that the repulsion is accompanied by a depression of the flame. The same philosopher further observed that the smoke that rises from the snuff of an extinct flame, fed by oil, alcohol, or wax, is subject to the same repulsive force.

Mr. Faraday, as soon as he became acquainted with these experiments of MM. Bancalari and Zantedeschi, took up, by a new method of experimenting, his researches upon gases, and arrived at results that showed him, conformably to what he had thought, that elastic fluids are not insensible to the action of the magnet, but, contrary to his former experiments, that there exist sensible differences between different elastic fluids with regard to their magnetic or diamagnetic properties.

He first satisfied himself that hot air is powerfully diamagnetic in respect to cold air. He arrived at this result by placing between the two poles of the electro-magnet, but a little below their surface, a helix of platinum, rendered powerfully incandescent by an electric current. So long as the electro-magnet was not magnetised, the current of hot air rose regularly between the two poles; but immediately magnetisation was produced, it was perceived by means of the thermometer, and even simply by the sensation experienced by the fingers, that the ascending current of hot air divided itself into two currents, mounting separately on the two sides of the axial line; and that there was between them a current of cold air, descending between the poles. The converse experiment was made; namely, by passing a current of air into a tube, surrounded by a freezing mixture; and it was found, by means of a thermoscope placed below the poles of the electro-magnet, that this current was carried upon the axial line; a further proof that cold air is more magnetic than hot air.

In order to operate upon the different gases, and to discover the direction they assume in the magnetic field, Mr. Faraday employed glass tubes open at both ends, about $\frac{2}{3}$ in. wide, and $2\frac{1}{2}$ in. long, arranged in different ways around, above, or below the poles of the electro-magnet, and containing within them a piece of paper moistened with ammonia. Each gas, when submitted to experiment, was itself mixed with a very slight quantity of muriatic acid, a quantity not sufficient of itself to give white vapours in air, but capable of producing them by its mixture with ammonia. In this way, the appearance of the white cloud indicated in which tube the gas had passed; whence it was easy to conclude what direction it had followed, and, consequently, if it were magnetic or diamagnetic in respect to the surrounding medium. A current of oxygen, which descended vertically between the poles, was in no way affected by the magnetisation of the electro-magnet; but the current of the gas having been slightly displaced and put outside the axial line, the oxygen was seen, under the magnetic influence, to approach this line and to descend in the tube placed directly below, and not in that in which it had previously descended. Thus oxygen is powerfully magnetic in respect to air. The reverse is the case for nitrogen. It was also found with hydrogen, notwithstanding the difficulty of operating with it, on account of its specific lightness, that it is very diamagnetic in ordinary air. He did the same, in respect to carbonic acid, which places itelf in the equatorial direction in a very decided manner. Lime water, by becoming white, indicated in an elegant manner into which tube the carbonic acid was directed. All the other gases, to the number of fifteen, that were submitted to experiment were found by Faraday to be diamagnetic, with the exception, perhaps, of nitrous gas, which appeared to be magnetic.

M. E. Becquerel, when observing the repulsion exercised by the poles of the electro-magnet upon different bodies, such as cylinders of wax or glass, placed in vacuum or in different gases, succeeded in recognising, as Mr. Faraday had done, the magnetic power of oxygen. The fraction $\frac{377}{1,000,000}$, which, according to M. Becquerel's accurate experiments, expresses the specific magnetism of this gas for equal masses, in respect to soft iron, places it among the most powerfully magnetic fluids; in fact, concentrated solution of protochloride of iron, the most magnetic liquid known, is nearly three times less attracted than oxygen for equal weights. The magnetic power of oxygen increases with the elastic force; and the effect appears to be very exactly proportional to this force, and consequently to the quantity of material particles contained under a given volume. Atmospheric air presents the same effects as oxygen, and nearly in the same intensity; which latter is less on account of the presence of nitrogen. M. E. Becquerel has made some further experiments upon the gases, by condensing them by means of fragments of charcoal, which he then suspends between the poles of the electro-magnet: he has again proved by this method the magnetism of oxygen, which, by its presence in the pores of carbon, renders this substance magnetic from being diamagnetic, which it is naturally; whilst other gases, condensed in the same manner, increase its diamagnetic power. With regard to nitrogen and hydrogen, they do not become sufficiently condensed in carbon to enable us to detect any sensible effect within the limits of the observations.

Faraday conceived a very elegant and very sensitive method of showing the magnetic and diamagnetic properties of gases; it consists in employing soap-bubbles of the gas that is to be experimented upon. When placed in the magnetic field, they are attracted or repelled according as the gas is magnetic or diamagnetic in respect to air; thus a bubble filled with oxygen is powerfully attracted. But, in order to operate in a more convenient and accurate manner, Faraday replaced the soap-bubbles by little balls of very thin glass, into which the gas is introduced; he places two of these balls, each filled with a different gas, upon one of the extremities of a horizontal wooden lever, suspended delicately to a torsion thread; and he so arranges his apparatus, that each ball is in the neighbourhood of the pole of the electro-magnet. The power necessary to bring them back to a position equidistant from the pole, becomes the measure of their magnetic or diamagnetic force. By means of this differential torsion balance, not only may gases be compared with each other, but the same gas may also be compared with itself at different degrees of density. Thus, it was found that oxygen was less magnetic in proportion as it is more rarified; but it is still so, even when a very great degree of rarefaction is produced. A ball in which a vacuum has been made after its having been filled with oxygen, may even compensate the effect of a ball filled with nitrogen under the ordinary pressure. This last gas, as well as several others, does not appear to undergo any alteration in its diamagnetic power by a diminution in its density. Elevation of temperature diminishes the magnetic power of oxygen, and exercises no influence over nitrogen. We shall see, in the Chapter of the Fifth Part upon Electricity and Terrestrial Magnetism, the application Mr. Faraday makes of this double opposite property of oxygen and nitrogen, in explanation of the several phenomena of terrestrial magnetism.

M. Plucker, on his part, had succeeded, after M. Bancalari's discovery, in showing the repulsion exercised by the poles of the electro-magnet upon the vapour of iodine, chlorine, bromine, nitrous acid, mercury, and water, as well as upon heated air. He had likewise observed the same effect upon the flames of essence of turpentine, fat, stearine, alcohol, sulphur, phosphorus, and hydrogen. We may see in *Fig.* 156. the apparatus employed by this philosopher in all his researches. It is an electro-magnet, surmounted by a Coulomb balance, with the suspension thread. It will be seen that this very powerful electro-magnet is formed by four thick copper wires, covered with silk, coiled separately around its two branches; and that the ends of each of the wires arrive at as many metal rings as there are ends. These rings are fixed one over the other, upon two insulating stems, so as not to communicate metallically together. By a combination of conductors easy to be understood, we may put the four wires parallel into the circuit, or place them so that the current traverses successively either the whole, or only two or three; and it is also easy to arrange them so that one only is in the circuit. A commutator, placed between the two small columns, to which the extremities of the four wires arrive, permits of our easily changing the direction of the current.

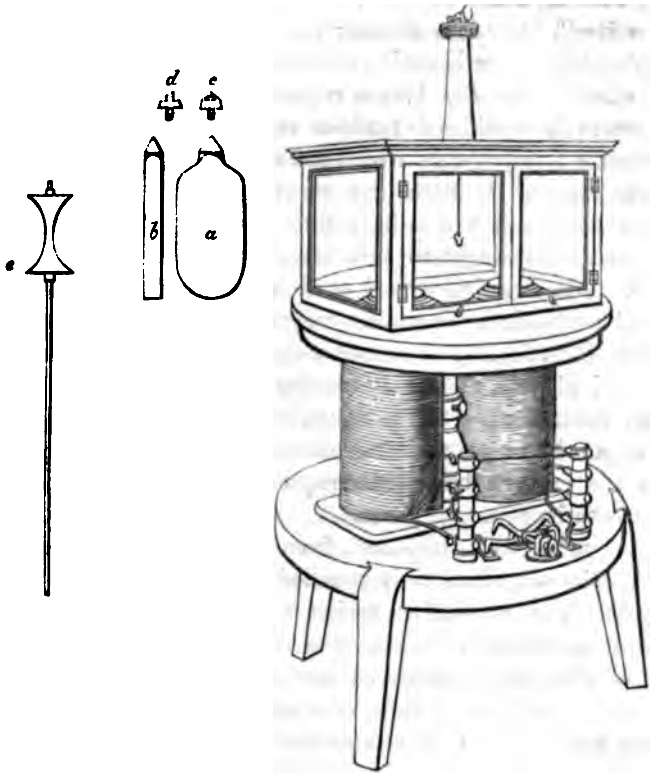

*Fig.* 156.

It was by means of this electro-magnet that M. Plucker made all his experiments, whether upon flames, upon liquids, or upon solid bodies, and particularly upon crystals. But, before setting forth their details, we should mention the experiment, by which he succeeded in proving, in an absolute manner, the repulsive action exercised upon particles of air by magnetism, — a result that we were not able to deduce from Faraday's experiments; which being always made upon a gas itself, placed in another gaseous medium, never gave, as this philosopher himself remarked, any other than a relative effect. The *Fig.* 156. *e.* represents an air thermoscope, the reservoir of which is made of very thin plates of brass, of a concave form, against which are accurately applied the two convex parts of the armatures, serving as poles to the electro-magnet, between which it is thus placed. By this means, the latter are brought to a distance of $\frac{1}{3}$ of an in. from each other. After having waited until equilibrium of temperature is well established, the electro-magnet is magnetised with ten pairs of Grove's, and we immediately perceive that the drop of coloured alcohol, which, by moving in the glass tube, serves as an index for the thermoscope, indicates by a depression of $\frac{1}{10}$ of an in. or so that the volume of air has augmented; then the current being interrupted, the drop immediately returns to its primitive place.

M. Plucker had concluded, from his experiments, that air is diamagnetic, since it is repelled by the two poles of the magnet. This conclusion, which is evidently erroneous, since it is in opposition to the results of the experiments of Faraday and of Becquerel, shows us that this mode of operating is defective; and, in fact, it is a difficult matter to abstract either the influence of temperature or that of the electro-magnet upon the substance of which the sides of the reservoir are formed. Has not M. Plucker pursued experiments of this kind too far? But, on the other hand, there is a class of phenomena, connected with the same subject, of which he made a special study; these are the very remarkable changes of form that result to visible gases, such as flames, and to liquids, from the action exercised upon them by the poles of the electro-magnet.

When flames are in question, it is necessary, in order to make this class of experiments, to remove the upper part of the glass cage, so that it shall not be altered by the heat or smoke arising from combustion; but to preserve the lateral sides, so as to prevent, as much as possible, the form that the flame assumes being disturbed by the agitation of the air. We must also adjust to the two armatures of the electro-magnet (*Fig.* 156.) *a* or *b*, in place of the conical points by which they are terminated, the sharper points *c* and *d*; and then bring them to a distance of about $\frac{3}{5}$ of an in. from each other, and so that they may be at $\frac{2}{5}$ or $\frac{7}{8}$ the height of the flame that is interposed between them. *Figs.* 157. and 157. *a.*, 158. and 158*a.*, represent respectively the equatorial and axial sections of the flame of a tallow candle subjected to the influence of the two polar points, the latter being at the distance of $\frac{3}{5}$ of an in. from each other, and successively at $\frac{7}{8}$ and at $\frac{1}{2}$ the height of the flame. *Fig.* 158. *b.* represents the flame in this latter case, seen from above downwards; it has the form of an elliptical ring, which surrounds a dark space, and which is itself surrounded by a narrow and but slightly

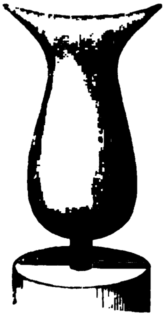
*Fig.* 157.

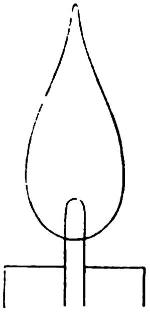
*Fig.* 157. *a.*


*Fig.* 158.

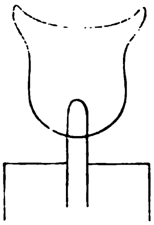
*Fig.* 158. *a.*


*Fig* 158. *b.*

illuminated ring. *Figs.* 159. and 159. *a.* represent the equatorial and axial section of the flame, when the two polar points are at the height of the upper extremity of the wick. Before the electro-magnet is magnetised, the presence of these iron points, by cooling the flame, prevents its burning with its full amount of brilliancy; but immediately the electric current is established, and, consequently, magnetisation is produced, the flame not only recovers its original brilliancy, but even burns with more force, although still being depressed. Of all flames, the one upon which the action of the magnetism is the most remarkable, and produces the most decided alteration of form, is the flame arising from the combustion of essence of turpentine. We see (in *Fig.* 160.) the appearance that it assumes, and the two columns of smoke that rise, like the branches of a parabola. When withdrawn from the influence of the poles of the electro-magnet, this flame is perfectly cylindrical and very short, and surmounted by a long column of smoke, also cylindrical. It is not without some difficulty that, in all these experiments, we succeed in bringing the two polar points as near as is necessary, without their mutual attraction bringing them into contact.

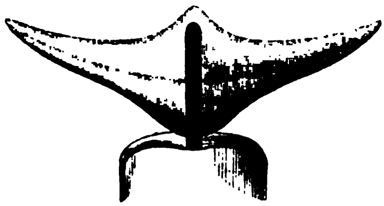
*Fig.* 159.

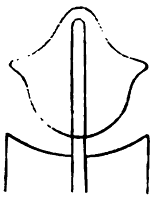
*Fig.* 159. *a.*

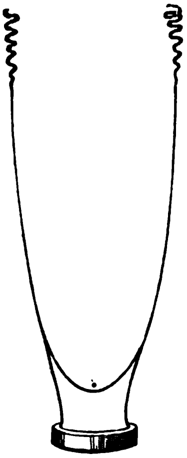
*Fig.* 160.

We have said that M. Plucker had also succeeded in demonstrating the magnetism and diamagnetism of liquids, whose particles, moreover, are movable, like those of elastic fluids, by means of the changes of form that are determined in them by magnetic influence. It is necessary for this to place the liquid in a very thin watch-glass, and to place this watch-glass so that it rests upon the two armatures of the electro-magnet, which are so turned that they each present, on the side where they face each other, a slightly rounded form, like the lower form of the piece *a* of the *Fig.* 156. If we pour into the watch-glass a magnetic liquid, for example, chloride of iron, so that it presents in its lower part a circular surface of about an inch in diameter, we see it successively assume forms which depend on the greater or less proximity of the two polar armatures. In all the figures that follow, the two arcs of the circle, described with large radii and marked with finer lines, represent the edges of the two armatures upon which the watch-glass rests; the dotted lines are the horizontal and vertical sections of the liquid before the armatures are magnetised, and the full and strong lines these same sections when magnetisation makes its influence to be felt. We see in the *Figs.* 161., 162., 163., 164., which represent the horizontal sections of the liquid, that, when the armatures are very near together, it assumes an elliptical form,

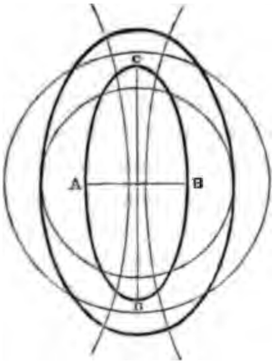

*Fig.* 161.

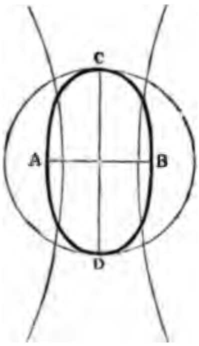

*Fig.* 162.

*Fig.* 161. *a.*

*Fig.* 162. *a.*

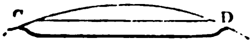

*Fig.* 161. *b.*

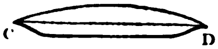

*Fig.* 162. *b.*

elongated in the equatorial direction, C D: and changes its form by elongating in the axial direction A B, in proportion as the armatures are drawn apart. The latter are placed successively at distances from each other of ·098, ·393, ·590, ·905, 1·21 inches. The same letters represent in each case

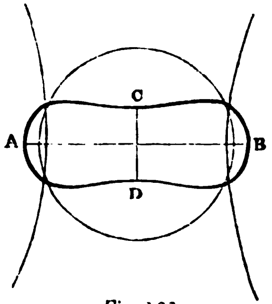

*Fig.* 163.

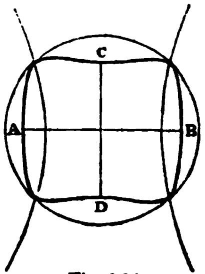

*Fig.* 164.

*Fig.* 163. *a.*

*Fig.* 164. *a.*

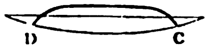

*Fig.* 163. *b.*

the vertical sections of the liquid: those marked with the letter *a*, in the direction of the axis, or axial; those marked with the letter *b*, in the direction perpendicular to the axis, or equatorial. *Fig.* 164. has no vertical section in the equatorial direction, seeing that this section is reduced to a simple right line. The mass of the liquid remains constantly the same in all the experiments.

At the distance of ·59 in. (*Fig.* 163.) the liquid contracts in the equatorial as well as in the axial direction; in this latter direction its convexity diminishes, and it changes in concavity in the former. With regard to the vertical section in the direction of the axis (*Fig.* 163.*a.*), it indicates a hollow, like a valley, in the middle, with two protuberances near the edges, exactly at the points corresponding to the vertical projection at the edges of the armatures. The vertical section, in the direction perpendicular to the axis (*Fig.* 163. *b.*), continues to be a right line, terminated at its two extremities by two slight curves. *Fig.* 164., which represents the form of the liquid when the armatures are at the distance of ·905 in., indicates the same effects, but in a still more decided manner; the contraction, in particular, in the equatorial direction, is much more powerful. When the distance is extended to 1·21 in., the edges of the armatures are found withoutside the circle formed by the liquid in its natural state, this circle being only about an inch in diameter. It follows from this that the alteration of form is feeble, and consists in the transformation of the circle into an ellipse, slightly excentric in the direction of the axis.

If, instead of a magnetic liquid, we place in the watch-glass a diamagnetic liquid, this liquid, when the armatures are at the distance of ·098 in., as in *Fig.* 161., acquires a form whose vertical section in the direction of the axis is represented by *Fig.* 165.; and by *Fig.* 166., when the two armatures are at the distance of ·590 in., as in *Fig.* 162. We see that the protuberance, that occurs at these small distances above the edges of the armatures, when the liquid is magnetic, is replaced, when the liquid is diamagnetic, by cavities; but which are less decided, it is true, than were the protuberances. In both cases, the liquid ceased to obey the laws of hydrostatics, by the effect of the attraction or repulsion exercised upon its particles.

*Fig.* 165.

*Fig.* 166.

In order to determine whether a liquid is magnetic or diamagnetic, it is sufficient, therefore, to pour a small quantity of it into a watch-glass, placed upon the two armatures, so arranged that they are about a tenth of an inch apart. The liquid immediately undergoes the change of form that we have been describing; and from the new form, which is different in each case, we conclude that the liquid is magnetic or diamagnetic. If the change of form is not sufficiently decided for us to perceive it by looking directly upon the surface of the liquid, we may render it sensible, provided it exists, by the image that is given by reflection upon this surface of a distant object. It is well to remark, in terminating this subject, that the arrangement assumed by a magnetic liquid, under the influence of the two poles, is altogether analogous to that which is determined upon a fine magnetic powder, such as iron filings, by this latter influence; that is to say, that the particles of the liquid, like those of the powder, tend towards all the points where the force of the magnet is the greatest. With a diamagnetic liquid, the form is such that the particles of liquid appear to avoid these same points. We may very readily prove by this means the diamagnetism of water, of alcohol, and even of mercury; for mercury we have merely to place it in a capsule of metal, the interior surface of which has been previously amalgamated. It is remarkable that, when subjected to this proof, the red solution of cyanuret of potassium showed itself magnetic, and the yellow diamagnetic; whilst, in the solid state, these two bodies, as Faraday observed, are diamagnetic.

### *Magnetic Properties of Crystals and the Magneto-crystalline Force.*

M. Plucker, being desirous of finding the extent to which the direction of the fibres in organic bodies might influence their magnetic or diamagnetic properties, was led to inquire whether in crystals the direction of the optic axes, which itself depends upon the arrangement of the particles, might not also exercise some influence. He first submitted to the action of the electro-magnet a thin plate of tourmaline, such as is employed in experiments upon polarisation, having its optic axis parallel to its longest length. It was very quickly perceived that the plate was magnetic, by the effect of the iron that it contains; but it was suspended successively in three ways, first so that its longest side was vertical, then so that the shortest side was vertical, and finally, so that the plate itself was horizontal. In the first case it is directed between the two points of the conical armatures of the poles, like a magnetic body; in the other two cases, on the contrary, it took the direction assumed by diamagnetic bodies, that is to say, a direction such that its longest length was perpendicular to the line joining the poles. This direction indicated that the optical axis was repelled by the two poles, and that this repulsion outweighed the magnetic properties of the crystal. Other tourmalines, obtained from different sources, which were submitted to experiment, both transparent as well as opaque, gave the same result. Although magnetic, they placed themselves, when at a certain distance from the poles of the electro-magnet, so that their optical axis was perpendicular to the axial line connecting the two poles. It is important to remark that the force which produces the repulsion of the optical axis diminishes in intensity with the distance of the poles of the electro-magnet from the crystal, in a proportion less rapid than the magnetic or the diamagnetic force that acts upon the entire mass of the substance. On which account, in order to annul the effects of this latter force, and to perceive that of the former, the magnetic poles must be withdrawn to a certain distance.

A plate of calcareous spar was submitted to the same proof; its two large faces were perpendicular to the optic axis, and it was first seen to direct itself equatorially, consequently, so that its optical axis was itself directed axially; a result of the diamagnetism of the substance. But the poles of the electro-magnet having been made to recede, the axis of the crystal assumed the equatorial direction, as if the substance were itself magnetic. Beryl, dioptase, vesuvian, which are all magnetic substances, present the same phenomenon as tourmaline and calcareous spar; we should not omit to remark that all those crystals endowed with double refraction are negative, that is to say, that in double refraction the extraordinary ray is repelled by the axis. With regard to the crystals with two axes equally negative, such as mica, their two axes are equally repelled by the two poles, which causes them to take a direction such that their mean line places itself equatorially. All these experiments were made with the apparatus, *Fig.* 156., in which a cocoon filament, terminated by a small hook, serves for suspending the crystal between the two conical armatures adjusted to the poles of the electro-magnet.

Some observations, that are not very decided, made upon quartz and topaz, which are positive crystals, namely, in which the extraordinary ray is attracted by the axis, had at first led M. Plucker to extend to all crystals the laws that we have just laid down; when some fresh researches of Mr. Faraday's established in this respect a characteristic difference between the different crystalline substances; differences, the accuracy of which were confirmed by further researches by M. Plucker himself.

Struck by the irregularities that certain specimens of bismuth presented to him in the action that is exercised upon them by the magnet, Faraday satisfied himself that, although always strongly diamagnetic, this metal presents a particular polarity in its crystalline state. Having obtained by the ordinary process well determined crystals of bismuth, and which weighed from 18 grs. to 100 grs., he suspended one delicately by a filament of cocoon silk between the poles of the electro-magnet. A first specimen, weighing 25 grs., commenced by oscillating powerfully round a given line, in the direction of which it finally fixed itself with force, returning to it as soon as it was removed from it: this direction was such that the great axis was situated axially in respect to the poles. Another specimen, whose axis was not, like that of the preceding one, situated in the longer length of the crystal, apparently directed itself equatorially, but always so that its axis was situated axially in respect to the poles. In general, pieces fashioned in all possible manners, all directed themselves and took a final position, which had no relation with the exterior form, but depended evidently upon the crystalline state of the substance. Bismuth in a mass always remains powerfully diamagnetic, and continues to be repelled by each of the poles of the magnet; which does not prevent its axis directing itself axially, as would that of a magnetic but not magnetised substance; for, providing that the direction remains axial, it is of little consequence whether it be one or other of the extremities of the axis, that is situated towards one or the other pole. Thus, the directive force and the final position of the crystal are axial, and the crystal may fix itself with equal facility and on equal permanence in the two positions diametrically opposed; so that, between the latter, there exist two positions of equatorial equilibrium, which are naturally unstable. On which account the property in question is better expressed by the words *axial* or *axiality*, than by the words *polar* and *polarity*. Mr. Faraday also called the line according to which the directive force is exercised the *magne-crystalline line*, in order to distinguish it from the force, which he calls *magneto-crystalline*.

The direction of the force is not easy to be determined beforehand in the crystal, although it is connected with the mode of crystallisation; but the latter is sometimes a little confused. In general, experiment shows that the magne-crystalline line is perpendicular to the small cleavage plane determined on removing one of the solid angles of the cube; that is, obtained by detaching an isolated crystal of bismuth from a solid mass. It is easy to recognise the direction of the line, by suspending the crystal in different manners; because it is always directed so that this line, or the plane containing it, is axial. If the mode of suspension is such that the magne-crystalline line is vertical, then the crystal does not direct itself at all, as was the case in M. Plucker's experiments with the plate of tourmaline. It is evident, in fact, that this axis has all its points situated symmetrically in respect to the two magnetic poles, and there is no reason that it shall not remain vertical. By combining together several pieces of bismuth, for example, three equal plates arranged rectangularly one in respect to the other, we may easily obtain a system that has lost all power of directing itself under the influence of the magnet, the force being neutralised in all directions. This happens with amorphous bismuth, which is obtained by melting a uniform mass of crystals and allowing them to cool tranquilly in a glass tube: the mass thus obtained is without magne-crystalline force. The same result is obtained by breaking the crystal and placing its fragments or its powders in a tube which is submitted to the action of the magnet. In every case the mass always obeys the laws of diamagnetism, and consequently places itself equatorially.

The surrounding media exercise no influence over the magne-crystalline property of bismuth, which establishes a further difference between this action and diamagnetic action. Mr. Faraday only found two crystals of bismuth, both of which, being directed by an electro-magnet, are able to exercise a mutual influence upon each other; he thought he found indications that a crystal, freely suspended, assumed a direction, under the magnetic action of the earth, so that its magne-crystalline axis was nearly parallel to the direction of the dipping-needle.

A crystal of bismuth takes a direction in a helix, traversed by an electric current, in such a manner that the magne-crystalline axis is parallel to the axis of the helix.

Antimony and arsenic present the same phenomena as bismuth. In antimony, the magne-crystalline line, which places itself axially, is directed, as in bismuth, from one of the solid angles to the opposite angle, and is perpendicular to the face obtained by knocking off the cleavage angle. Antimony presents a singular phenomenon, that is due to its conducting power for electricity, which is superior, when the metal is in its crystalline state, to that of bismuth. There is a kind of stopping or revulsive action, that it experiences in its movement of direction, at the moment when the current, by which the electro-magnet is magnetised, is interrupted. The development of inductive currents is the cause of it; so that this particular species of action depends greatly upon the continuity of the mass. Thus it happens that a large piece of antimony possesses it in a higher degree than several small fragments, and the latter in a higher degree than the substance reduced to powder. In order to protect it from this revulsive movement, which may sometimes prevent the very distinct manifestation of the magne-crystalline power, it is preferable to employ an ordinary magnet, which, being more feeble than an electro-magnet, is sufficient for determining the direction of the magne-crystalline axis, without leading to the inconvenience of producing inductive currents. Whatever may be the case, if we operate upon small fragments, and in particular with narrow plates, which have as much directive force as wide plates, but which are unfavourable to the production of inductive currents, we obtain the desired direction in a very evident manner. With a little attention, we also see this direction manifested, even when these precautions have not been taken; and it is easily detected in the midst of the revulsive movements, and of the kind of resistance which this crystal appears to undergo.

With regard to arsenic, although powerfully diamagnetic, it no less possesses, in the crystalline state, the magne-crystalline force. A plate, whose cleavage faces were very flat, when placed before one of the poles of the electro-magnet, was strongly repelled; but, when suspended between the two poles, directed itself immediately so that its magne-crystalline line was axial.

It was in vain that Mr. Faraday endeavoured to discover the magne-crystalline force in other metals in the crystalline state; he was not able to succeed, except perhaps with two alloys, one of iridium and osmium, and the other of titanium and tellurium, which gave him some signs. But, on the other hand, sulphate of iron, and that of nickel in the crystalline state, clearly manifested a magne-crystalline direction, completely independent of their magnetic properties.

It is easy to see that Faraday's experiments are altogether of the same order as those of Plucker. Thus, this latter philosopher was led to admit, that, among crystals, there are some whose axis is attracted, as there are others whose axis is repelled, by the magnetic poles; the crystals studied by Faraday belong to the former category, those upon which M. Plucker made his first experiments belong to the latter. Now, crystals of bismuth, antimony, and arsenic have the form of rhomboids; they are, consequently, crystals with a single axis: but, as they are not transparent, we cannot know whether they are negative or positive. On the other hand, by subjecting other crystals to experiments, M. Plucker arrived at this simple law, namely, that if the crystal is positive, there is attraction; that is to say, the optical axis is directed axially; whilst, as we have seen, if the crystal is negative, there is repulsion, and the axis is directed equatorially. According to this, the crystals of bismuth, antimony, and arsenic would be positive, as are quartz, diopside, augite.

A very remarkable thing is that a crystal of cyanite, delicately suspended from a cocoon filament, is influenced by terrestrial magnetism, as it is by a magnet; and, in consequence, it takes the same direction as is taken by a true magnetised needle. It is not necessary that the crystals of cyanite should have been previously submitted to the action of a magnet, in order to acquire this property; they possess it of themselves. It appears that terrestrial magnetism developes in them a true polarity; for it is always the same extremity that is directed towards the north, and the same towards the south. But, of all crystals, that which is most powerfully directed by terrestrial magnetism is stannite, or oxide of tin; this is a positive crystal of one axis, whose optical axis is perpendicular to its greatest dimension: whence it follows that, when it is directed by the terrestrial globe, one of its extremities is turned toward the east, and the other toward the west. This same crystal presents a phenomenon that others have not been able to offer to us; it is that, when it is brought near to a delicately suspended magnetised needle, so that its axis is very close to this needle and is parallel to it, it draws this needle with it, thus surmounting the directive force of the globe. Mr. Faraday, by taking great precautions, had already obtained the same result with a crystal of bismuth, but the effect was much less decided.

The magne-crystalline phenomena, of which we have been speaking, are not the only ones that, in crystals, are connected with the direction and the nature of their axes. Independently of the optical phenomena, which were the first to be recognised and studied, there are others that depend also on the position of the axes. Thus Savart, when making crystalline plates of quartz and carbonate of lime vibrate, succeeded in determining a relation between the acoustic figures that are produced in them, and the particular mode of the crystallisation of the substance. He found that the direction of the optical axis is constantly connected with that of the principal forms of the acoustic figures. With regard to the molecular structure of crystals, it follows, from the same experiments, that the only difference there appears to be between carbonate of lime and quartz is that, in the former of these crystals, the small diagonal of the rhomboid is the axis of least elasticity of the substance; while it is that of the greatest elasticity in the latter. This important difference, which indicates an arrangement of particles not identical in the two systems, must necessarily exercise an influence over the phenomena of light, peculiar to each; we know, in fact, that one is a negative crystal of double refraction, and the other a positive of double refraction.

M. Mitscherlich had remarked, that crystals do not expand uniformly by the effect of heat; but that this dilatation is greater in one direction than in the other; and that this difference is connected with their crystalline form. M. de Sénarmont has lately observed a no less remarkable fact;— it is, that conductibility for heat, which is equal in all directions for the crystals of the regular system, acquires in others a maximum or a minimum value, according to directions parallel to the crystallographic axes; so that the isothermic surfaces, which are spheres in the former case, are, in the other, ellipsoids elongated or flattened in the same direction. These observations show the analogy existing between calorific and luminous propagation, which are both equal in all directions in crystals of the regular system; and which, in others, acquire a maximum or minimum value, according to the axis of the form. The optical axes do not altogether coincide with the principal axes of conductibility for heat; but this coincidence is very near existing, if we take the red luminous rays, whose lengths of undulation approach the nearest to those of calorific rays. It is enough, therefore, to suppose heat comparable, not to ordinary luminous radiations, but to radiations enjoying the properties of the extreme red,—a supposition confirmed by a great many other facts, including the phenomena observed by M. Sénarmont. According to this system, the thermic ellipsoid ought to be flattened in attractive crystals and elongated in repulsive ones; which, up to the present time, has been confirmed by the results of experiments.

Finally, M. Wiedmann, by employing a fine point, through which he made electricity arrive upon a surface that he had powdered with licopodium, or red-lead, succeeded in determining, by means of the form assumed by this light powder, the conductibility of crystals in different directions. On a surface of glass the powder, which dispersed itself around the points, in consequence of electric repulsion, forms a circular figure traversed by radii, similar to Lichtemberg's figures. When a pallet of gypsum is put in place of the glass, the figure is found to become elliptical, and the great axis of the ellipse forms a right angle with the principal crystallographic axis; which proves that the electricity distributes itself more easily in a direction perpendicular to the axis than in any other. In quartz, the form is, in like manner, elongated in a direction perpendicular to the axis. In tourmaline, and in carbonate of lime, for example, the elongation of the form occurs in a direction parallel to the principal axis. M. Wiedmann draws from these different observations the conclusion, that crystals which possess a better conductibility in the direction of the principal axis, all belong to the class of negative crystals; whilst those which have a better conductibility in the direction perpendicular to the axis are positive; which indicates that the direction of best conductibility for electricity is also that according to which light is propagated relatively with greater velocity.

The rapid glance we have cast upon the principal physical properties of crystals, shows us the important part played by their optic axes. These are the same axes that we find in magne-crystalline phenomena; but the nature of the influence exercised by them over this order of phenomena is the point upon which we are far from having any very decided ideas.

M. Plucker, as we have seen, had thought he was able, from his experiments, to arrive at the simple law that, in negative crystals, the optic axis is repelled by the magnetic poles, and that in positive crystals it is attracted; that, consequently, it places itself equatorially in the former case, and axially in the latter. With regard to crystals of two axes, it is the mean line which divides into two equal parts the acute angle formed by these axes, that is repelled or attracted according as the crystals are themselves negative or positive. Cyanite, a negative crystal of two axes, presents this property in a very marked manner.

These laws being established, M. Plucker, setting out from Fresnel's theory, according to which the optical phenomena of crystals of one or of two axes depend on the particular distribution assumed by the medium in which light is propagated, and which philosophers call *ether*, thought he was able to connect the attraction and the repulsion exercised respectively by a magnet on the axes of positive and negative crystals, with this fact,—that, in the former, the axis is the place of least elasticity, and, in the latter, that of the greatest elasticity of the ether. But some anomalies, presented especially by crystals of sulphate of iron, have compelled him to renounce this idea.

Mr. Faraday was struck, as M. Plucker had also been, with what is so extraordinary in a force which, emanating from the poles of the magnet, directs from afar a prism of tourmaline, for example, so that the extremities of the crystal recede from the same poles which attract its total mass. He had consequently admitted that this force is neither attractive nor repulsive, but a simple directive force due to a species of radiation, which, emanating from the magnetic poles, traverses the interposed crystal, and compels it, according as it is either positive or negative, to place itself so that its axis is parallel or perpendicular to the line according to which this radiation operates. This manner of regarding the action had been suggested to Faraday by the phenomena presented by polarised light when it is traversing transparent bodies submitted to magnetic influence, phenomena upon which we shall be engaged in the sequel. A circumstance that, in his opinion, shows the difference existing between the two species of force, is the different law they obey, according to distance; that which acts upon the whole mass, and which is attractive or repulsive, diminishing more rapidly than that which acts upon the optic axis alone, and which is only directive. Observations made upon several crystals, and especially upon that of sulphate of iron, would become inexplicable without this mode of regarding the phenomena.

It is impossible, however, not to perceive, that Faraday's theory does not justify, any more than Plucker's does, the extraordinary circumstance of seeing the same crystal susceptible of presenting perfectly contrary phenomena, according as it is regarded in its mass or in its optical axis. These two philosophers are equally compelled to admit, that the axis, in its quality of axis, and independently of the very nature of the substance of the crystal, enjoys peculiar properties more frequently in apposition to those possessed by the substance itself, or which at least are altogether independent of them. They are therefore constrained, contrary to the opinion of one of them, M. Plucker, to admit that magnetic action may be exercised independently of ponderable matter; which is the case when the axis is subjected to the action.

But from the new experiments made by MM. Tyndall and Knoblauch, subsequently to those of Plucker and Faraday, it follows that it is not necessary to admit, as these two philosophers had thought, two different species of action or force. MM. Tyndall and Knoblauch succeeded, by a very detailed study of the subject, in recognising that the magnetic properties of the optical axis are connected with a general principle, namely, that when the molecular constitution of any body is such that the particles of which it is formed are nearer to each other, according to a certain direction, than in the rest of the mass, this direction, all other circumstances remaining the same, is that in which the forces which are acting upon the body manifest their action with the greatest energy; so that the line which represents this direction places itself axially or equatorially, according as the substance is magnetic or diamagnetic. If this predominant influence of the action exercised upon such of the particles as are situated in the direction in question is not always manifested, it is due to circumstances whose effect admits of easy explanation.

Thus, when the two electro-magnetic poles terminate in cones whose summits are very near to a crystal suspended between them, the local action of these poles upon the faces of the crystal that are very near to them exceeds that which is exercised upon the more distant axis; because this latter, although the more powerful, is exercised at a distance proportionately much greater: but, if the polar points are separated, the influence of the relative distance of the faces and of the axis of the crystal in respect to these points becomes much less, and almost null; and then it is the action exercised upon the axis that becomes the more powerful. Tourmaline, as we have seen, furnishes us with a remarkable example of this effect. If, instead of being terminated by points, the poles of the electro-magnet present surfaces a little extended, between which the crystal is suspended, the latter, being entirely plunged in the field of magnetic forces, directs itself according to the action exercised upon its axis, even when it is very near the polar surfaces. In this mode of explaining these phenomena, the action of the magnet is always exercised upon the particles; and it is according to their magnetic and attractive, or their diamagnetic and repulsive nature. The only difference that exists in this respect between crystals and other bodies is, that by the fact of their non-homogeneous structure, crystals present certain directions, according to which the action, whether magnetic or diamagnetic, is more energetic than it is for other directions, on account of the greater approximation of the particles that occurs in these same directions; a phenomenon altogether analogous to that of dilatation for heat, which, in a crystal of calcareous spar, for example, operates more powerfully, according to Mitscherlich, in the direction of the optical axis, because the particles, being more closely packed along this direction than along the others, repel each other with more energy for the same elevation of temperature.

The theory that we have been explaining is based upon very numerous facts, observed and analysed with great care by MM. Tyndall and Knoblauch. We shall content ourselves with describing some of them, selecting the most salient:—First, in order to show the influence of structure upon the direction assumed between the poles of the electro-magnet by any substance, we have merely to cut some pieces of gutta percha which has been rendered fibrous in manufacture, so that the fibres are in the direction of the greatest length, or in a direction perpendicular to this greatest length, to see them direct themselves axially or equatorially. Ivory, whose toothy structure renders it naturally fibrous, may also, according to the manner in which it is cut, direct itself axially, although diamagnetic. We may thus imitate, with gutta percha and with ivory, almost all the experiments that are made with the negative and positive crystals.

This influence of structure becomes evident in magne-crystalline phenomena themselves, when, instead of confining ourselves to certain kinds, our observations are extended over a very large number of crystals, care being at the same time taken to wash them and to remove from their surface the slightest traces of impurity, the presence of which is sufficient to give rise to grave errors. We find, for instance, that a crystal of calcareous spar and a crystal of carbonate of iron, which have necessarily the same crystalline form, take a direction, the former being diamagnetic, so that its optical axis is situated equatorially, the latter magnetic, so that its axis is situated axially. It is even sufficient, in the crystal of calcareous spar, that a part of the lime be replaced by an oxide of iron, as in dolomite, without the crystalline form being changed, for the optical axis to become directed axially, from having formerly been equatorially. Sulphate of magnesia and sulphate of zinc have exactly the same crystalline form, and they are both diamagnetic: they place themselves so that their axis is directed equatorially, whilst a crystal of sulphate of nickel, which has the same form as the two others, has its axis directed axially, even when it is much more contracted in the direction of the axis than in all other directions. It follows, therefore, from this, that it is not the crystalline form, but rather the chemical nature of the crystal which is the influencing cause. A very great number of other crystals form an equal exception to Plucker's law:

thus, in sugar, which is a negative crystal, the plane of the axis is directed axially; topaz, which is a negative crystal, places itself axially and not equatorially, if care be taken to free it from all the impurities with which its surface is generally covered, by boiling it in muriatic acid, and then rubbing its surface with very fine white sand. In fine, among the positive crystals of two axes, that do not obey Plucker's law, we may mention heavy spar, cœlestine, and ferro-cyanuret of potassium; among negative crystals of one axis, carbonate of lime and of iron, and a great number of others; among negative crystals of two axes, dichroite, sugar, sulphate of zinc, and sulphate of magnesia. There are, on the other hand, a certain number of crystals, such as calcareous spar, tourmaline, beryl, arragonite, which enter into the law; these are precisely those upon which M. Plucker's observations had been principally made*: but the number of exceptions is too considerable for the law to be maintained; whilst all the facts are in accordance with the principle which makes them depend upon the non-uniformity of the molecular constitution.

It is easy to show how merely a certain direction of the axis, according to which the particles are more closely congregated, is required in order to determine the position of the whole mass. A small circular cake or disc, made of a mixture of flour and iron filings, places itself naturally in an axial direction between the poles of the magnet. If we transpierce it by a small fragment of iron wire passing through its centre, the disc places itself equatorially, although magnetic, by virtue of the tendency possessed by the iron wire of placing itself axially; but the repulsion is only apparent: if we replace the iron filings by bismuth powder, and the iron wire by a fragment of bismuth, the reverse phenomena occur; the disc, although diamagnetic, places itself axially, by the effect of the tendency of the fragment of bismuth to place itself equatorially, and the attraction in this case, too, is only apparent. We may even imitate artificially the natural ar-

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* M. Plucker, in a recent and more complete work made with M. Beer, has himself recognised a great number of exceptions to the law, which he had at first thought to be general.

rangement of particles that is assumed in this mode of explaining the phenomena. Fine bismuth powder, mixed with gum water, may be made to form a cylinder, which, when suspended between the magnetic poles, directs itself equatorially; but, if this kind of paste be pressed very strongly between two sheets of pasteboard, a thin plate is made of it, which directs itself axially with much force, although its length may be ten times its thickness. Under similar conditions, a paste of carbonate of iron and gum water conducts itself precisely in an inverse manner. The cause of this double phenomenon is evident; the line, according to which the contact of particles is more intimate, is in each of the two cases perpendicular to the surface of the plates, in consequence of the pressure which the particles have undergone in this direction. And this perpendicular line takes an equatorial or an axial position, according as the substance of the plate is diamagnetic or magnetic. What is here obtained artificially must occur naturally in such cases as those presented by crystals, whose mass is not perfectly homogeneous, and in which, consequently, there exists a certain direction in which the action of the forces is exercised in a more favourable manner than in others. This direction may be called the *line of elective polarity;* it is axial in magnetic bodies, equatorial in diamagnetic.

It is not so much the direction of the axis, as it is that of the planes of cleavage, which influences the position assumed by a crystal between the poles of the electro-magnet, a position which must be such that the planes of cleavage take the equatorial direction in diamagnetic crystals, and the axial direction in magnetic. In the examples that we have already quoted, the influence of the planes of cleavage is confounded with that of the axes, seeing that the position of these planes is in each of the crystals the same in respect to the axis. But there are other cases in which, this position being no longer the same, we may prove that it is the direction of the plane that is the influential cause. Two cubes of the same dimensions, the one of beryl, the other cut in a prism of scapolite, both magnetic crystals, direct themselves, the former so that its axis is situated equatorially, the latter so that it is situated axially. This comes from the planes of cleavage being perpendicular to the axis in beryl, whilst they are parallel in scapolite; we see that, equally in both cases, the planes of cleavage are directed axially, as with sulphate of nickel. On the other hand, two cubes, one of saltpetre, the other of topaz, crystals that are both diamagnetic, place themselves, the former with its axis directed equatorially, the latter with its axis directed axially, which is due to the planes of cleavage being parallel to the axis in saltpetre, and perpendicular to the axis in topaz; but it hence follows that equally in both cases, the planes of cleavage are directed equatorially, as with sulphate of zinc and sulphate of magnesia.

We may very well explain this influence of the planes of cleavage, by bearing in mind that crystals may be considered as formed of very thin molecular plates, juxtaposed and adhering by the effect of cohesion; without, however, their being in absolute contact with each other. The empty spaces that are assumed, in the corpuscular theory, to separate the particles from each other, are found in crystals to separate the parallel plates whose union constitutes the crystal. Hence nothing is more natural than that these plates should take an axial direction if they are magnetic, and an equatorial if diamagnetic. It is even easy to prove directly that such must be the case, by imitating artificially this structure of crystals.

We make use of sand-paper, in which the sand or emery on the surface is magnetic, while the paper itself is comparatively indifferent. By cutting a number of strips of this paper an inch long and a quarter of an inch wide, and gumming them together, so as to form a parallelopiped, we have a model of magnetic crystals, which cleave parallel to their axis, the layer of sand representing the magnetic crystalline plate, and the paper the intermediate space between two plates. For such a model, one position only is possible between the poles, the axial. If, however, the parallelopiped be built up of squares, equal in area to the cross section of the model just described, by laying square upon square until the pile reaches the height of an inch, we have a model of those magnetic crystals which cleave perpendicular to their axis. Such a model, although its length is four times its thickness, and the whole strongly magnetic, will on closing the circuit recede from the poles as if repelled, and take up the equatorial position with great energy. The deportment of the first model is that of scapolite; of the second, that of beryl. By using a thin layer of bismuth paste, instead of the magnetic sand, the deportment of saltpetre and topaz will be accurately imitated. M. Rieu, by employing pieces of thin card strongly compressed against each other, by means of silk ribbons, had long ago observed that two parallelopipeds constructed one like the former model and the other like the latter, were directed by terrestrial magnetism, the former axially, that is, so that all its planes were parallel to the magnetic meridian; the latter equatorially, that is, so that the planes were perpendicular to the magnetic meridian. This directive property of clusters of pieces of card is evidently due to the card itself being slightly magnetic, as may be proved by the action exercised upon it by the electro-magnet. It is, nevertheless, very remarkable; and I should add that the author of this experiment was led to it by views of a very different order, and which I shall have occasion to describe when I am treating upon terrestrial magnetism.

When the crystals present several planes of cleavage, we must substitute for the notion of thin plates that of small prisms, and even small cubes, if there are three perpendicular planes. In the latter case, which is that presented, among others, by rock-salt, the directive force is null; the cleavages neutralise each other. Quartz, like common glass, possesses a directive power that is scarcely sensible, which is due to there existing in the one, as well as in the other, mere traces of cleavage. If, instead of presenting planes of cleavage, a crystal has a fibrous structure, the force acts in the direction of the fibres. In a word, everything that affects the molecular structure, must affect, in a corresponding manner, the line of elective polarity. If the structure disappears, the directive power also disappears, as occurs, according to Faraday's observations, when the temperature of crystals of bismuth and antimony is raised to the point of fusion.

Thus have we considered the special properties presented by crystals, in regard to the action exercised upon them by magnets, not as an exception to the general laws of magnetism and diamagnetism, but as a consequence of a particular mode of grouping of their particles, which is also the cause of the unequal dilatability, and of the unequal conductibility for heat and for electricity, according to different directions presented by crystalline substances.

### *Action of transparent Bodies, subjected to magnetic Influence, upon polarised Light.*

We here arrive at the important discovery, by which Faraday prefaced his researches upon diamagnetism, which, however, are so independent that we have been able to explain them first, as, indeed, the logical connection of the facts required of us.

It is well known that a ray of light may be polarised in various ways,—either by reflection under a certain angle, which varies according to the nature of the reflecting surface, —or by its passage through a series of transparent plates, or also by being transmitted through a crystal, endowed with double refraction. In this latter case there are two polarised rays instead of one; the ray that has experienced ordinary refraction is polarised as it would have been by a reflecting surface of glass, whose plane of incidence should be *parallel* to the principal section of the crystal; and the ray that has undergone extraordinary refraction, as it would have been by this same reflecting surface with a plane of incidence *perpendicular* to the principal section of the crystal. In the experiments of which we have been speaking, this latter mode of polarising the light was employed for convenience' sake; but, instead of using any crystal of calcareous spar, a rhomboid was selected, ·44 in. in length, and ·393 in. in width, and about the same in thickness, which is cut into two pieces by a plane passing through the parallel diagonals of two of the long faces; and which two fragments are then united by Canada balsam into the position they had previously occupied. The ray is made to pass through this rhomboid, thus prepared, in the direction of its length, and instead of having two emergent rays we obtain but one,— that which undergoes extraordinary refraction; the other, the ordinary one, on encountering the layer of Canada balsam, is, by the effect of the great refracting power of this substance, reflected interiorly, and, consequently, is not able to pass out of the rhomboid: this difference between the coming out of the two radii results from the ordinary ray having in calcareous spar an index of refraction greater than the extraordinary ray, and hence undergoing total refraction more easily. A Nichol's prism,—(the rhomboid of calcareous spar arranged as we have been describing, thus called from the name of its inventor,)—presents a very convenient means of obtaining a ray of polarised light. When the ray, that passes out of it, is received upon a second similar prism, so that it traverses it also in the direction of its length, we observe, conformably with the laws of polarisation, the following phenomena: If the planes of the principal sections of the two prisms are parallel, the ray comes out of the second prism with all its primitive intensity; if the two planes are perpendicular, the ray is completely extinguished. We may obtain the same result by employing, instead of the Nichol's prisms, two tourmalines cut, the one parallel, the other perpendicular to the optical axis, for they then possess the singular property of absorbing, one the ordinary, the other the extraordinary ray; so that each of them allows one ray only instead of two to pass out, although endowed with double refraction: so that when they are combined in such a manner that the principal planes of their section are parallel, the ray that has traversed the former is extinguished in its passage through the latter; but if the two planes are perpendicular there is transmission of light. The combination of two tourmalines, as well as that of two Nichol's prisms, presents, therefore, the phenomenon of total darkness, produced by the superposition, according to a certain mode, of two transparent bodies. But for observations of this kind we generally prefer the employment of two Nichol's prisms to that of two tourmalines on account of their greater transparency, for the tourmalines are always more or less coloured, and consequently less translucent than crystals of calcareous spar. The name of *analyser* is given to the prism or crystal of any kind, upon which the polarised light is received, and which serves to determine, in fact, whether this light is polarised, in what proportion it is polarised, if it is not totally so, and what, finally, is the direction of its plane of polarisation. The name of *polariser* is given to the prism or crystal by which the light in the course of its transmission has been polarised.

I will now suppose that we have two Nichol's prisms placed at a certain distance from each other on the same horizontal line, and that we are looking through these prisms at the light of the clouds, or, which is better still, at that of a lamp: from what we have just seen, by turning the prism against which the eye is applied, namely the analysing prism, we may give it such a position that the light is completely extinguished. If we place between the two Nichol's prisms a piece of glass 1½ or 2 in. long and ⅔ in. wide and thick, so arranged that the polarised ray traverses it in its length, no change occurs in the result of the experiment; but if this interposed glass prism is situated on the axial line that joins the two poles of an electro-magnet, and so that these poles are very near to its extremities, still, however, allowing the ray of light to pass above them, the phenomenon is then entirely modified. I will suppose the Nichol's prisms so arranged that the polarised ray is extinguished: now by the mere fact that the electro-magnet is magnetised, the light reappears, it disappears again at the moment when the electric current ceases to circulate around the electro-magnet. When the ray appears again under the magnetic influence, in order to make it disappear again we have merely to turn one of the prisms, for instance, the analyser, through a certain angle, to the left or right, according as the north or south pole of the electro-magnet is on one side or the other. But if in this new position of the Nichol's prism, we put an end to the magnetic state of the electro-magnet, without, however, making any change in the arrangement of the other portions of the apparatus, the ray shows itself again.

This experiment makes manifest this important fact,— that the passage of a polarised ray through a glass prism interposed between contrary magnetic poles, changes its plane of polarisation and makes this plane turn to a certain angle, which is determined by measuring the angle through which the analysing prism must be turned in order again to extinguish the ray, that is, in order to bring back anew the two planes of polarisation to being perpendicular to each other. In order to measure this angle, the analysing prism is fixed in a piece of metal placed in the centre of a divided circle, and movable on its axis. An index affixed to the piece, and the points of which can traverse successively all the degrees of the division, serves to measure the number of degrees through which the prism has been turned.

The substance in which Faraday recognised for the first time this remarkable property, is the same heavy glass (borosilicate of lead) that he also recognised to be highly diamagnetic. We shall presently see that the larger portion of transparent bodies present the same property; however, in different and lesser degrees than the heavy glass. But we must first study a little more closely, and in its details, the curious phenomenon that we have been describing.

Before Faraday's discovery, several substances were known which, without the aid of magnetic force, by virtue of their proper molecular constitution, possess the faculty, when they are interposed in the route of a polarised ray, of making its plane of polarisation turn to a certain angle. Among the number of these substances, one alone is solid,— a plate of rock crystal cut perpendicularly to its optic axis. But it has been remarked that, according to the particular crystal from which the plates are taken, they make the plane of polarisation turn from the right to the left, or from the left to the right. This circumstance evidently denotes differences of structure between various specimens of rock crystal; and, in fact, these differences had already been pointed out by Haüy. They are due to the crystals of quartz having trapezian faces placed on the angles comprised between the faces of the prism and the faces of the pyramid; and to the fact that those faces, called by Haüy *plagiedral*, are always on one side only; to the right in some crystals, and to the left in others. Circular polarisation indicates this difference, and enables us to recognise the class of crystals to which the cut plates of quartz belong; but what is very remarkable is, that quartz is one example more to be added to those presented by tourmaline and boracite, which, as we shall see, possess different electricities at their two extremities; a proof that dissymmetry in crystals is always accompanied by a peculiar physical property. Moreover, plates derived from the same crystal of quartz make the plane of polarisation turn in the same direction, and in a quantity proportional to their thickness; and, when many plates are superposed, the total effect is equal to the sum of the effects produced by each, or to the difference of the sums of the similar effects, if all the plates do not act in the same direction. Finally, when the polarised rays are of homogeneous light, and not of white light, the deviation of the plane of polarisation is greater, as the polarised light is of a more refrangible nature. In order to give an idea of the considerable difference existing in this respect between the different species of light, we will quote an experiment of Biot's, who found with a plate of rock crystal ·039 in. thick, that the deviations of the plane of polarisation are, for the extreme red (the least refrangible) 17° 29′ 47″; for the limiting ray of yellow and green (mean refrangible) 25° 40′ 3″; for the extreme violet ray (the most refrangible) 44° 4′ 58″.

It follows, from this last property, that when the polarised light is white light, it can never be completely extinguished, because the angle, through which the analysing prism must be turned, in order to find the plane of polarisation of the red ray, for example, is different from that which would be given by the plane of polarisation of another ray. Thus, instead of alternations of light and darkness, we obtain, when using white light, a series of coloured tints. These tints are composed of the mixture of all the rays for which the angle, through which the apparatus has been turned, is not that through which their plane of polarisation has been deviated by the passage of the light through the crystalline plane. Thus, with an angle of about 18°, which is that of the deviation of the planes of polarisation in the case of a plate of rock crystal ·039 in. in thickness for the *red* ray, this ray alone is extinguished; and we obtain a complementary tint to the red, arising from the mixture of all the other rays. With an angle of about 40°, it is the violet ray that is extinguished, and we obtain a complementary tint to the violet. When the analysing prism that is employed is not a Nichol's prism, but a simple prism of calcareous spar, there are two images instead of one; and these two images, arising from rays whose planes of polarisation are perpendicular to each other, since one is the ordinary and the other the extraordinary image, are found, by the interposition of the plate of rock crystal, to have their planes of polarisation equally deviated, but always in rectangular positions relatively to each other, so that their tints are complementary. Of this we may easily satisfy ourselves by remarking that, whenever the two images impinge upon each other, there is a perfectly white spot. M. Biot was even able to calculate beforehand the tint of each image by thus determining the rays of which it would be composed; and the calculation was found perfectly in accordance with experiment. Among these tints there is one that has been termed tint of passage, because it lasts only an instant, when a succession of tints are obtained by rotating the analysing prism; and he has adopted it, in order to determine the deviation of the plane of polarisation in each special case. It has the advantage of being very distinct, and of corresponding to only one well defined angle, which is not the case with the other tints, for they are more vague.

It is given by the extraordinary ray, consequently it is equally obtained with a Nichol's prism, which allows only one ray to pass out. This tint is a bluish-violet, which immediately follows the intense blue, and immediately precedes the yellowish-red in the progress of the rotation. As much by its special nature, as by its decided opposition to the other two, between which it is always comprised, it is impossible not to recognise it with perfect evidence when once it has been sought for. By multiplying the deviation obtained for this tint by $\frac{23}{30}$, we may bring it back to that one of the red rays, which is generally the tint, to which the various rotatory powers are referred.

This last observation leads us to add that M. Biot has recognised that although quartz is the only solid substance presenting the phenomena of circular polarisation, there exist a great number of liquid bodies possessing the same property: such, amongst others, are the essential oil of turpentine, the essential oil of citron, concentrated syrup of sugar, tartaric acid, dextrine, — a substance that is extracted from starch, and which has received its name from the very property upon which we are engaged, in order to indicate that it makes the plane of polarisation turn from left to right.

As the result of the profound study he made on the rotatory power of liquids, namely, on the power they possess of making the planes of polarisation of luminous rays deviate proportionally to their thickness, M. Biot established that this effect results from a proper action exercised individually by the molecular groups that are encountered in the course of the transmitted ray, — an action equal in all the groups if the ray is homogeneous, and thus producing equal successive deviations, because the plane of polarisation of each simple ray shows itself equally deviable, after having been deviated; then the total angular deviation experienced by this plane through a measurable thickness of active liquid, is the sum of the infinitely small deviations produced by the molecular groups, that the ray has encountered in its course. By separating this sum from what is due to differences of refrangibility, of density, and of length, so as to reduce it to elements always comparable, we are able to deduce from it an angular value, proportional to the infinitely small deviation, that would be produced by a single constituent molecular group of the liquid, acting in a constant physical condition upon the same ray: this value, thus obtained, is what M. Biot termed *the molecular rotatory power of bodies.*

The molecular rotatory power undergoes no change whatever by the influences that modify the mutual distances of the molecular groups, without altering their constitution. Thus solutions in water, or in alcohol, of sugar, gum, or camphor, have each a molecular rotatory power, which remains the same, however diluted the solution may be; although their absolute action, if the thickness of the stratum remains the same, depends on their degree of concentration. In like manner also, the essential oils that possess this power, those even that exercise it in contrary directions, may be mixed in all proportions together, or with others that do not possess it, and the sum of the proper powers of the active particles always gives the power of the mixture. But when the active molecular groups undergo a change of constitution or of chemical composition, their power changes notably. It is the same with modifications in the intimate nature of bodies, which chemical analysis has not the power of discovering, and which are made manifest by the change of molecular rotatory power. M. Biot succeeded in forming out of this property one of the most sensitive of chemical tests; it is unfortunate that it can be applied to only a very limited number of substances.

Finally, a general consideration which demonstrates that the action thus exercised upon light is molecular, is the impossibility there is for a ray of light that penetrates perpendicularly a homogeneous liquid, or gas, to be able to undergo any change by an action of masses. In fact, all the actions of mass, that the medium is able to exercise upon the ray, produce symmetrical resultants around the normal of incidence; they cannot, therefore, impress upon this ray a dissymmetry around this normal. It is this, however, that occurs when the medium makes the plane of polarisation deviate to the right or to the left of the primitive plane; but always in a fixed direction for the same ray and for the same state of material particles, whatever be the relations of position or of distance that are established between them, by agitating them or by mixing them with others that only separate them without modifying them chemically, and without themselves having any rotatory power. Such an effect as this increasing in a continuous and uniform manner, with the number of molecular groups that are traversed by the ray, requires, therefore that each of them should produce its proportional part, although infinitely small in the total deviation, that is observed through a finite thickness, and that it should always produce it the same in all positions, under which it may be presented to the ray. Then the dissymmetry thus brought about is easily conceived, whilst it would be incomprehensible as the action of the mass, or, to express ourselves better, it would be mechanically impossible.

Without staying longer upon the phenomena that we have been describing, we shall confine ourselves to remarking that the rotatory power of liquids is incomparably more feeble than that of quartz; for the most efficacious of these liquids, concentrated syrup of sugar, is thirty or forty times less so than quartz. Thus, a thickness of ·039 in. of syrup gives but about 30′ of rotation to the extreme red, whilst it is 17° 30′ with quartz. So, in order to compare the rotatory power of different liquids, they are placed successively in tubes of greater or less strength, carefully closed by plugs made of very white and very smooth glass, and we thus increase, by the thickness of the bed of liquid, that the polarised ray is called upon to traverse, the total effect of the deviation of the plane of polarisation. When we are engaged upon elastic fluids, for example, the vapour of essence of turpentine, in which M. Biot recognised the existence of a rotatory power, it is necessary to employ much longer tubes; because, in general, in order to produce the same effect, the length of the path of the polarised ray in a liquid and in vapour ought to be in inverse ratio to their respective density.

Finally, among the liquids submitted to experiment, we will point out *turpentine, essence of laurel,* and *gum arabic,* as making the plane of polarisation turn from right to left, and *essence of lemon, syrup of sugar, alcoholic solution of camphor, tartaric acid,* and *dextrine,* as making it turn from left to right.

Let us now return to Faraday's experiments. We had seen that magnetism is able, by its influence, to impress upon a glass prism the same property that quartz alone, among solid substances, possesses naturally, namely, that of making the plane of polarisation deviate. All transparent substances, with the exception, perhaps, of certain crystals and gases, are susceptible of experiencing this influence, but the rotatory power that the action of the magnet is able to develope in them, present certain special characters, which it is important to study in order to obtain an accurate idea of this class of phenomena. In fact, although the general effect is the same, there are very notable differences between the circular polarisation produced by magnetism, and that which is naturally inherent in certain bodies. Thus, for example, this latter is the more considerable as the length of the course through the substance is greater; it is much the same with the former, but with one condition, that we must not be compelled to separate the polar armatures in order to lodge the interposed substance; for then we should weaken the magnetic force, and should lose on the one hand what we might gain on the other. We shall see further on what the laws are, by which this diminution and augmentation are regulated, and what are the limits of length for the transparent substance, and, consequently, the distance for the poles that must not be exceeded, in order to obtain the maximum effect.

In order to obtain the rotation of the plane of polarisation, it is important that the transparent substance (the heavy glass, for example) should be placed so that the polarised ray traverses it in the direction of the line that joins the poles of the electro-magnet; the effect, however, may occur even when only one pole is acting upon the extremity of the glass prism, but it is much more feeble. It also occurs if an ordinary horse-shoe magnet is substituted for the electro-magnet. But in all these cases it is essential that the glass prism be so placed that the forces emanating from the poles, and which are characterised in their direction by the magnetic curves, should pass through the glass in the direction parallel, or nearly so, to that of the ray. Thus no effect is observed when the glass prism is situated equatorially, that is to say, perpendicularly, to the line that joins the poles of the electro-magnet.

The direction of the rotation of the plane of polarisation, as we have said, is connected with the position of the magnetic poles in respect to the direction along which the polarised ray travels; and this direction is such, that if the north pole of the electro-magnet is turned on the side of the observer who is receiving the ray, and, consequently, the south pole on the side whence the ray comes, the rotation occurs for the observer from left to right. If the place of the poles is changed by changing the direction of the current that is circulating around the electro-magnet, the rotation occurs from right to left. We may reduce to a very simple law the relation that exists between the direction of the rotation of the plane of polarisation and that of the magnetism, by which the rotation is produced; for this, we have merely to suppose a piece of soft iron put in place of the transparent substance, and to represent the direction of the currents that in Ampère's theory circulate around this piece of iron in consequence of the magnetisation it undergoes. Now, the law is that the rotation occurs in the same direction as that according to which this current travels. A more direct mode of making this law manifest, is to put in place of the electro-magnet a bobbin, in the axis of which the glass prism is placed, so that it is enveloped from one end to the other by a girdle of electric currents. The effect of these currents is to produce, in the same manner as the magnetic poles, the rotation of the plane of polarisation; and the direction of this rotation is such, that we may say that when an electric current circulates around a transparent substance that is transmitting a ray of polarised light in a direction perpendicular to that of the current, it causes the plane of polarisation of this ray to rotate in a direction similar to that according to which it is itself travelling.

When we employ bobbins or helices to produce the rotation of the plane of polarisation, we notably increase the effect by lengthening them, because it enables us to give greater length to the substance traversed by the ray, such, for example, as a column of water; but it is useless to give it a greater length than that of the helix in the interior of which it is placed. It is also indifferent, when the transparent body has a less diameter than that of the helix, to place it in the axis or out of the axis, provided it is in the interior of the helix; for out of the helix the effect is null. Finally, when the rotatory power is produced by means of electric currents, we must take the necessary precautions to prevent those currents, which are generally very intense, from heating the substance that is placed in the interior of the helix.

### *Determination of the magnetic rotatory Power of different transparent Substances.*

Faraday, in his first researches, had already operated upon a large number of substances, both solid and liquid; he had not been able to discover any trace of rotatory power either in air or in other gases, although he submitted them to the action of a powerful electro-magnet, and to that of a long helix, traversed by an energetic current. With regard to liquids, he had tried a very great number, and had found them all capable of acquiring in different degrees the rotatory power under the influence of magnetism; even those which, like essence of turpentine, already possess it naturally: and this rotatory power, superinduced by magnetic action, is altogether independent of that which the substance possesses of itself; so that if the two rotations occur in the same direction they are added to each other, and if they occur in contrary directions, the more feeble is subtracted from the more powerful, in order to obtain the definitive result.

This law has been verified upon many liquids, such as essences, solutions of sugar, tartaric and tartrate acid, which make the plane of polarisation turn from the left to the right; as well as upon others, which make it turn from the right to the left. With regard to solids, Faraday constantly found that the effect is at its maximum in boro-silicate of lead, and subsequently in glasses containing lead; but he was not able to succeed in producing it in crystals endowed with double refraction, no matter in what way they were cut. Rock salt, on the contrary, acquired, under magnetic influence, a rotatory power almost equal to that of flint, but which was scarcely the third of that of the heavy glass.

M. Edmond Becquerel, in order to increase the action of the electro-magnet upon substances submitted to experiment, conceived the happy idea of placing upon the polar surface armatures, each pierced with a horizontal cylindrical opening at the very spot where the magnetic pole is situate, that is to say, at the point whence the magnetic forces seem to emanate. The two armatures and the transparent substances are so arranged, that the polarised ray that traverses it the direction of its greatest length may pass through the two poles, on the outside of which are placed, on one side, the polarising prism, and on the other, the analysing prism. By means of this apparatus, M. Becquerel successfully repeated Faraday's experiments. In order to measure the rotation of the plane of polarisation, he made use of the tint of passage pointed out by M. Biot, and he obtained, with heavy glass, a deviation of 16°.

He recognised that among liquids the chlorides, especially that of zinc, possess a considerable rotatory power. A stratum of chloride of zinc, only 0·39 in. in thickness, made the plane of polarisation deviate 6°. Finally, he was able to obtain a slight rotation by submitting to the magnetic action certain crystals endowed with double refraction. With this view he took two plates of quartz, of the same thickness, and of opposite rotation, so that on placing them perpendicularly in the route of the polarised ray, their effects neutralised each other. Each of the plates was ·196 in. in thickness. The electro-magnet was put in action, and the effect was manifested, sometimes in one direction, sometimes in the other, according to the direction of the magnetisation, as upon a plate of glass, but much more feebly. The magnetic rotation was 5° with a specimen of beryl ·039 in. in thickness, placed perpendicularly to the axis. These are two examples, which prove that bi-refracting crystals present the phenomenon of circular magnetic polarisation, although in a much more feeble degree than other substances.

M. Mathiessen, in a series of experiments, out of a hundred crystals that he examined, found only rock salt which was sensible to magnetism; the rotation that was produced by a thickness of 1·02 in., which is that at which the maximum effect occurs, is little inferior to that of boro-silicate of lead; for it is 6°, the other being 9°. Furthermore, M. Mathiessen found several vitreous combinations that are more heavy than Faraday's glass; in particular, pure silicates of lead, which give an effect more than double that of the boro-silicate. Unfortunately they tarnish rapidly in the air. On subjecting to experiment two hundred and forty species of glass, the same philosopher was able to determine very exactly the influence of the chemical composition over the rotatory power of the glass; he found that the silicates and the chlorides hold the first rank in respect to sensibility; that oxide of lead is the base that acts most energetically, then bismuth, antimony, zinc, mercury, silver. The rotation is manifested in glasses with magnetic bases: perhaps they would produce more effect than all others, if their deep colours did not cause our being compelled to employ them only in the state of very thin plates. A very remarkable fact is that, when a glass contains iron, cobalt, or nickel in so small a quantity that it preserves a sufficient transparency, the rotation gradually increases with the thickness of the glass, up to 3¼ inches, which is the greatest separation that can be given to the poles in the apparatus that was employed; whilst glasses without a magnetic metal, and at the same time without boracic acid, without soda, and without potassa, have their maximum of effect at a much less thickness, which varies between half an inch and an inch. An electro-magnet, that can sustain 55lbs., gives, with silicate of lead, 20° of rotation, for a thickness of ·59 in., and gave no more for a thickness of 1·57 inches. With Faraday's heavy glass, on the other hand, under the same magnetic influence, 4° were obtained with ·59 in., and 9° with 1·57 inches of thickness.

Faraday had observed, that magnetic action does not instantaneously develope in a substance the maximum of rotatory power, but that this power increases gradually for a few seconds, whilst it ceases immediately with magnetisation. M. Mathiessen remarked that, for certain slightly annealed glasses, the augmentation of rotatory power with the duration of the magnetic action is very sensible; but that this augmentation especially occurs, if we change the poles of the electro-magnet between which the glass is placed. This happened to a silicate of lead, which at first gave 18°, and which afterwards gave 20°, after three or four changes of the poles: a greater number of subsequent changes made it fall back to 18°, and afterwards to 15°. After a certain time of rest, the same series of operations may be recommenced, and with the same results. It would seem to follow from this that the sudden interruption and re-establishment of the magnetism diminish the temper, and consequently increase the rotation of the plane of polarisation; but that if they are repeated too great a number of times consecutively, they restore a new temper, which diminishes the rotatory power.

Moreover, experiment shows that it is indeed in the very interior of the body and not at its surfaces, whose effect would rather consist in diminishing the result, that the phenomenon of circular magnetic polarisation occurs. Six plates of the same glass superposed, the assemblage of which constitutes a thickness equal to that of another single piece of the same glass, gave a lesser rotation almost in the relation of 11 to 13: these six plates, cemented together with Canada balsam, regain almost the force of the single piece.

All these results clearly indicate a relation between the rotatory powers and a peculiar molecular arrangement, that is determined by the influence of magnetism in transparent bodies: but, before entering upon the study of the causes of the rotation, we have yet to expose the more complete experimental researches that have been made upon this subject, and which are due to M. Bertin.

M. Bertin's experiments all give what is called total rotation; that is to say, the angle formed by the two planes of polarisation, that is obtained by directing the electric current first in one direction and then in another; it is clear that this angle is double that which we have hitherto called the angle of rotation of the plane of polarisation; but this is of little consequence, since we are here concerned in relations alone. Furthermore, he determines the rotation of the two planes of polarisation by means of the two tints of passage, one observed when the current is travelling in a certain direction, and the other when it is travelling in a contrary direction. This mode of observation is superior in accuracy to that which is generally employed, because it gives a greater angle, and is independent of the determination, which is always very uncertain, of the zero, that is, of the position of the analyser, for which the light is extinct before the passage of the current. M. Bertin, in his researches, employed an electro-magnet, furnished with the system of armatures employed by M. Ed. Becquerel, or with greater advantage still, of an arrangement contrived by M. Rumkorff. This arrangement consists in placing the two poles of the electro-magnet facing each other. They are two cylinders of soft iron 1·18 in. in diameter, and 3·54 in. in length, surrounded by a copper wire, ·078 in diameter, covered with silk. These two cylinders, fixed horizontally by means of a double frame of cast iron, so that their axis is on the same right line, are pierced with a round hole, ·39 in. wide, in the direction of the axis, in order to allow a ray of light to pass freely (*Fig.* 167.); the two poles facing each other are ·39 in. apart; and in this space allow of the interposition either of a solid body, or of a small tube con-

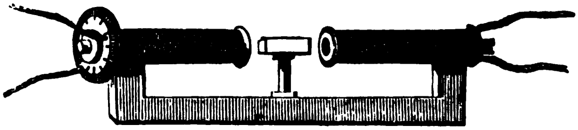
*Fig.* 167.

taining a liquid, and terminated by two flat surfaces. The two prisms — the polariser and the analyser, are fixed respectively upon each upright of the frame at the centre of the hole, so that the light meets one on entering, and the other on coming out.

M. Bertin also employed advantageously several bobbins placed successively along the same axis, and containing an iron core pierced along its axis by a cylindrical hole; so that the ray of light might freely travel in the direction of the axis from one end to the other. If several glasses are placed in the intervals by which the bobbins are separated, care being taken that the electric current traverses them all in the same direction, we find, as might have been expected, that the rotations produced by all these glasses are added together; for they all occur in the same direction, which is that of the direction of the current, according to the law discovered by Faraday. By this means, we may indefinitely multiply the action of a substance, and, consequently, render this action visible, however feeble it may be. A file of bobbins 3·93 in. wide, and each containing an iron cylinder 1·18 in. in diameter pierced along its axis, were centred in succession, one after the other, in a wooden trough. This file presented five intervals, including the extremities, in which the substances could be placed that were submitted to the magnetism; and the following are the very remarkable results of an experiment made with five small vessels filled with sulphuret of carbon, each presenting a stratum ·393 in. in thickness: —

| | | |
|---|---|---|
| With 5 vessels placed in the five intervals | 8° 5′ | of rotation. |
| „ 3 „ (the two extremes are removed) | 6° 25′ | „ |
| „ 1 only (the middle ones are removed) | 2° | „ |
| „ 5 in contact between two double bobbins | 4° | „ |

Various similar experiments made with other substances equally show that the increase of rotation is less due to the increase of thickness of the body, that is submitted to the magnetic influence, than it is to the distribution of its different strata in the intervals of the bobbins.

Some philosophers had thought, at the origin of Faraday's discovery, that all solutions had the same rotatory power. The facts observed by M. Bertin demonstrate, in the most peremptory manner, that this is an error. The following, for instance, are the numbers that he found for the rotation produced by different anhydrous liquid substances, and for water : —

| | Thickness. | Rotation. |
|---|---|---|
| Bichloride of tin - - - | ·393 in. | 7° 30′ |
| Sulphuret of carbon - - - | „ | 7° |
| Protochloride of phosphorus - - | „ | 5° |
| Water - - - - - - | „ | 2° 20′ |

If we pass on to solutions, we find for them a less rotatory power than that of anhydrous liquids, especially for alcoholic solutions, which are inferior in this respect to aqueous solutions. Thus, —

| | Thickness. | Rotation. |
|---|---|---|
| Chloride of magnesium dissolved in water | 5·11 in. | 6° 5′ |
| „ „ „ alcohol | „ | 3° 20′ |
| Water - - - - - | „ | 4° 15′ |
| Alcohol at 36° - - - - | „ | 3° |

M. Bertin, desirous of establishing, for each substance, its coefficient of magnetic polarisation, was compelled with this view to try and determine the laws that are followed by the double opposed influence that is exercised upon the intensity of magnetic polarisation by the increase of the thickness of the substance, and that of the distance of the magnetic poles, by which it is necessarily accompanied. He found, as the result of numerous experiments, by employing a single bobbin, and successively removing from it a piece of flint-glass which had at first been in contact by one of its extremities with this bobbin, that *if the distances of the flint glass increase in arithmetical progression, the rotations of the plane of polarisation decrease in geometrical progression.* Then, by putting the piece of flint-glass between two bobbins, he succeeded in determining the action of each of them; an action that is compounded of the mutual influence, variable with their relative distance, which is exercised upon each other by the opposite magnetic poles, between which the flint-glass is placed. However, he succeeded in obtaining a formula in which a term, dependent only on the nature of the body submitted to experiment, and, consequently, independent of its thickness, of its distance from the poles, and of the force of the latter, might be determined by means of data furnished by experiment. He called this term the coefficient of magnetic polarisation. It represents the rotation that a plate $\frac{1}{25}$ in. in thickness would produce, supposing it was in contact with the pole. The following table contains these co-efficients for different substances compared with Faraday's heavy glass: —

| | |
|---|---|
| Faraday's heavy glass - - - - | 1° |
| Guinaud's flint-glass - - - - | 0·87 |
| Mathiessen's „ - - - - | 0·83 |
| Very dense „ (from the Conservatoire) - | 0·55 |
| Common „ - - - - - | 0·53 |
| Bichloride of tin - - - - - | 0·77 |
| Sulphuret of carbon - - - - | 0·74 |
| Protochloride of phosphorus - - - | 0·51 |
| Chloride of zinc, dissolved - - - - | 0·55 |
| Chloride of calcium „ - - - - | 0·45 |
| Water - - - - - - | 0·25 |
| Ordinary alcohol at 36° - - - - | 0·18 |
| Ether - - - - - - | 0·15 |

### *Examination of the Nature and of the Cause of the rotatory Power that is acquired by Bodies under magnetic Influence.*

The results that we have been describing show us that magnetic rotatory power is a specific property of bodies; that is to say, that it depends essentially for each on their chemical and physical nature.

But what is the relation that exists between this property and the double nature of the body? Before attempting, not to resolve, which, in the present state of science, would be impossible, but simply to attack this question, let us endeavour to establish satisfactorily the character itself of the phenomenon of circular magnetic polarisation, and its relations of resemblance or non-resemblance with that of natural circular polarisation.

These two phenomena are of the same order; they present themselves under the same form: and we have seen from

Faraday's experiments that, in the same liquid, natural rotation and magnetic rotation are added together or are deducted from each other, according as they are in the same or in opposite directions.

An experiment of M. E. Becquerel's comes also entirely to confirm this mode of viewing it. Having obtained a deviation of 16° with Faraday's heavy glass, he prepared a solution of sugar, which, when placed in a glass tube of a suitable length, produced the same deviation. Then, by making the polarised ray pass successively through this solution and the heavy glass, while submitted to magnetic influence, he obtained a deviation of 32°, or a null deviation, according as the two rotatory powers act in the same direction or in contrary directions.

But, although the two classes of phenomena may be of the same order, there is a fundamental difference between them; it is relative to the direction of the rotation. In circular magnetic polarisation this direction is absolute; it only depends on the direction of the magnetisms or the currents: the polarised ray always turns in the same direction as that according to which the electric currents travel, that are acting either directly or by the intervention of magnetism upon the substance submitted to experiment. In natural circular polarisation, the direction is always relative to the position of the observer in respect to the polarised ray and the substance it is traversing. Thus, if we call one of Nichol's prisms *a*, and the other *b*, each being able to serve indifferently as polariser or analyser, the following is what happens in the case of circular magnetic polarisation. If the north pole is on the side of *a*, and the south pole on the side of *b*, or, what comes to the same thing, if the electric currents circulate from left to right around the transparent substance, the plane of polarisation will be deviated to his right; but if the observer transfers himself to *b*, and the polarised ray goes from *b* to *a*, instead of going from *a* to *b*, all other circumstances remaining the same, the plane of polarisation is indeed deviated in the same manner; but, as far as the observer is concerned, in *his new position* this deviation occurs toward his left, and no longer toward his right. When the circular polarisation is natural, things occur quite differently: if, the observer being at *a*, the plane of polarisation is deviated from right to left for any substance, such as essence of turpentine, this deviation will still occur from right to left, in respect to the observer, when he transfers himself to *b;* and the polarised ray is passing from *b* to *a* instead of from *a* to *b*. The direction of the deviation, relatively to the observer, will indeed have remained the same, but its absolute direction will have changed; a result exactly the reverse of what we obtained with circular magnetic polarisation.

This important difference explains why, in this latter case, we may increase the deviation of the plane of polarisation, by making the ray go and return several times in the transparent substance that is submitted to magnetic influence; whilst, in the other case, we gain nothing by this mode of operating. Take, in fact, a prismatic piece of heavy glass, ·59 in. square, and about 2·36 in. long; take care that its two small extreme faces are well polished, and cover them with a silver leaf, that presents interiorly a reflecting surface (*Fig.* 168.). Remove the silver, from a space only ·118 in. wide, on each of the two faces, and so arrange the glass that a ray of polarised light, introduced obliquely through the exposed part of one of the small faces, after two or more reflections upon the silvered surface, shall come and escape from the part also exposed on the other small face. If the glass is submitted to magnetic action, the plane of polarisation will have undergone a deviation three times more considerable after two reflections than it would have experienced had the ray only pursued its direct course through the glass. In fact, it has made in it three courses instead of one; and, in each, its plane of polarisation has been deviated to an equal angle. Had it undergone four reflections, and consequently made five courses, this deviation would have been quintuple. Then, in the experimental combination that we have just been describing, we find a means of multiplying considerably the magnetic

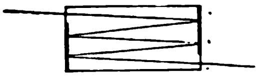
*Fig.* 168.

rotatory effect. In one of Mr. Faraday's experiments, the deviation was 12° for a ray that had traversed but once a piece of heavy glass: it became 36° when the ray, having undergone two interior reflections, had traversed the piece of glass three times; and 60° when it had traversed it five times, having undergone four interior reflections. Here the greatness of the effect obtained is exactly proportional to the length of the ray submitted to the action of the magnetic force: this is due to our being able to increase the length of the course, without in any way changing the intensity of the magnetic force; whilst, when, in order to obtain this increase, it is necessary to lengthen the transparent substance, we are obliged to separate the poles; and, as we have already said, we lose on the one hand what we gain on the other.

If we operate in the same manner with a substance naturally possessing circular polarisation, the result is quite different. In fact, the plane of polarisation of the reflected ray, which retrogrades in the substance, experiences a rotation equal to that which it would have experienced in the first course of the ray; but this second rotation occurs in a contrary direction to the first, that is, from left to right if the former occurred from right to left; which experiment has taught us. It follows from this, that these two rotations annihilate each other; and that when the ray, reflected a second time, finally goes out of the substance, the deviation of its plane of polarisation, notwithstanding its three courses through this substance, is no greater than it would have been had it made but one. Generally, if the number of courses is even, the effect is null; if they are odd, it is the same as if there had been but a single course.

The difference that we have been pointing out enables us, in a very simple manner, to bring about circular magnetic polarisation in quartz: it is sufficient for this to have a single reflection, and consequently only two courses of the polarised ray in this crystal; for this double course annihilates its natural circular polarisation, and doubles, on the contrary, that which is determined in it by the influence of the poles of the magnet.

A more convenient manner of demonstrating the opposite effect, according as one or the other of these cases is under consideration, that is produced by the double course in opposite directions in the same substance of a polarised ray, consists in employing for these experiments Noremberg's very simple polarising apparatus (*Fig.* 169.). In this apparatus, the polarisation is produced by the reflection of the light upon an inclined transparent glass surface; the light is first reflected from above downward by this oblique glass; it is then reflected from below upward by a horizontal tinned glass placed below, and traverses vertically the oblique glass plate, in order to arrive at the analysing crystal placed on the top of the apparatus, and which may be made to rotate round a graduated circle. The lower horizontal mirror is arranged upon the pole of a powerful electro-magnet; then upon this mirror is placed the transparent substance, a piece of Faraday's heavy glass, for example: so long as the current does not pass around the wire of the electro-magnet, there is no effect; but as soon as it passes it is necessary to turn the analyser 10° if the glass is ·7 in. in thickness, and 21° if it is 1·88 in., in order to recover the plane of polarisation: these two numbers, therefore, express the rotation of this plane. But, by this arrangement, the polarised ray has traversed the heavy glass twice; once, when reflected by the oblique glass plate, it was directed from above downward; a second time, when reflected by the horizontal glass, it was sent back vertically from below upward. The effect, therefore, is doubled by the magnetic circular polarisation; it is, on the contrary, annihilated in natural circular polarisation: and

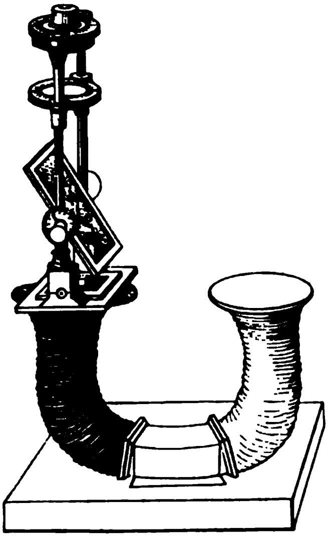
*Fig.* 169.

thus it is that, by operating in this manner, we prove in the best manner possible circular magnetic polarisation in quartz, because we annihilate the natural polarisation.

Let us now return to the comparison between the two modes of circular polarisation, and to the fundamental difference that we have established between them. It is evident that the natural rotatory property of certain bodies, such as essence of turpentine, is due to the nature, and not to the arrangement, of their particles; for, whatever be the direction according to which the polarised ray traverses this fluid, the rotation that it undergoes is always the same, from right to left; it depends only on the direction of the ray itself: the power by which it is produced appears, therefore, to belong, in all directions and in all times, to the molecules of the fluid. Circular magnetic polarisation, on the contrary, existing in a single direction only, namely, in a plane that is perpendicular to the line of the magnetic force, it must consequently be due to a particular arrangement impressed by magnetism upon the particles, according to which they are capable of acting, in certain directions in a certain manner; depending on the direction of the magnetic or the electric force, and not in all directions in a uniform manner, as in the preceding case. The natural rotatory property, therefore, is inherent in the atom or the molecule, and, consequently, may be considered as atomic or molecular, as M. Biot had seen. The artificial rotatory property is due to a species of polarity, impressed upon the atom or the molecule, which causes it to act only according to a direction, and in this direction alone, in one way or the other, according as these contrary polarities are on one side or on the other.

Now, what is this peculiar state of the molecule,—this polarity, that is impressed upon it by the action of magnetism or of electric currents? It has been thought that it is due merely to a new arrangement called into being by this action; or, in other words, several philosophers have supposed that the property of acting upon light acquired by transparent bodies under this influence, arises only from a change in the relative position of particles, that it would bring about

In support of this opinion, we may first call to our aid its analogy with what occurs in magnetic bodies, such as soft iron, in which the action of magnetism, or of electric currents, produces a new arrangement of the particles. M. Mathiessen's experiments, which seem to indicate a modification in the tempers of the specimens of glass submitted repeatedly to the action of powerful magnetic forces, would also lead us to admit that this action modifies the molecular state of bodies. Finally, M. Matteucci's researches would seem to furnish a still more remarkable proof of this. This philosopher found, that a compression exercised upon heavy glass, and upon flint-glass, when subject to magnetic influence, modifies their rotatory power; and in crown glass it makes it entirely disappear. The specimens submitted to experiment were cubical; and they were compressed in the direction normal to the direction of the polarised ray, and consequently of the magnetic force. In order to make the experiment, we begin by compressing the glass to a certain point; we then see the colours appear, and we turn the analyser, in order to return to zero. We then make the current pass around the electro-magnet; we immediately obtain a rotation, but it is no longer equal in the two directions, as it was before the glass was compressed. What is curious is, that it is stronger in the same direction, in which it had already been necessary to turn the analyser, in order to regain the zero, under the effect of simple compression, without magnetisation. The difference is very sensible: thus, with compressed heavy glass, M. Matteucci obtained a rotation that was 5°·6 and even 8° in one direction, and only 3° or 4° in the contrary direction. Immediately that the compression ceased, the two rotations became exactly equal. Flint-glass gave similar results, but a little less decided. The same philosopher also found that elevation of temperature increased, in heavy glass and in flint-glass, this aptitude to manifest the rotatory property under magnetic influence. By always employing the same current for the magnetisation, he obtained double the rotation, by giving to the heavy glass upon which he was operating the temperature of boiling oil. The rotation returned to what it had been before it was heated, when the glass was cold.

These different facts, therefore, prove the relation of the phenomena discovered by Faraday with the molecular condition of the bodies submitted to experiment. But there is a wide difference between this and admitting that this condition is the cause of it. In fact, with the exception of a few traces of temper, and these somewhat dubious, observed by M. Mathiessen, nothing hitherto has shown directly that the electric and magnetic forces may influence, by their exterior action, the molecular constitution of solid non-magnetic bodies. Further: liquids, which all manifest, though in different degrees, it is true, the rotatory property under magnetic action do not owe it to a modification impressed by this action upon their molecular constitution; for we may agitate them, may make them be traversed by electric currents in all directions, without the property being in the slightest degree altered. Moreover, direct observations, made with great care, do not seem to indicate that the exterior influence of magnetism or electricity exercises any effect upon the physical constitution of liquids, upon their volume, their fluidity, &c.

If it is not to an alteration in the arrangement of their particles that bodies owe the rotatory power that they acquire under the influence of magnetism, we must endeavour to seek the origin in some other modification which they experience beneath this influence. In fact, this phenomenon does not arise from a direct action exercised by magnetism upon light; the body is a necessary intermediate; for a polarized ray travelling in vacuo, or even in a gas, does not undergo any action on the part of a powerful electro-magnet. This has been proved by Mr. Faraday and several other philosophers: the presence of material molecules, or of molecules tolerably near together, such as those constituting a solid or a liquid, seems therefore to be a necessary condition. On the other hand, the action not being exercised upon the particles, so as in any way to modify their relative position, it is necessary to admit that it is upon the particles in their relation with the ether by which they are enveloped that it occurs; but, in order that the action which the particles exercise naturally upon the ether may be modified by the magnetic force to which they are subjected, it is necessary that this ether be in that particular state that follows from the close approximation of the particles. Now this particular state consists in that it is more dense and more elastic in solid and liquid media than in the gases; which, as we know, is the cause of the high refracting power of the first two classes of bodies.

Thus the magnetic force would not act upon the ether by the intervention of the particles, except when it is in a certain state of density, arising from the action exercised naturally upon it by the particles, and would act the more powerfully as this density should be more considerable. As it does not depend wholly upon that of the body, that is, upon the nearness of the particles of which it is constituted, but rather upon the nature of these particles, it is not always the densest bodies that are the most refracting, and which consequently ought to experience the greatest amount of circular magnetic polarisation. Experiment entirely confirms this mode of viewing the subject; and if we cast our eyes over the table, which as yet is very limited, it is true, and very imperfect in the co-efficients of magnetic polarisation, we are struck with the fact that the substances follow each other in this table, almost in the same order as in the table of their refracting powers. Further researches are necessary, in order to establish on still more solid bases the analogy that I have been pointing out; and especially to determine the nature of the modification experienced by the action of the particles upon the ether under magnetic influence; a modification, the essence of which is to break the uniformity of its mode of action around the particle; to substitute for it another, occurring only according to a certain direction, and moreover in a contrary way at the two opposite extremities of this direction; a mode of action that the word polarity characterises very well.

However, not attributing the production of the rotatory power for magnetism to a molecular derangement produced by this agent, we do not deny that the arrangement of the particles of a body influences its optical properties. Thus every arrangement that disturbs its uniformity of structure, such as is determined by nature in crystals, and which is produced artificially in glass, by compression, for example, gives rise to phenomena of double refraction and of polarisation, which can only be explained by admitting that this alteration of molecular constitution causes, as its consequence, the ether not to have the same elasticity in all directions equally.

But if the molecular arrangement, be it natural or artificial, developes optical properties in certain bodies, I do not at present know that it has determined in them circular polarisation, which appears to me essentially due, as M. Biot also remarked, to the intimate nature of the molecules rather than to their state of aggregation. Now, what is it that characterises the intimate nature of the particle if it is not, with its weight, its action upon the ether by which it is enveloped? It is this action, therefore, that the presence of the magnetic force would modify, by giving to it, as we have said, a particular direction and a polarity. I know that we might suppose that the particles in their natural state exercise this kind of action upon the ether, that is, that they are naturally polar. In this case certain substances would have of themselves, and others would acquire under the influence of magnetism, the property of manifesting this molecular polarity, which would be in all ordinary cases neutralised by the mutual action of the particles upon each other; a neutralisation that would constitute a state of equilibrium. But it would be necessary in this explanation to suppose a change of position of the particles in respect to each other; a change that does not appear very probable; and which, at all events, it is not easy to admit, until it shall have been demonstrated directly.

To sum up: in the ideas at present received on the constitution of matter, we think that the phenomena discovered by Faraday ought to be attributed to an action of magnets and electric currents, exercised neither on the particles alone, nor on the ether alone, but on the manner of the existence of the particles in respect to the ether.

### *Action of Magnetism upon Polarised calorific Rays.*

Radiating heat is polarised the same as light, as several philosophers have succeeded in showing. It is electricity that furnishes, in the thermo-electric pile, as we shall see further on, the fittest instruments for proving this property.

M. Wartmann, a short time after Faraday's discovery, announced that a piece of rock salt, placed in the route of polarised rays of heat, determines the rotation of the plane of polarisation, if a powerful electro-magnet is made to act upon it. Rock salt, in the experiment, plays for radiant heat the same part that glass plays for light; namely, it transmits it without its experiencing a sensible diminution in intensity; and like glass, when under the action of magnetism, rock salt, in like manner, makes the plane of polarisation of the rays that are traversing it deviate. MM. de la Prevostaye and Desains have confirmed the result that M. Wartmann had at first obtained, by employing slightly different means, and, in particular, by making use of solar heat. They even succeeded in measuring the deviation of the plane of polarisation,—a determination that is very difficult, and which requires the employment of very delicate processes and apparatus. We shall return to this subject when we shall have made known these processes and apparatus.

# NOTES

RELATIVE TO

# MATHEMATICAL DEVELOPMENTS

OF

# CERTAIN PARTICULAR POINTS.

## NOTE A. (p. 12.)

In the experiment that serves to establish the law of the inverse of the square of the distance, for electric attractions and repulsions, we take, as a measure of the distance by which the two electrised balls are separated, the arc that separates them, and not the chord, which is the true distance. Furthermore, we take no account of the fact, that the attractive or repulsive force acts obliquely upon the needle; and that, consequently, it does not contribute in its full amount towards making it turn. Although the obliquity is very small, on account of the small extent of the arcs, — a circumstance that also renders the error very small that is committed in taking the arc for the chord, — it is, however, very necessary, considering the importance of the law which this experiment tends to establish, to show that it is indeed a rigorous consequence, and not only approximative. With this view, let F represent the intensity of the total force, when the distance between the two electrised balls is unity; this force at the distance D will become $\frac{F}{D^2}$, if we set out on the supposition that the law we are desirous of demonstrating exists.

Let *a b* (*Fig.* 1.) be the chord of the arc that separates the two

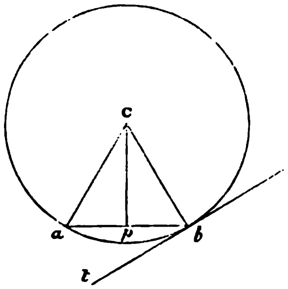

*Fig.* 1.

balls, and $c\,b$, the radius of this arc. By decomposing the force that acts in the direction $a\,b$ into two, the one directed according to $c\,b$, which is destroyed by the resistance of the axis of rotation, the other along the line $b\,t$, perpendicular to $c\,b$, and consequently tangent to the arc; this latter alone will contribute to the movement. But it will be equal to the force directed according to $a\,b$, namely, to $\frac{F}{D^2}$ multiplied by the co-sine of the angle $a\,b\,t$, which is the complement of $a\,b\,c$. But the triangle $a\,b\,c$ being isosceles, the angle $a\,b\,c = 90° - \frac{1}{2}\,a\,c\,b$; hence co-sine $a\,b\,t = \sin.\ a\,b\,c = \cos.\ \frac{1}{2}\,a\,c\,b = \cos.\ \frac{1}{2}\,a$, letting $a$ represent the angle $a\,c\,b$. Thus the force will be expressed by $\frac{F}{D^2}\cos.\frac{1}{2}a$; on the other hand, the distance $D$ or the chord $a\,b = 2\,r \sin.\ \frac{1}{2}\,a$, which is found immediately, by drawing the perpendicular $c\,p$, and calling $r$ the radius, that the movable ball describes, namely, $c\,b$; we have, in fact, $a\,p = r \sin.\ \frac{1}{2}\,a$ and $p\,b = r \sin.\frac{1}{2}\,a$; therefore $a\,p + p\,b$ or $a\,b = 2\,r \sin.\ \frac{1}{2}\,a$. Thus we easily find as an expression of the force $\frac{F \cos.\ \frac{1}{2}\,a}{4\,r^2 \sin.^2 \frac{1}{2}\,a} = n\,A$; $A$ representing the angle of torsion that produces equilibrium to the force, and which is consequently proportional to it, and $n$ the co-efficient dependent on the torsion balance that indicates this relation. We draw from this equation

$$\frac{F}{4n\,r^2} = A \sin.\ \tfrac{1}{2}\,a \times \frac{\sin.\ \frac{1}{2}\,a}{\cos.\ \frac{1}{2}\,a} = A \sin.\ \tfrac{1}{2}\,a \text{ tang. } \tfrac{1}{2}\,a.$$

This last expression must be constant, if the hypothesis from which we set out — namely, the law of the inverse of the square — is correct. For $\frac{F}{4n\,r^2}$ is a constant quantity, so long as the force $F$, — namely, the electric charge of the two balls — does not change; since $n$ and $r$ are themselves constants, that depend only upon the apparatus employed. Now, the following Table of Experiments, very carefully made by M. Biot, shows that this is really the case: —

| | $a$ | A | A sin. $\frac{1}{2}a$ tang. $\frac{1}{2}a$ |
|---|---|---|---|
| 1st Experiment | 36° | 36° | 3·614 |
| 2d " | 18° | 144° | 3·568 |
| 3d " | 8½° | 575½° | 3·169 |
| In like manner supposing | 9° | 567° | 3·557 |

The variation in the result of the third experiment corresponds to an error of about half a degree in the observation of the arc; although this error may be tolerated, it is probable, however, that it is due to an effect of induction, arising from the great proximity of the two balls, and which thus disturbs the result.

The calculation that we have been giving is equally applicable to the case in which the force F is either repulsive or attractive; however, in the latter case, we must pay regard to an important circumstance that occurs when attraction is in question, as will be easily understood from what follows.

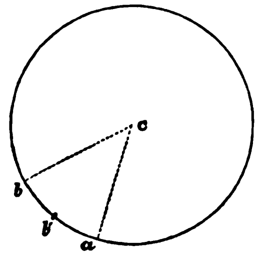

*Fig.* 2.

Let $c$ or $a\,b$ (*Fig.* 2.) be the angle at which the zero of torsion has been displaced, which in this case cannot rest where it first was, as in the case of repulsion, namely, at the point where the two balls are in contact; let $a\,b'$ or $a$ be the smaller arc than $c$, which separates the two balls when being charged with contrary electricities, equilibrium is established between their mutual attraction and the torsion that tends to separate them; it is evident that $c-a$ expresses the angular quantity to which the movable ball has been displaced, viz., the angle of torsion. On the other hand, the attractive force, taking the arc $a$ for the chord, which we have thought we could do without sensible error, is $\frac{F}{a^2}=m\,(c-a)$; $m$ being for all arcs a constant co-efficient, which depends on the instrument. Now it is easy to see that this equality, which amounts to $F=mca^2-ma^3$, is not always possible; for F can be neither null nor negative. By putting this expression under the form of $ma^2\,(c-a)$, we may remark that it commences to increase from 0°, that is, from $a=c$, in proportion as $c-a$ increases; but it attains its limit at a certain value of $a$. To have the greatest value of which it is susceptible, we must differentialise the expression in respect to the value $a$, and make the differential co-efficient equal to 0. We thus obtain, $2\,mca-3\,ma^2=0$; whence $a=\frac{2}{3}c$. Thus,

$\frac{F}{D^2}$ has its maximum value, when $a=\frac{2}{3}c$, and this value is $\frac{4}{27}mc^3$. Consequently, every time $\frac{F}{D^2}$ exceeds this value, tension can no longer make equilibrium with attraction, and the balls will necessarily come into contact. It is necessary, therefore, to take care that the distance D or the arc $a$ is never less than $\frac{2}{3}$ the arc $c$, to which the 0° of torsion has been driven from the 0° of the division that serves as a starting point to the measure of the arcs. Thus, to make the experiment is a very delicate matter, seeing that the slightest oscillation of the needle, which renders the arc $a$ less than $\frac{2}{3}$ of $c$, would determine the movable ball to throw itself upon the fixed ball, and would consequently nullify all the results.

We shall not terminate this note without adding that M. Marié Davy, by new experiments made with great care, has just confirmed Coulomb's law, which was rendered doubtful by Sir William Snow Harris's experiments. Only he has found that, in order for it to be true for two spheres, it is necessary that their distance should exceed nine or ten times their radius, which shows that, for physical points, whose extent is very small, we have at all distances the inverse of the square; that, consequently, this law is the elementary law of electrical repulsions and attractions, with which indeed all the results of M. Marié Davy are in accordance. The same philosopher has also found that, in order that the electric balance shall give good results, it is necessary to employ metal discs rather than balls of pith or cork, and to combine the experiments, as Coulomb did, so that the discs may be maintained at the same distance, and that the torsion alone may vary.

## NOTE B. (p. 103.)

### *Note relative to Disguised Electricities.*

LET E be the quantity of electricity with which the disc of the condenser is naturally charged, that is, in communication with the source of electricity, when this disc is insulated and not subject to any induction. This quantity depends upon the extent of the surface of the disc, and on the electric re-action of the source. Let A be the total quantity of electricity, in part free, in part disguised, with which this same disc is charged, when under the induction of a similar disc brought as near to it as possible, but not in contact with it, and which is put in communication with the ground. Let A′ be the quantity of electricity disguised by this induction. We have evidently $A-A'=E$, since the disguised electricity does not prevent the disc from becoming charged with the same quantity of free electricity that it would have taken had it not been subject to any induction. The second disc has a quantity of electricity contrary to that of A, which may be expressed by B: as it arises from the decomposition of the natural electricity of the second disc, brought about by the induction of the first, the quantity B is naturally less than A; namely, the positive electricity of the first disc, if added to the negative electricity of the second, would not form neutral fluid, but there would be an excess of positive, more or less considerable, according to the mutual distance of the two discs. Suppose, therefore, that B can neutralise only $mA$ instead of A, $m$ being less than 1; we shall, therefore, have $mA+B=0$. Now, in its turn, B of the second disguises the quantity $A'$ of the electricity of the first; we shall, therefore, equally have, since the second effect occurs between the two same discs and the distance has not changed, $A'+mB=0$. By replacing B, in this second equation, by its value drawn from the first, we shall have $A'=m^2A$; and $A-A'$, namely $E=A(1-m^2)$; finally, $\frac{E}{A}=\frac{1}{1-m^2}$. $\frac{A}{E}$ expresses the relation between the total quantity of electricity with which the first disc is charged, when under the influence of the second, and the quantity with which it is charged naturally, when out of this influence. This quantity expresses, therefore, the effect of this induction, or the *condensing power.*

The value of $m$ depends on the degree of approximation of the two discs. If they could be in immediate contact, still remaining electrically insulated from each other, so that the two electricities could not neutralise each other, we should have $m=1$; and then the condensing power would be $\frac{1}{0}$, that is to say, infinite. But it is easy to see that this case cannot be realised; there must always be an insulating stratum between the two discs; and, however thin it is, its thickness is never nothing; but the less the thickness is, the greater is the condensing power. If, for example, it is such that $m=\frac{99}{100}$, we have

$$\frac{1}{1-m^2}=\frac{1}{1-\left(\frac{99}{100}\right)^2}=\frac{1}{\frac{10000-9801}{10000}}=\frac{10000}{199}=50,$$

by substituting 200 for 199, which may be done without sensible error. The condensing power would therefore be equal to 50; that is to say, the disc in communication with the source would become, by the mere fact of the induction exercised upon it by the second disc, capable of becoming charged with fifty times more electricity than it could have acquired had it been in communication with the same source, without being under the influence of the second disc.

In order to determine $m$ experimentally with a given condenser, we charge it with electricity; we then separate the two discs, taking care that they do not lose their electric charge. We touch the first with the proof plane of the torsion balance, and on carrying the plane to the balance, we obtain an angle of torsion $a$, which is proportional, as we know, to the total charge of the disc, namely to A. We have, therefore, $a=n\text{A}$, $n$ being a fraction smaller than unity. We do the same with the second disc, charged with the contrary electricity, B; we have, therefore, an angle $b=n\text{B}$, provided we take the precaution to touch this disc in a point placed in a similar manner to the point that had been touched of the first disc. It is essential to remark that the two discs are in all respects perfectly similar, of the same size, the same form, &c. We have, therefore, $a=n\text{A}$ and $b=n\text{B}$; therefore,

$$\frac{b}{a}=\frac{\text{B}}{\text{A}}=m.$$

When we are considering a Leyden jar, whose insulating stratum is very thick, since it is a plate of glass, the quantity $m$ is far removed from unity, and B is much smaller than A. Also, when we unite the two coatings of the jar, in order to produce the discharge, or the neutralisation of the two electricities, there remains, after this discharge has taken place, a considerable quantity of electricity in the coating that had been in communication with the source. We may easily calculate this quantity by remembering that $\text{A}=\frac{\text{F}}{1-m^2}$, and $\text{B}=m\text{A}=\frac{m\text{E}}{1-m^2}$. After the discharge, there remains therefore on the coating that had been charged with the quantity A, a quantity A − B, or

$$\frac{\text{E}}{1-m^2}-\frac{m\text{E}}{1-m^2}=\text{E}\frac{(1-m)}{1-m^2}=\frac{\text{E}}{1+m}.$$

## NOTE C. (p. 179.)

### *Note relative to the measure of Magnetic Forces.*

We have said that there are two modes of measuring magnetic forces; the first, based upon the employment of the torsion balance; the second, upon the principle of oscillations. In either method we must take into account the action of the terrestrial globe, which contributes, independently of the force whose intensity we are measuring, to the total effect given by direct observation. This action of the terrestrial globe, in fact, is exercised upon the magnetised needle according to laws susceptible of being subjected to rigorous calculation, of which the present note is intended to give a summary description, and the results of which will not only serve for the demonstration of the principles that we have already implicitly admitted, but will be indispensable to us in the sequel in the study that we shall be called upon to make of terrestrial magnetism. We shall divide this note into three parts: — 1st. The general expression of the effect of terrestrial magnetism upon a needle in equilibrium; 2d. Law of the movement of the needle when it is deranged from its position of equilibrium, but enabled to turn around its centre of gravity, still remaining in the plane of the magnetic meridian; 3rd. Law of this movement, when the needle goes out of the plane of the magnetic meridian.

### § 1. *General expression of the effect of terrestrial magnetism upon the needle in equilibrium in the magnetic meridian.*

We will suppose (*Fig.* 3.) a magnetised needle, $ab$, of any form, suspended by its centre of gravity. Let $\mu$ be the quantity of free magnetism in one of its points, for example in M; this point will be attracted by forces arising from the north pole of the earth, and will be repelled by those arising from the south pole; the former will act in the direction MA, and the latter in the direction MB. These two forces will themselves have a resultant, MR, situated in the plane formed by their directions; we will call this

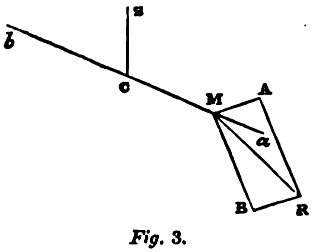

*Fig.* 3.

resultant $g'$, in order not to confound it with $g$, which expresses the force of gravity; the total effect on the point M will therefore be expressed by the product $\mu g'$. Each of the other points of the needle will therefore be solicited by a same force $g'$, since the resultant of the magnetic forces of the globe cannot vary in the small extent that is occupied by the length of the needle; $\mu$ only, namely the quantity of free magnetism, varies from one point to the other. The general expression, therefore, of the effect upon each point will be $g'\mu dm$, $dm$ representing the element of mass for which $\mu$ does not vary.

We may remark that all the resultants of the magnetic force of the globe, represented by $g'$, are parallel; consequently, all the forces $g'\mu dm$ are parallel to each other, and their general resultant is equal to their sum. Expressing this sum by S, we shall have the general resultant equal to $Sg'\mu dm$. But $S\mu dm$, in this expression, represents the sum of the free magnetisms in each of the points of the needle. Now, as there are as many south magnetisms as there are north magnetisms, and as a certain quantity of south magnetism neutralises an equal quantity of north magnetism, the sum $S\mu dm$ must be equal to 0; and, consequently, the general resultant $g'S\mu dm$ must be null. This result indicates that, when a needle has taken such a direction as the sum of the forces of terrestrial magnetism tends to impress upon it, these forces cannot impress upon it any motion of translation in space. Experiment confirms this: for a steel needle does not increase in weight by the effect of magnetisation; and, if it is arranged as indicated in *Fig.* 76. p. 184., it directs itself just as if it had been suspended immediately by its centre, without having been carried either forwards or backwards.

### § 2. *Laws of the movement of the needle, when compelled to move around its centre of gravity in the plane of the magnetic meridian.*

The needle whose movement will next engage our attention is what has been called the *dipping-needle* (*Fig.* 74. p. 161.). We represent it by a simple right line, although in reality it is composed of several parallel right lines; but it is easy to see that the real case may be reduced to the hypothetical elementary case. Let $ab$ (*Fig.* 4.) be this needle; let MR be the resultant $g'$ of the forces of terrestrial magnetism, necessarily comprised in the plane of the magnetic meridian, and whose direction forms with the

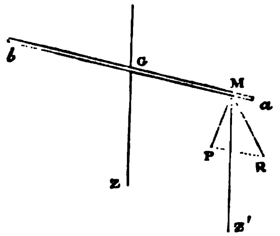

*Fig.* 4.

vertical an angle $i$, constant for the place of observation, and for a given time. Supposing the needle suspended by its centre of gravity, the resultant $g'$ tends to destroy its horizontality, and to give it an inclination, which, in our hemisphere gives the branch that is directed towards the north, namely that wherein we suppose the point M to be situated, a tendency to incline toward the earth. In *Fig.* 4. the needle $ab$ is no longer represented as horizontal; and, in order to ascertain the direction that it will assume, we decompose the resultant $g'$ or MR into two components; one, MP, drawn perpendicularly to the direction of the needle, the other drawn in the same direction as the length of the needle. The first is evidently the only one that contributes to cause the needle to turn, and it is equal to $g'$ cos. PMR; and by letting $z$ represent the variable angle formed by the needle with the vertical, we have $\mathrm{PMZ'}=90^\circ-z$; and $\mathrm{PMR}=90^\circ-z+i$; or cos. PMR, or $\cos.\ (90^\circ-z+i)=\sin.\ (z-i)$: so that the perpendicular component will become equal to $g' \sin.\ (z-i)$; and the action exercised upon the point M is $\mu g' \sin.\ (z-i)$, supposing that at this point there is $\mu$ of free magnetism. In order to obtain the real effect of its force, or its movement around the centre of suspension C, we must multiply its expression by the distance $r$ from M to C, which gives $\mu r g' \sin.\ (z-i)$. Now, $z-i$ is the angle formed by the direction of the resultant with that of the needle, which shows that the force which causes the point M to turn is analogous to that which draws back each of the points of a pendulum to the vertical: which, when this pendulum is drawn out from the vertical to an angle $a$, is equal to $g \sin.\ a$, $g$ being the force of gravity; and its momentum is $gr \sin.\ a$, $r$ being the distance of the extremity of the pendulum from its centre of suspension.

In order to obtain the effect, not only upon the point M, but on the whole extent of the needle, it is necessary to consider each of its halves separately, or each of the two arms of the lever C$a$ and C$b$. The sum of the moments for each will be $\int \mu r g' \sin.\ (z-i)$; but $g' \sin.\ (z-i)$ is a quantity that does not change in passing from one point to another, or may therefore be regarded as constant; and the expression become $g' \sin.\ (z-i) \int \mu r dm$.

$s\mu r dm$ must be obtained separately for each of the halves of the needle: for the magnetisms in the two halves are contrary and equal, and if one tends to make the needle descend, the other tends to make it ascend; so that the effects are added together in order to make it turn. Let us call the two sums $s'$ and $s''$; we obtain, for the total momentum, by which the needle is actuated, $g'(s'+s'')\sin.(z-i)$; an expression that becomes null when $z=i$; namely, when the direction of the needle coincides with the resultant of the magnetic forces of the earth. Thus, so long as the needle is out of this position, it is solicited to return to it, and it does return to it by oscillating from one side to the other, about the direction of its fixed inclination, until its momentum is destroyed by the resistance of the air and the inertia of suspension. These oscillations of the needle are perfectly analogous, and are subjected to the same laws as are those executed by a pendulum when drawn from the vertical, in order to return to it by virtue of its gravity. In fact, the terrestrial magnetic forces that solicit the divers points of a needle, have directions parallel to each other like the forces of gravity; and like as those forces have a resultant that is applied to a point which is the centre of gravity of the body, there exists for each part of the needle in which a similar kind of magnetism resides, a magnetic centre, to which we may suppose all the magnetic force of the earth applied. It is true, that here the magnetic forces are not all equal to each other, since $\mu$, which enters as a factor into the expression $\mu g' dm$, varies from one point of the needle to another, but this circumstance makes no change in the analogy that we have established; for the existence of centres of gravity does not depend upon the equality, but upon the parellelism of the forces of gravity. We may therefore calculate the position of the point of application of the resultant of the magnetic forces, as we calculate the place of the centre of gravity in a heavy body. The distance of these points from the centre of suspension of the needle will be, for each of the halves of the needle, equal to the sum of the momentums divided by the sum of the forces; that is to say, by $\frac{s\mu r dm}{s\mu dm}$. $s\mu dm$ is not null here, since it is relative to only each of the halves of the needle.

It follows from what has been said that, like as intensities of gravity are measured from the duration of very small oscillations made by a pendulum around the vertical, those of the magnetic forces of the terrestrial globe may be measured by the duration of oscillations made around its normal direction by a dipping-needle placed in the magnetic meridian; and if, for the same needle, this duration varies from one place to another, we may conclude that the intensities of terrestrial magnetism vary proportionately to the square of the number of oscillations made by the needle in a given time, or inversely to the square of the time of oscillations. In fact, in the formula of the compound pendulum $\mathrm{T}^2 = \frac{\pi^2 \mathrm{S} r^2 dm}{g}$, we must put in place of $g$ the quantity $g'\,(\mathrm{S}'+\mathrm{S}'')$, which expresses the sum of the magnetic forces of the globe acting upon the whole length of the needle; and we obtain $\mathrm{T}^2 = \frac{\pi^2 \mathrm{S} r^2 dm}{g'\,(\mathrm{S}'+\mathrm{S}'')}$. For another place of the earth, we should obtain $\mathrm{T}'^2 = \frac{\pi^2 \mathrm{S} r^2 dm}{g''\,(\mathrm{S}'+\mathrm{S}'')}$ for the same needle, $\mathrm{S}'$ and $\mathrm{S}''$ not changing; for they represent, for each of the branches of the needle, the sum $\mathrm{S}\mu r dm$, which is constant for the same needle whose magnetism is invariable.

From the above two equations we derive $\frac{\mathrm{T}^2}{\mathrm{T}'^2} = \frac{g''}{g'}$; or, by letting N and N′ represent the number of oscillations made in a given time, $\frac{\mathrm{N}^2}{\mathrm{N}'^2} = \frac{g'}{g''}$.

It would now be easy, by making a needle oscillate under the influence of a force that is not terrestrial magnetism, and then under the influence of terrestrial magnetism alone, to take account of this latter influence, and consequently to obtain the value of that of the given force. But the employment of the dipping needle presents many inconveniences, the principal of which are, the difficulty of placing the needle accurately in the magnetic meridian; and especially the impossibility of obtaining a mode of suspension sufficiently delicate for the apparatus to be very sensible. In fact, the needle is compelled to move around a horizontal axis, passing through its centre of gravity, the two extremities of which rest on two knife edges; a system that presents considerable friction, whatever precautions may be taken. There is an advantage, therefore, in estimating the value of magnetic forces, to employ, as much as possible, the horizontal declination needle, whose mode of suspension may be as delicate as possible, rather than the dipping-needle; and although, in most cases, the result of observation gives less directly the measure of the effect that we desire to estimate, as we shall see, yet we may equally obtain it by a slight transformation in the formula.

### § 3. *Laws of the movement of the needle when it is set in motion out of the magnetic meridian.*

Let $ab$ (*Fig.* 5.) be the needle, and MR the resultant of the magnetic forces, at the point M; as this resultant is parallel to the plane of the magnetic meridian, and as $ab$ is no longer in this plane, MR is not in the same vertical plane as $ab$. We decompose the force MR or $g'$ into two; the one MZ$'$ or Z vertical; the other, MH$'$ or H horizontal and parallel to the plane of the magnetic meridian. The first will be equal to $g'$ cos. $i$; and the second, to $g'$ sin. $i$, $i$ still representing the angle RMZ$'$ formed by the resultant MR with the vertical. Let us now decompose the force H, which, equally with RM, is out of the vertical plane that contains the needle $ab$, into two others, one H$'$P or Y perpendicular to this plane, the other MP or X directed horizontally in this plane; by letting $a$ represent the angle formed by the vertical plane in which the needle is situated with the plane of the meridian, we shall have $\text{Y}=\text{H}$ sin. $a$ and $\text{X}=\text{H}$ cos. $a$; in which, by substituting for H its value, we shall have $\text{X}=g'$ sin. $i$ cos. $a$, and $\text{Y}=g'$ sin. $i$ sin. $a$; and we have already $\text{Z}=g'$cos. $i$. This is the system of the three forces acting upon the needle.

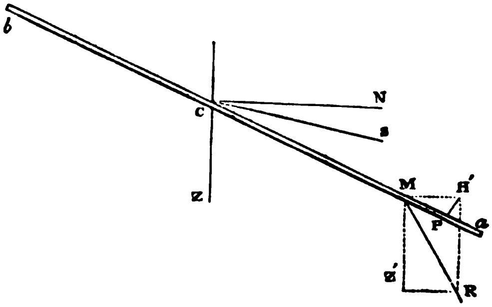

*Fig. 5.*

Let us examine successively what occurs in the case in which the magnetised needle is a dipping-needle, whose suspension is such that it does not allow it to go out of its azimuth, and in the case in which this needle is a declination needle, free to place itself in any azimuth, but always maintained in a horizontal direction, by a counterpoise fixed upon its south branch.

*a. The Dipping-needle.*—In the dipping-needle, suspended so as not to be able to move out of its azimuth, the force Y that acts perpendicularly to this azimuth, in order to bring it back to the plane of the magnetic meridian, when it is moved out of it, is destroyed by the resistance of the axis. There remain, therefore, only the other two forces, which have a resultant R, so that $R^2 = X^2 + Z^2$, since the two components are perpendicular to each other; but $\frac{X}{Z} = \text{tang.}\, i'$, $i'$ being the angle which their resultant (which naturally is not the same as that of the three forces X, Z, and Y, namely, MR) forms with the vertical; now, substituting their value for X and Z, we obtain, $R^2 = g'^2 \sin.^2 i \cos.^2 a + g'^2 \cos.^2 i$; which gives $R = g' \sqrt{\cos.^2 i + \sin.^2 i \cos.^2 a}$, or $R = g' \cos. i \sqrt{1 + \text{tang.}^2 i \cos.^2 a}$, and $\text{tang.}\, i' = \frac{X}{Z} = g' \text{ tang. } i \cos. a$.

It follows from these formulæ, that the intensity of the force which solicits each of the points of the dipping-needle, when moved out of the plane of the magnetic meridian, diminishes in proportion as it is removed from this meridian; for it diminishes in proportion as the angle $a$ increases, which is formed with the meridian by the azimuth, in which it is placed. Indeed, the greater $a$ is, the smaller does the $\cos. a$ become. The greatest value of the force occurs when $a=0$, and, consequently, when $\cos. a = 1$; which gives $R = g' \cos. i \sqrt{1 + \text{tang.}^2 i} = g' \sqrt{\cos.^2 i + \sin.^2 i}$, namely, $R = g'$, which should be the case, since, when $a=0$, the needle is in the plane of the meridian. The smallest value occurs when $a = 90°$; then, $\cos. a = 0$, and $R = g' \cos. i$; this occurs when the azimuth of the dipping-needle is perpendicular to the plane of the magnetic meridian.

It is not only the value, but also the direction of the force R, that varies with the value of the angle $a$; in other words, the dipping-needle changes its direction when its azimuth is changed. First, in the plane of the magnetic meridian, in which $a$ is null, and $\cos. a = 1$, we have $\text{tang.}\, i' = \text{tang.}\, i$; whence $i' = i$; which should be the case, since the resultant of X and of Z is the same as that of X, Z, and Y, namely, the resultant RM of the magnetic forces of the globe. We may remark, also, that it is in the plane of the magnetic meridian, that the dipping-needle forms the greatest angle with the vertical, or, which comes to the same thing, inclines the least below the horizontal; for the greatest value of $i'$, corresponding to $\cos. a = 1$, is to be equal to $i$. When the dipping-needle is placed in a plane perpendicular to the magnetic meridian, $a = 90°$, and $\cos. a = 0$; hence, $\text{tang.}\, i = 0$, namely the direction of the resultant makes no angle with the vertical, or, which comes to the same thing, coincides with it. This last result furnishes a very simple means for determining the plane of the magnetic meridian with the dipping-needle alone, without the necessity of having recourse to the declination needle. In fact, we have only to find the azimuth, in which the needle holds itself exactly vertical; then, by removing 90° from this, we have the plane of the meridian, and are able, consequently, to determine the dip, by placing the needle in this plane.

By means of the value of tang. $i$, we may also determine the meridian dip $i'$ in an indirect manner; a method that is constantly employed, in order to verify the result of direct observation. For this purpose, we have merely to observe $i'$ in any two azimuths, forming between them a right angle; in fact, let us designate by $i'$ and $i''$ the two observed angles, we shall have

$$\text{tang. } i' = \text{tang. } i \text{ cos. } a,$$

and consequently $\text{tang. } i'' = \text{tang. } i\,(90-a) = \text{tang. } i \text{ sin. } a;$

whence $\text{tang.}^2\, i\,(\text{cos.}^2\, a + \text{sin.}^2\, a) = \text{tang.}^2\, i' + \text{tang.}^2\, i'';$

whence $\text{tang. } i = \sqrt{\text{tang.}^2\, i' + \text{tang.}^2\, i''}.$

By this process, we may multiply the observations in different planes, and, by taking a mean between them, may reduce the errors of partial observations.

With regard to oscillations, all that we have said in reference to those which are produced by the resultant $g'$ in the magnetic meridian, are equally applicable to the oscillations produced by the resultant R of the two forces X and Z, in any plane in which the needle is forcibly directed. Only the force $g'$ becomes $g' \text{ cos. } i \sqrt{1 + \text{tang.}^2\, i \text{ cos.}^2\, a}$, a factor, which contains only constant terms, so long as the needle remains in the same azimuth.

*b. Declination Needle.*—We have said that, whenever it is possible, there is an advantage, especially in the method of oscillations, to employ the horizontal needle, the more delicate suspension of which renders the observations susceptible of much greater precision. When the declination needle is removed from the magnetic meridian, no obstacle occurs, as in the case of the dipping-needle, to prevent its returning to it. Thus the component Y, which acts perpendicularly to the vertical plane, in which the needle is situated, in order to bring it back to the magnetic meridian, is not destroyed. But, as we take care, by means of a small counterpoise, to render the needle horizontal, the effect of the vertical force Z, which gave it a tendency to turn in the vertical plane, becomes null. With regard to the horizontal ces X, which are always situated in the direction of the length of the needle, they have no influence to cause it to change its azimuth; and the directive force, therefore, is only expressed by Y. In order to obtain its total effect upon the needle, we must multiply by $\mu$, the quantity of free magnetism at the point upon which it acts, by $dm$, the element of the mass, and by $z$, the length of the arm of the lever, at the end of which it acts perpendicularly; which gives as the momentum $g'$ sin. $i$ sin. $a\,\mu\, r\, d\, m$, by putting in place of Y its value found above: but this expression is only relative to the momentum of a single point, making, therefore, the sum of all these momentums for all the points of the needle, we have $g'$ sin. $i$ sin. $a s \mu r dm$; and by taking the sum separately for each of the halves, we obtain as an expression, of the total momentum that is acting upon the needle, $g'(s'+s'')$ sin. $i$ sin. $a$.

In this expression there is only sin. $i$ that varies when the azimuth in which the needle is placed is changed. Thus we shall arrive at the law that we have already found by experiment, namely, *that the force which tends to bring back the needle into the magnetic meridian, when it is withdrawn from it, is proportional to the sine of the angle that the new vertical plane in which it is situated makes with the plane of the magnetic meridian.*

It only remains for us to examine what is concerned in the method of oscillations applied to the horizontal needle. In order to observe them with precision, we must suspend the needle horizontally to one or more cocoon threads arranged parallel, so that their torsion may be insensible; then, on withdrawing the needle, however little, from the meridian, we abandon it to the action of the horizontal forces that are acting upon it. The vertical force Z is here destroyed, as in the preceding case; but the needle, by this mode of suspension, being no longer subject to turn only around its centre, the force X, which acts in the direction of its length, contributes to its movement as well as Y, which acts perpendicular to the plane in which it turns. Now the resultant of the two horizontal forces is, as we have seen, $H = g'$ sin. $i$. We have, therefore, only to replace $g'$ by $g'$ sin. $i$, in the formula drawn from that of the pendulum, in order to express the number and the time of the oscillations for the dipping-needle, situated in the plane of the magnetic meridian. Now sin. $i$, for the same place and the same time, is as constant as $g'$, which is the same as saying that the inclination of the magnetised needle may be regarded as constant in the same place, as well as terrestrial magnetism, at least within the certain limits of time, that are more than sufficient for observations; it follows from this, that the substitution of the constant $g'$ sin. $i$ for the constant $g'$, does not in any way change the conclusions that may be deduced from the experiments, and that we may draw the same results from the observation of the number of oscillations, by employing the horizontal instead of the dipping-needle, since the relations only are concerned, in which the absolute and constant intensity of the force arising from terrestrial magnetism disappears. See in this respect (pp. 182. and 187.) the application that we have made of the method of oscillations of the horizontal needle for the determination of the laws of distance, and the distribution of magnetic forces in a magnetised bar.

## NOTE D. (p. 186.)

### *Demonstration of the Law of the Inverse of the Square of the Distance, by Calculation of Magnetic Curves.*[*]

SETTING out from the form of magnetic curves observed by Dr. Roget, we are about to show that the action of each of the poles of a magnetised bar upon those which are determined by induction in a particle of iron filings, varies in inverse ratio with the square of their distance.

Let A and B represent the two poles of a magnet, of a contrary or of the same name, between which the magnetic curve is formed; and let us first seek the equation of the latter of these, in respect to two rectangular axes drawn in its plane. Let M represent any one of its points, whose co-ordinates will be $x$, $y$; let the line AB represent the axis of $x$, its origin being in the middle O, the positive $x$ being calculated on the side OA, and the positive $y$ on the side of the curve.

Let $h$ represent the length OA=OB, $r$, $r'$ the distances AM, BM, and $i$, $i'$ the angles MAB, MBA; finally, let fall from M upon AB the perpendicular MP. We have, evidently, AP=AM cos. MAB=$r$ cos. $i$; on the other hand, AP=AO−OP=$h-x$, consequently cos. $i=\frac{h-x}{r}$; in like manner, we shall find cos. $i'=\frac{h+x}{r'}$. According to Mr. Barlow's first law we have, in the whole extent of the curve, cos. $i \pm$ cos. $i'$=const., taking the upper or the lower

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[*] This note was furnished to me by M. Ch. Cellerier; and is now published for the first time.

line, according as the poles A and B are of a contrary or of the same name. By substituting the above values for cos. $i$, cos. $i'$, we shall find the equation of the curve,

$$\frac{h-x}{r} \pm \frac{h+x}{r'} = \text{const.}$$

Here $r$ and $r'$ are put in place of their values,

$$r=\sqrt{\overline{\text{AP}}^2+\overline{\text{MP}}^2}=\sqrt{(h-x)^2+y^2}\,;\ r'=\sqrt{(h+x)^2+y^2}.$$

Now, let A$'$B$'$ be the poles of a particle of filings situated at M; A$'$ being of the same name as A. The resultant of the actions of A and B upon A$'$, and that of their actions upon the very neighbouring point B$'$, will evidently be two equal forces, but in contrary directions; their common direction is that which will be assumed by the particle A$'$B$'$, if it is free to move. It will therefore be tangent to the curve formed by several particles, when adhering to each other, by poles of the contrary name; for the little right line A$'$B$'$ is then an element of this curve.

Let $g$ represent the angle comprised between the axis of $x$ and the tangent to the curve at the point M. We shall clearly have, tang. $g=\frac{dy}{dx}$; and the deduction $\frac{dy}{dx}$ will be obtained by differentialising the equation of the curve, making $x$ and $y$ vary together. We then, by the known rules, find

$$\frac{-r\,dx-(h-x)dr}{r^2} \pm \frac{r'\,dx-(h+x)dr'}{r'^2}=0\,;$$

by differentialising the values of $r\,r'$, we further obtain

$$dr=\frac{-(h-x)dx+y\,dy}{r},\ dr'=\frac{(h+x)dx+y\,dy}{r'}.$$

By substituting in the previous equation, and multiplying it by $-\frac{r^3r'^3}{y}$, we find

$$r'^3\big(y\,dx+(h-x)dy\big)\pm r^3\big((h+x)dy-y\,dx\big)=0\,;$$

and the value that we deduce from $\frac{dy}{dx}$ or tang. $g$ is

$$\text{tang. } g=\frac{-r'^3y\pm r^3y}{r'^3(h-x)\pm r^3(h+x)}.$$

The tangent to the curve coincident with the direction of the resultant of the actions of A and B upon A$'$, letting F represent this latter, and X, Y its components according to the axes, we shall have

$$\text{X}=\text{F} \cos. g\,;\ \text{Y}=\text{F} \sin. g, \text{ whence tang. } g=\frac{\text{Y}}{\text{X}}.$$

' Let R be the intensity of the repulsive action exercised between the poles of the same name, A and A′; R′ that of the repulsive or attractive action exercised between B and A′. The first, making with the axis of the positive $x$ an angle of $180°-i$, will have, according to the axes of $x$ and $y$, components R cos. $(180°-i)$, or $-$R cos. $i$, and R sin. $i$; or, finally, $-R\frac{h-x}{r}$ and $R\frac{y}{r}$, remarking that $\frac{y}{r}=$sin. $i$. The components of R′, acting like the preceding on the side of the positive co-ordinates, will be found in like manner, and will be $\mp R'\frac{h+x}{r'}$ and $\mp R'\frac{y}{r'}$, by taking, as we have hitherto done, the upper or the lower signs, according as B is of the contrary or of the same name with A, and according as R′ represents an attraction or a repulsion. The components of the total action exercised upon A′ will therefore be,

$$X=-R\frac{h-x}{r}\mp R'\frac{h+x}{r'};\quad Y=R\frac{y}{r}\mp R'\frac{y}{r'};$$

whence we deduce,

$$\text{tang. } g=\frac{Y}{X}=-\frac{y(Rr'\mp R'r)}{Rr'(h-x)\pm R'r(h+x)}.$$

By equalising this value with that which we had found,

$$\text{tang. } g=-\frac{y(r'^3\mp r^3)}{r'^3(h-x)\pm r^3(h+x)};$$

whence results the relation

$$(Rr'\mp R'r)\left(r'^3(h-x)\pm r^3(h+x)\right)-\left(Rr'(h-x)\pm R'r(h+x)\right)(r'^3\mp r^3)=0.$$

By developing the calculations and separating the terms that contain $h-x$ and $h+x$, it becomes

$$(\mp R'rr'^3\pm Rr^3r')(h-x)\pm(+Rr'r^3-R'rr'^3)(h+x)=0;$$

or by reducing and dividing by $\pm 2hrr'$,

$$Rr^2=R'r'^2.$$

This equation, in which R and R′ represent functions of $r$ and $r'$ respectively, occurs in all the points of each magnetic curve; and as one may be passed through every point of space, it occurs for any point whatever, $r$ and $r'$ designating distances to A and B. We may therefore make $r$ vary arbitrarily by leaving to $r'$ a constant value; representing by H the independent value of $r$ then taken by $R'r'^2$, we shall have, whatever $r$ may be, $Rr^2 = H$; whence,

$$R = \frac{H}{r^2}.$$

Consequently the intensity R of the mutual action of the poles A, A′, varies in inverse ratio with the square of their distance $r$.

## Note E. (p. 217.)

### *Note relative to the Law of the Action of a Point of an Electric Current upon the Magnetised Needle.*

Experience demonstrates that the intensity of the action, exercised by an indefinite rectilinear current upon a magnetised needle, is in inverse ratio to the distance of the needle from the current. We have said the consequence of this experimental law is, that the elementary action of a simple point, or of a section of the current, is in inverse ratio, not to the simple distance, but to the square of the distance.

Let M N be the indefinite current; A, the centre of oscillation, that is to say, the middle of the magnetised needle, the point upon which we may suppose the action of the current as being concentrated; let A B, or $c$, be the shortest distance from the needle to the current; finally, let A C be the distance from any point of the current to the needle. The action of the point C, by supposing the law of the inverse of the square, will be expressed by $\frac{h\,ds}{AC^2}$; $h$ being a constant, depending on the mutual force of the current and the needle; and $ds$ the rectilinear element of the current whose action is being investigated. But $AC^2 = CB^2 + BA^2 = s^2 + c^2$, $s$ being the distance CB from any point C to the fixed point B; the quantity $s$ is a variable, because the form of the expression which gives the value of the action is the same, whatever be the point of the current that is taken. We have, therefore, only to integrate this expression $\frac{h\,ds}{s^2 + c^2}$ between $\frac{1}{0}$ and $-\frac{1}{0}$ to obtain the value of the total action of the

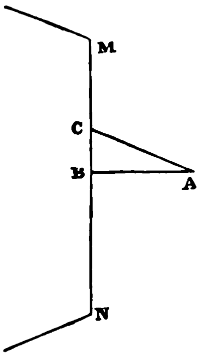

*Fig. 5.*

indefinite current MN; since we suppose that it extends indefinitely, setting out from B in both directions.

Now we have $h\int\frac{ds}{s^2+c^2}$ is $\frac{h}{c}$ arc. tang.$=\frac{s}{c}+$ constant; taking the definite integral between the limits $\frac{1}{0}$ and $-\frac{1}{0}$, we find that the expression becomes $\frac{h\pi}{c}$; a quantity in which $h$ and $\pi$ are constant, and in which $c$ only, namely the distance from the needle to the current, may vary. The action of an indefinite rectilinear current upon a magnetised needle is found, therefore, to be, as we have said, the inverse of the simple distance from this current to the needle, when we suppose that the action of a simple element of the current is in inverse ratio to the square of this distance.

Calculation likewise demonstrates that if the current is angular instead of rectilinear, and we admit that the action exercised by an element of this current upon a magnetised particle varies, not only in inverse ratio with the square of the distance, but also proportionately to the sine of the angle made with the direction of the current by the line joining the centres of the element and of the particle, we arrive at the result that the total action of the current is not only, as we have just seen, the inverse of the simple distance, but also proportional to the tangent of half the angle formed by the current that has become indefinite. This second result of calculation has been verified, like the former, by an experiment of M. Biot's. We shall not give here this latter calculation, in which the same course is pursued as for the former.

## NOTE F. (p. 246.)

### *Note relative to the Calculation of the mutual Action of two Electric Currents.*

THE very great development that I have given to this note is due to my desire to make known, in a tolerably complete manner, by endeavouring to place within the reach of the generality of readers the admirable mathematical theory upon which Ampère has based the explanation of all electro-dynamic phenomena; a theory so perfect that, by its means, the celebrated philosopher to whom it is due was able so to predict, even in their minutest details, all the different phenomena to which it relates, that subsequent experiment has never been able to gainsay it.

From the very origin of electro-dynamic phenomena three hypotheses were set forth in explanation of them.

The first consisted in admitting that the electric current confers upon the conductors which it is traversing a transverse magnetic polarity, so that the effect of the current may be assimilated to that of a multitude of small very short magnets, perpendicular to its direction and, consequently, parallel with each other. This hypothesis explains the first effects that were observed, and especially the law discovered by MM. Biot and Savart, relative to the mutual action of an element of the current and a magnetic molecule; a law which we have seen, in NOTE E., to be derived from experiments made with a current of very great length, and a very short magnet brought to various distances. The mutual action of magnetic elements would, under this hypothesis, have been an elementary action.

The second hypothesis, proposed by M. Ampère, consists in regarding as elementary the mutual action of two currents, and in explaining the mutual action of currents and magnets, and of magnets upon each other, by considering a magnet as an assemblage of electric currents, circulating around its particles, and acting either upon the electric currents of another magnet, or upon those of a conducting wire, precisely as experiment has proved that the currents of conducting wires act upon each other.

Finally, the third hypothesis consists in supposing that there exists between an element of a conducting wire, traversed by a current, and a magnetic molecule, a primitive elementary action, tending at the same time to make the molecule move round the element and the element round the molecule. This last hypothesis differs from the two former in that, instead of admitting between the material points that are acting on each other, merely direct forces following the right lines by which they are joined, it supposes, between the element of the current and the magnetic molecule, an action represented by two equal and opposite forces, but both perpendicular to the plane that passes through the element and the magnetic molecule, applied one to the middle of the element, the other to the molecule, and thus forming what M. Poinsot has called a pair; so that, even though the element and the molecule should be connected invariably together, the solid assemblage they would form would acquire, by their mere mutual action, a rotatory motion. Experiment has not verified this conclusion, which was decisive; for it was irreconcilable with the two former hypotheses. This might have been expected, for to regard a revolving action as a primitive action would appear contrary to the first principles of dynamics, according to which the mutual action of different parts of a solid system can never impress upon it any motion. We should, however, remark that Œrsted's first experiment, joined to the phenomenon of continuous rotation discovered by Faraday, would seem indeed to indicate as a primitive action a revolving action, in which the attraction and repulsion, that might then alone be apparent, were merely a transformation occasioned by the mode of arranging the apparatus. This idea was at first put forth by the two philosophers that I have just mentioned, but was subsequently abandoned in consequence of Ampère's more recent researches.

We must not be astonished at the diversity of views that existed among philosophers in the early days of electro-dynamics, as to the nature of the new force with which the successive researches of Œrsted, Arago, Ampère, and Faraday had enriched physical science. In fact, the mutual action of currents discovered by Ampère was the first example, with which nature had presented us, of forces, whose action is exercised in a line perpendicular to, and not in the same line with their direction; and for which, consequently, the intensity of the action was not simply a function of the mutual distance of the acting particles, but depended also on that variable element which we have called the *direction* of the current.

And thus many philosophers were originally favourable to the first hypothesis, in which the currents were no longer the primitive force, but were the cause that, by bringing about a transverse magnetism in conductors, developed the force, whose direction was thus found to be the same as that of the action to which they gave rise. However, the hypothesis of this transverse polarity could not long sustain the test of examination; it became very complicated as soon as it was investigated more closely in explanation of the mutual action of electric currents; and it was irreconcilable with the phenomenon of continuous rotation. They were compelled, therefore, to have recourse to the second—M. Ampère's—which is now generally adopted, and which new discoveries appear still more to confirm.

M. Ampère was not slow in applying his deep mathematical knowledge to the calculation of the forces, whose curious effects he had discovered by actual experiment. He commenced by expressing, by means of a formula, the value of the attractive or repulsive force of two elements or infinitely small portions of the currents, in order that he might be enabled to deduce from this, by the known methods of integration, the action that occurs between two portions of conductors, their form and situation being given. As it is impossible to submit infinitely small portions of a current to direct experiment, we must needs set out from observations made upon currents of finite size, and satisfying two conditions, namely, — that the observations be susceptible of great precision, — and that they be moreover proper for determining the value of the mutual action of two infinitely small portions of these currents. We may obtain this result by two methods; one consists in measuring, with the greatest accuracy, the values of the mutual action of two portions of the current of finite dimensions, by placing them successively, in respect to each other, at different distances, and in different positions; for it is evident that the action does not depend simply on the distance; then, by making an hypothesis on the value of the mutual action of two infinitely small portions, we deduce from it the value of the action that should occur to the conductors of finite dimensions, upon which we are operating, and we modify the hypothesis until the results of calculation accord with those of observation. Thus we proceeded in Note E., in order to determine the law by which the mutual action of an element of the current and a magnetic molecule is governed. But this method, good though it was in that case, is not applicable to that in which the mutual action of two currents is concerned, in consequence of the difficulties of execution and of calculation which it presents.

The second method, which is that employed by M. Ampère, consists in establishing various cases of equilibrium in the mutual action of currents upon each other. These different cases of equilibrium immediately give so many laws, which lead directly to the mathematical expression of the force exercised by two elements of electric currents upon each other; first, by making known the form of this expression, and then, by determining the constant but at first unknown numbers contained in it; precisely as Kepler's laws demonstrate first, that the force by which the planets are retained in their orbits, tends constantly to the centre of the sun; as well as that it changes for each planet in inverse ratio to the square of its distance from this centre, so that the constant co-efficient which represents the intensity, has the same value for all the planets.

We have seen that these cases of equilibrium are four in number (pp. 241, 242, 243, 244, and 245.). The first two were established by M. Ampère, from the period of his first researches, namely, in 1820; it was these which enabled him to frame the mathematical expression: he was more recently led to establish, successively, the other two cases, in order that he might be enabled to determine the constant co-efficients that entered into his formula, without having recourse, as he had already done, to experiments, in which, instead of two currents, a magnet and a current were acting upon each other. He was for a long time contented with the third case, which gave him a relation between the two constants that entered into his formula, and he established their absolute value by analogy with what occurs in nature. M. Savary, being desirous of getting free of this hypothesis, arrived in 1823 at the same value for these two constants, by means of an observation made upon magnets, combined with the third case of equilibrium; then it was that M. Ampère, wishing that his theory should rest upon more solid bases, sought and succeeded in determining directly this value of the two constants, by adding the fourth case of equilibrium to the third, which he had already found.

Let $i$ and $i'$ be the relations of the intensities of two given currents, to the intensity of the current taken as unity; $ds$ and $ds'$ the lengths of the elements in each of them that are under consideration; $ids$ and $i'ds'$ will express the respective intensities of their elements, and $ids \times i'ds'$, or $ii'ds\,ds'$, their mutual action when they are perpendicular to the line that joins their centres, and consequently parallel to each other, and situated at a unity of distance from each other; care must be taken to employ this product with the sign + when the two currents, by moving in the same direction, attract each other, and with the sign — in the contrary case.

Now, on considering two elements of currents, placed in any manner, and consequently not in the same plane, their mutual action will evidently depend on their lengths, on the intensities of the currents of which they form a part, and on their respective position. This position is determined by means of the length $r$ of the right line that joins their centres,—of the angles $\theta$ and $\theta'$ made with this line produced by the direction of the two elements, taken in the direction of their respective currents,—and finally of the angle $\omega$, formed by planes drawn through each of these directions, and through the right line that joins the centres of the elements. By analogy with what passes in nature in all the phenomena of attraction and repulsion, we may admit that the force, for which we are seeking an expression, acts also in inverse ratio to a certain power of the distance, which we will call the $n^{\text{th}}$, $n$ being a constant that is to be determined. Then, representing by $\rho$ the unknown function of the angles $\theta$, $\theta'$ and $\omega$, in the value of the action, we obtain $\rho i i' ds\, ds'$ for the general expression of the action of two elements $ds$ and $ds'$ of two currents, having for intensities $i$ and $i'$.

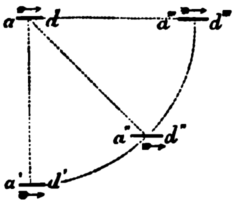

Fig. 6.

We must now determine the function $\rho$. For this purpose, we first consider two elements $ad$ and $a'd'$ (*Fig.* 6.) as parallel and situated at a distance $r$ from each other; their action is expressed by $\frac{ii'ds\,ds'}{r^n}$ as we have seen. Supposing $ad$ to remain fixed, let $a'd'$ be transported parallel to itself, so that its centre is always at the same distance from that of $ad$; as the angle $\omega$ is null, since the directions of the two currents are in the same plane, the value of the mutual action of their two elements is a particular function of the angles $\theta$ and $\theta'$, which we will designate by $\phi$, and must be expressed by the formula $\frac{ii'ds\,ds'\phi(\theta\theta')}{r^n}$. Calling $k$ the constant quantity to which $\phi\ (\theta, \theta')$ is reduced, when $a'd'$ is at $a'''d'''$, in the extension of $ad$, and moving in the same direction, we see that $k$ expresses the relation existing between the action of $ad$ upon $a'''d'''$, which is, therefore, $\frac{kii'ds\,ds'}{r^n}$; and that of $ad$ upon $a'd'$ which is $\frac{ii'ds\,ds'}{r^n}$; this relation is independent of the distance $r$, of the intensities $i$ and $i'$, and of the lengths $ds$ and $ds'$ of the elements under consideration. The two particular cases in question are relative; the one, that of the action of $ad$ upon $a'd'$, to the action of two parallel currents that attract or repel each other, according as they are in the same or in contrary directions; and that of the action of $ad$ upon $a'''d'''$, to the repulsion of two currents, moving in the same direction along the same right line; or, which comes to the same thing, the two consecutive parts of the same rectilinear current.

In order to discover the general form of the function $\rho$, let us now make use of our first two cases of equilibrium, and particularly of the second, which shows us that the attraction of an infinitely small rectilinear element is the same as that of any other sinuous element, terminated at the two extremities of the former, which enables us to apply to the new kind of forces, at least when we are considering them in their elements, the laws of the decomposition of forces, demonstrated in mechanics by those which are acting in the same direction with themselves, but which could not have been applied to these other forces had it not been for the experimental demonstration of this possibility. We have still need of a self-evident principle that an infinitely small portion of an electric current does not exercise any action upon another infinitely small portion of a current situated in a plane that passes through its centre, and is perpendicular to its direction.

Let, therefore (*Fig.* 7.), M$m = ds$, and M$'m' = ds'$, be two

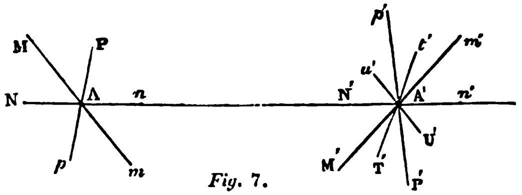

*Fig.* 7.

elements of electric currents, whose centres are at A and A$'$: let a plane, M A$'$ $m$, pass through the right line, A A$'$, that joins them, and through the element M $m$. In like manner, let a plane M$'$A $m'$ pass through the element, M$'$ $m'$, and the right line, A A$'$. The current directed along M $m$, namely, $ids$, may be replaced by its two components, N $n$, or $ids$ cos. $\theta$, according to the right line A A$'$, and P $p$, or $ids$ sin. $\theta$, according to a perpendicular at A on A A$'$ in the plane M A$'$ $m$. The current M$'$ $m'$ or $i'ds'\theta$ may, in like manner, be replaced by its two components N$'$ $n'$ or $i'ds'$ cos. $\theta'$, according to A A$'$, and P$'$ $p'$ or $i'ds'$ sin. $\theta'$, according to a perpendicular at A$'$ to A A$'$ in the plane M$'$A $m'$. Finally, the component, $i'ds'$ sin. $\theta'$, may itself be replaced by $i'ds'$ sin. $\theta'$ cos. $\omega$, directed in the plane M A$'$ $m$ along T$'$ $t'$, and by $i'ds'$ sin. $\theta'$ sin. $\omega$, directed according to a right line, U$'$ $u'$, drawn in A$'$, perpendicular to the plane, M A$'$ $m$. All these decompositions may be brought about by virtue of the second case of equilibrium, which enables us to apply to the forces on which we are engaged the general laws of decomposition. The mutual action of two elements of the current $ids$ and $i'ds'$, represented by $Mm$ and $M'm'$, may, therefore, be replaced by that of the *five* elements of the current that we have now traced out.

Let us now see to what the mutual action of these five elements may be reduced: —

Let us commence enumerating them, by referring to *Fig.* 7.

$Nn$ or $ids$ cos. $\theta$, following the direction $AA'$;

$Pp$ or $ids$ sin. $\theta$ perpendicular to $A$ at $AA'$, in the plane $MA'm$;

$N'n'$ or $i'ds'$ cos. $\theta'$, in the plane $M'Am'$, in the direction $AA'$;

$T't'$ or $i'ds'$ sin. $\theta'$ cos. $\omega$, in the place $MA'm$, passing in $A'$ perpendicular to $AA'$;

$U'u'$ or $i'ds'$ cos. $\theta'$ cos. $\omega$, perpendicular to the plane $MA'm$ in $A'$.

These currents, situated in respect to each other either in the same or in different planes, all have their centres, the former in $A$, the latter in $A'$. In order to calculate the mutual action of these five elements, we must remember that it is reduced to that of $Nn$ and $Pp$, which supply the place of $Mm$, upon $N'n'$, $T't'$, and $U'u'$, which supply the place of $M'm'$. It is clear that $Nn$ and $Pp$, components of the same current, do not act upon each other; and the same is true of $N'n'$, $T't'$, and $U'u'$, which are the components of $M'm'$. The action of $U'u'$ or $i'ds'$ cos. $\theta'$ cos. $\omega$ upon $Nn$ and upon $Pp$ is null; because $Uu$ has its centre in $A'$ in the plane $MA'm$, to which it is perpendicular, and $Nn$ and $Pp$ are in this plane, — the former in the direction $AA'$ of the line that joins its centre with that of $U'u'$, the other in a direction perpendicular to this right line; it will not be the same of the action of $T't'$, upon $Nn$, for the direction of $T't'$ is perpendicular to the direction produced of $Nn$, upon which its centre is situated. The action of $Pp$ upon $N'n'$ is also null for the same reason. These nullities of action are a consequence of the principle that we have mentioned above.

There remains only the mutual action of $Pp$ or $ids$ sin. $\theta$ and $T't'$ or $i'ds'$ sin. $\theta'$ cos. $\omega$; and that of $Nn$ or $ids$ cos. $\theta$ and $N'n'$ or $i'ds'$ cos. $\theta'$. The action of the two given elements, $Mm$ and $M'm'$, is reduced, therefore, to these two remaining actions; and, as they both act in the direction of the right line $AA'$, which joins the centres of the portions of the current, between which they are exercised, we have merely to add them together in order to obtain the expression that we are seeking, of the mutual action of two given currents.

P$p$ and T$'t'$ are in the same plane, and are at the same time both perpendicular to AA$'$, and consequently are parallel; from what we have seen at the commencement of this note, their mutual action will be, taking their respective values for the elements of the current, and representing the distance AA$'$, that separates them by $r$. $\frac{ii\,ds\,ds' \sin.\,\theta \sin.\,\theta' \cos.\,\omega}{r^n}$. N$n$ and N$'n'$ are not only in the same plane, but on the same right line, that is to say, the direction of the one is upon a prolongation of the direction of the other. These latter circumstances, as we have also seen at the commencement of this note, makes it necessary to multiply by $k$, the formula that would give the general expression of their mutual action, in the case in which they were parallel, and the expression thus becomes $\frac{k\,ii'\,ds\,ds' \cos.\,\theta \cos.\,\theta'}{r^n}$. The total action of the two elements, M$m$ and M$'m'$, or $i\,ds$ and $i'ds'$ on each other has therefore this expression: $\frac{ii'\,ds\,ds'}{r^n}$ $(\sin.\,\theta \sin.\,\theta' \cos.\,\omega + k \cos.\,\theta \cos.\,\theta')$.

The form of the general expression of the mutual action of two elements of the current being found, it remains to determine the value of the two constants $k$ and $n$. M. Ampère accomplished this by employing the third and fourth cases of equilibrium. He first made use of the third case alone, and by integrating the differential expression, that we have just found, he calculated the total amount of rotation, which the actions of the different parts of a closed circuit tend to impress upon a portion of a circular current, a momentum which, according to the third case of equilibrium, must be equal to zero.* This equality led him to a first equation between the constants $n$ and $k$; namely, $n+2k-1=0$. We shall not follow M. Ampère in the long and difficult calcu-

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* The experiment by which the third case of equilibrium (*Fig.* 100. p. 244.) is established, is but little susceptible of precision, on account of the friction of the moveable arc upon the mercury, contained in the two troughs: thus M. Ampère had at first deduced the value of $k$ from another experiment, that did not present the same inconveniences; it consisted in proving that a movable supporter of conducting wire, whose two extremities are in the vertical axis, around which it turns freely (*Fig.* 120. p. 272.), cannot move around this axis by the action of a horizontal circular conductor, whose centre is in the same axis. It is evident that the conductor is much more mobile by this mode of operating than by the other; but M. Ampère had abandoned it because the calculation that he employed to deduce from it the value of $k$, supposed that there was established relatively to each of the elements of the circular conductor, what experiment demonstrated only from the totality of this conductor.

lations, by means of which he arrived at this equation; it would be going beyond the limits that we have imposed on ourselves; we shall merely add that, by calculations no less profound, he succeeded in discovering the expression of the mutual action of two circuits of a finite length, situated in the same plane, by considering their areas $\lambda$ and $\lambda'$, as divided in every direction into infinitely small elements; and, by supposing that these elements acted on each other, according to the right line that joins them, in direct ratio to their surfaces, and in inverse ratio to the powers $n+2$ of their distance. The expression is $\frac{n(n-1)}{2} \cdot \frac{ii'\lambda\lambda'}{r^n+2}$.*

Now, if we consider two similar systems, each composed of two closed and plane circuits, the similar elements of their areas would be proportional to the squares of the homologous lines, and the distances of these elements would be proportional to the first powers of these same lines. Let $m$ represent the relation of the homologous lines of two systems, the action of the two elements of the first being still represented by the formula that we have just given, that of the two elements of the second will become $n\left(\frac{n-1}{2}\right)\frac{ii'\lambda\lambda' m^4}{r^{n+2}m^{n+2}}$. In fact from the remark we have been making, it is necessary to multiply by the square of the number that expresses the relation of the homologous lines, viz. by $m^2$, the expression which represents the individual action of each of the elements of the first system, in order to obtain that which represents the action of each of the elements of the second: whence it follows that the product of the expressions of the two elements of the second system, which gives their mutual action, is found to be the product by $m^4$ of the expression of the mutual action of the two elements of the first. With regard to the expression $r^{n+2}$ of this expression, it is necessary, in order to pass to that of the second system, to multiply it by $m^{n+2}$, because $m$ still expresses the relation that exists between the respective distances of the elements

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* By taking up M. Ampère's calculations, M. Plana found that this expression is erroneous, and ought to be replaced by $\frac{n^2-1}{2}\left(\frac{ii'\lambda\lambda'}{r^n+2}\right)$; but, as the same rectification must be introduced into the following expression, no change occurs in the value of their relation, which is the only thing of importance in the determination of $k$ and $n$, which are here in question. M. Ampère's error, therefore, is of no importance to the object upon which we are engaged; it possesses some advantage for the cases in which we require to express the absolute force, without even then, as M. Plana perceived, any change occurring to the general results, obtained by M. Ampère.

of each of the two systems; in such sort, that if we call $r'$ this distance for the second, we have $r'=mr$, $r$ being the distance for the first, whence it follows that $r'^{n+2}=m^{n+2}\,r^{n+2}$.

Now, the fourth case of equilibrium (*Fig.* 101. p. 245.), proves that the action of the second system must be equal to that of the first; for, in the first experiment by which it is established, the larger circle and the mean circle form a system similar to that of the mean and the smaller circle; the mean circle, which is movable, remains in equilibrium between the two extreme circles which are fixed when the circumference of all these is traversed by the same electric current. Now the relation that exists between the expressions of these two actions is $\frac{m^4}{m^{n+2}}$ or $m^{2-n}$; and, since they are equal, this relation must be equal to unity, or $m^0$; which gives $n=2$, and in virtue of the equation $1-n-2k=0$, $k=-\frac{1}{2}$.

Thus the general expression of the mutual action of two elements of any currents, situated in any planes, by putting in the place of $n$ and $k$ their respective values $+2$ and $-\frac{1}{2}$, becomes

$$\frac{ii'\,ds\,ds'}{r^2}\left(\sin.\,\theta\,\sin.\,\theta'\cos.\,\omega-\tfrac{1}{2}\cos.\,\theta\,\cos.\,\theta'\right);$$

an expression which no longer contains any unknown quantities.

We may remark in passing, that, from the formula $\frac{n\,(-1)}{2}\,\frac{ii'\lambda\lambda'}{r^{n+2}}$ relating to the mutual action of two closed currents, it follows that this expression being now only the function of the distance, since, with the exception of $r$, all the quantities that enter into it are constant, there can never result from this action a continuous rotatory movement. This important consequence is completely confirmed by experiment, which equally shows that it is impossible to produce a continuous rotatory movement by the mutual action of two magnets, which are both assemblages of closed currents.

We have seen in NOTE E., that, by applying calculation to one of M. Biot's experiments, the mutual action of an element of a current and a magnetic molecule is found to be in inverse ratio to the square of their distance; but this result could not be extended to two elements of the current, except by admitting that the action of magnets is due to electric currents; whilst the demonstration that has been given of it by M. Ampère, while confining himself to cases of equilibrium, in which electric currents alone are in play, is independent of all hypotheses that might be made upon the constitution of magnets.

It was not always so. M. Ampère was at first contented with the former relation between the two constants $k$ and $n$, founded upon the fact that a conductor, movable around an arc at which it terminates on both sides, whatever be its form, does not experience any tendency to turn always in the same direction, by the action of a portion of the circular conductor, whose centre is in the axis of rotation, and whose plane is perpendicular to this axis. This rotation, which M. Ampère replaced, as we have seen, by the third case of equilibrium, gives $n + 2k - 1 = 0$. From analogy between the divers phenomena of attraction that occur in nature, and particularly with the result of M. Biot's experiment in NOTE E., to which we have just referred, M. Ampère had originally admitted, without direct demonstration, that the exponent $n$ ought to be 2, which gave, as we have seen, $k = -\frac{1}{2}$. More recently, M. Savary discovered a second relation between $n$ and $k$, by means of an experiment by MM. Gay-Lussac and Welter, which is, that a magnetised steel ring exercises no exterior action, although its particles are really endowed with magnetisation, since its magnetic properties are manifested in its divers parts, as soon as it is broken. M. Ampère then made the same experiment, by replacing the ring by an assemblage of circular currents, arranged like those which he admits to be around the molecules of magnetised steel. By letting 0, according to experiment, represent the action of this system upon any exterior point, M. Savary obtained between $n$ and $k$, independently of all assimilation between magnets and electric currents, a second relation $n + 1 = 0$; which, on being combined with the former, $n + 2k - 1$, gives the equation $n^2 - n - 2 = 0$ or $n = \frac{1}{2} \pm \frac{3}{2}$. We thus find for $n$ two values, namely, 2 and $-1$, which correspond for $k$ to $-\frac{1}{2}$ and to $+\frac{1}{2}$. We have, therefore, to choose between the two systems ($n = 2$ and $k = -\frac{1}{2}$) and ($n = -1$ and $k = 1$). Now M. Ampère has shown by a direct experiment that $k$ must be negative; for this constantr epresents the relation between the actions of two elements of currents (*Fig.* 6.) when, the distance being the same, they are supposed first to be directed along the same right line, and then both in the same plane, and perpendicular to the right line by which they are joined, viz., parallel; this last action being positive, viz., attractive, the other is negative, viz., repulsive, the relative direction of the currents remaining of course the same; this follows from the experiment, in which we see that two portions of the current, moving in the same right line, and in the same direction mutually repel each other (*Fig.* 92. p. 230.). These two same portions of the current, when transported parallel to each other, are found to travel in the same direction.

We shall not follow M. Ampère in the application that he made of his formula to the determination of all the circumstances of motion that a fixed rectilinear or circular current must impress upon a movable current, when the relation is known of the position of the conductors, by which the currents are transmitted. We have already seen how M. Ampère, by means of his theory explains in particular all the phenomena of continuous rotation, arising from the mutual action of currents, as well as all the effects of terrestrial magnetism, by reducing them to those of one fixed indefinite current. The results of calculation, when applied to considerations of this kind, are found perfectly confirmed by those of experiment. Perhaps the most difficult and the most delicate point is that concerning the assimilation of magnets to an assemblage of circular currents, arranged in a regular manner and constituting ***solenoïds.***

In 1823, M. Savary, in a work to which we have already made allusion, endeavoured to calculate the action of this assemblage, and was on this occasion led to determine $n$ and $k$, by combining the equation $n + 2k - 1 = 0$, originally found by M. Ampère, and $kn + 1 = 0$. This was before M. Ampère had arrived, by the consideration of his fourth case of equilibrium, to determine it in a direct manner from these two constants. M. Savary then found, by calculating the effect of all the actions exercised upon an element of a current, placed at a very great distance, by a succession of circular and very small currents, whose planes were perpendicular to a right or curved line, that all the actions are reduced to two forces, directed according to perpendiculars to the two planes, passing through the element and through the extremity of the solenoïds. The intensities of these forces are in inverse ratio to the squares of the distances by which the element is separated from the extremities of the electro-dynamic cylinder, and proportional to the sines of the angles made by the lines, by which these distances are measured, with the direction of the element. These forces are thus independent of the form of the curve, to which the planes of the circular currents are perpendicular. This law, which M. Savary had deduced simply from the theory of the mutual action of voltaic currents, is the same as that which was the result of the experiments of MM. Biot and

Savart, for expressing the action of a magnet upon an element of a current (NOTE E.). There is a single difference: it is, that the centres of action, which may be substituted for all the circular currents, that constitute an electro-dynamic cylinder, are the very extremities of the cylinder, whilst the centres of action or the poles of the magnet are at certain distances from these extremities. In general, a solenoïd conducts itself like a magnet, having the same axis; and, setting out from the elementary law of the mutual action of two infinitely small currents, calculation leads to results in conformity with experiment, when it is applied to the action of a current of the given form, or a solenoïd, and to the mutual action of two solenoïds.

In his work, entitled *Theory of Electro-dynamic Phenomena*, M. Ampère has confirmed and generalised the results obtained by M. Savary upon solenoïds; and, by the consideration of the fourth case of equilibrium, he succeeded in explaining all the phenomena that are presented by magnets, by considering them as the results of assemblage of electric currents, forming very small circuits around their particles. He showed, in particular, that two systems, composed of very small solenoïds, act upon each other, according to his formula, like two magnets, composed of as many magnetic elements as there may be supposed to be solenoïds in these two systems; one of these systems acts also upon an element of the electric current just as a magnet does; consequently, *all the explanations, all the calculations*, founded both upon the consideration of the attractive and repulsive forces of these molecules in inverse ratio to the square of the distances, and upon that of the resultant forces between one of these molecules and an element of the electric current are necessarily the same, whether the phenomena that produce the magnets in these two cases, be explained by electric currents, or, if we prefer it, by the hypothesis of two magnetic fluids. Neither in these calculations, therefore, nor in these explanations, can objections be sought against Ampère's theory, nor proofs in its favour. These proofs follow rather from its reducing to one action three sorts of actions, which the whole of the phenomena prove to be due to one common cause, which cannot be otherwise reduced; namely, the mutual action of two currents, the mutual action of two magnets, and the mutual action of a magnet and a current. It was at first thought that they all might have been explained by the mutual action of two magnets, by supposing, as we have already mentioned that, from the passage of the electric current in a conductor, there is developed in it a transverse magnetic polarity; but the phenomena of continuous rotatory motion are in complete contradiction to this idea. It was therefore necessary, if M. Ampère's theory were not adopted, to regard the three kinds of action, which he has reduced to one common law, as three sorts of phenomena absolutely independent of each other. In fact, the mutual action of magnetic molecules, if it existed, could not be regarded as the elementary force, since, being proportional to a function of the distance, it could never give rise to the motion, always accelerated and in the same direction, which the phenomena of rotation present. Still less does the elementary force depend upon that which is manifested between a magnetic element and an element of the current; viz. between two bodies in truth of very small volume, but of which one is necessarily compound, whichever manner of interpreting the phenomena be adopted. But if it be the mutual action of the two elements of the current, that is regarded as the elementary force, then we are able to explain all the phenomena; and the mutual action, either of two magnetic elements, or of a magnetic element and an element of a current, are then compound actions; because, in this case, the magnetic element must be considered as a compound. We may remark that although from the whole collection of facts it is natural to conjecture that the three kinds of action depend on a single cause, it is by calculation alone, and without any prepossession as to the nature of the force which two elements of the current exercise upon each other, that M. Ampère has proved, by seeking from the data of experiment alone, the analytic expression of this force, and by demonstrating that from it are deduced the values of the other two, such as they have been also given by experiment.

With regard to the nature of the elementary force, that two portions of conductors, in which electric fluids are moving, exercise upon each other, these effects are so different from those that are manifested when the two fluids are at rest in bodies charged with static electricity, that it has even been assumed that the former ought not be attributed to the same fluids as the latter. This is precisely as if we concluded from the suspension of mercury in the barometer being an entirely different phenomenon from that of sound, that we ought not to attribute them to the same atmospheric fluid at rest in the former case, and in motion in the latter, but rather to two different fluids, one pressing on the surface of the mercury, the other transmitting the vibratory movements that produce sound.

However, there is nothing to prove that the force expressed by M. Ampère's formula cannot result from the attractions and repulsions of two electric fluids in inverse ratio to the squares of the distances of their molecules. Only we must not suppose that these molecules are distributed upon the conducting wires, so as to remain fixed there, and to allow consequently of their being regarded as invariably connected together. In fact, it follows from the principle of the preservation of active forces, which is a necessary consequence of the very laws of motion, that when elementary forces are expressed by simple functions of the mutual distances from the points between which they are exercised, and that a part of these points are invariably connected together, and do not move except in virtue of these forces, the others remaining fixed, the former cannot return into the same situation in respect to the latter, with greater velocities than those which they had when they departed from this same situation. Now, in the movement of continuous rotation that is impressed upon a movable conductor by the action of a fixed conductor, all the points of the former return to the same situation with greater and greater velocities at each revolution, until friction and the resistance of the mercury or of the acidulated water, into which the extremity of the conductor is plunged, set a limit to the increase of the velocity of the rotation of this conductor; it then becomes constant, notwithstanding these frictions and this resistance. We ought, therefore, to conclude, from what has been said, that these phenomena are due to the fact that the two electric fluids traverse the conducting wires continuously, with an extremely rapid motion; and alternately unite and separate in the intervals of the particles of these wires. As soon as we suppose that the electric molecules, when set in motion in conducting wires by the action of the battery or of any other source of electricity, continually change places, as we have just expressed it, it is no contradiction to admit that from the actions, in inverse ratio to the squares of the distance, exercised by each molecule, there might result between two elements of conducting wires a force depending not only on their distance, but also on the directions of the two elements, according to which the electric molecules are moving, and are reuniting to molecules of the opposite kind, in order to recompose neutral fluid, and separating at the following instant to go and recombine with others. Now, precisely and only from this distance, and from these directions, is the force derived, which is then developed, and whose value is given by M. Ampère's experiments and calculations. We shall see in the Fourth Part of this Treatise, the ideas that may be formed of the motion in question, or in other words, on the mode of the propagation of dynamic electricity. What is important here was to prove, independently of all hypotheses as to its nature, the necessary existence of this movement, in order to explain the phenomena classed under the name of *electro-dynamics* by M. Ampère, who was the first to establish this important principle, of which no idea had previously existed.

It was in November, 1826, as we have already said, that M. Ampère published a complete exposition of his mathematical theories of electro-dynamic phenomena, summing up and completing in this work, the curious researches that he had himself made on the same subject since 1820, and to which M. Savary and M. de Montferrand had added some important developments. Since that time little attention has been paid to this branch of electricity; whence it might seem that nothing remained to be done. Two German philosophers, however, MM. Weber and Neumann, resumed it on account of induction currents; the former essentially in an experimental point of view, the latter exclusively in its mathematical relations. I have already made allusion to their works in the chapter on *Induction*, p. 433.; I will confine myself to remarking that these works do not in any way change the fundamental basis of M. Ampère's theory. The same is the case with the recent, and as yet unpublished, remarks of M. Cellerier, which this young philosopher communicated to the Academy of Sciences of Paris, on June 3d, 1850 (*Comptes Rendus de l' Ac. des Scien. de Paris* of June 3., 1850; and *Arch. des Scien. Phys. Biblio. Univ.* t. xiv. p. 211.); and the object of which is to establish Ampère's formulæ and laws, setting out of the question all previous hypotheses, even of the forms to be given to the expression of the action of the forces in play: a work that had become necessary to secure these results from being shaken by the effect of changes that, from the progress of science, may be introduced into the ideas that are formed of the very nature of electricity. In the ignorance in which we are as to the manner in which electro-dynamic actions result from the properties of electric fluids, or are influenced by the ambient medium, it may be that the very simple forms assumed for the action of two elements which could not be directly verified by experiment, may not be exact; and that this action is composed of many distinct forces, and may not have a resultant, directed according to the right line that joins the two elements. In order to know exactly its form and value, we must make it consist of an entirely arbitrary system of forces, which may even have no resultant, and the components and moments of which may be unknown functions of quantities, by which the relative position of the elements is determined. This is the course that was followed by M. Cellerier, and by means of which he succeeded in establishing, upon a still more solid basis, the admirable results that were arrived at by Ampère, and which this philosopher had conceived to be free from all objection, never imagining that the principles from which he set out, and which he had regarded as axioms in mechanics, might be contested.

Finally, a mathematician well known for his beautiful researches in celestial mechanics, and in physical mathematics, M. Plana, directed his attention to the same subject, namely, to dynamic electricity, after having treated, in a remarkable work, the questions of static electricity, which M. Poisson's labours did not appear to him to have made sufficiently clear. To give an idea of the point of view under which he regarded the question of electro-dynamics, I cannot do better than quote what he wrote to me on this subject at the end of December, 1847:—"Ampère's formula is an expression of a law of nature; I know not whether it is *primitive* or *secondary*; but it contains a vast number of consequences of the highest importance, which cannot be disclosed except by the *integral calculus*. Towards the commencement of 1847, I published at Rome two pamphlets upon this subject, but I know not whether they have been much looked into by philosophers, because the difficulties of the calculus do not permit of their being an agreeable subject for reading. The most simple of curves is the circle; but this circle, when traversed by a voltaic current, becomes capable of exercising a force upon an electric element of the same or of the contrary name. Very well! we must employ *elliptic transcendents*, in order to express the resultants of the force that emanates from the periphery of the circle. But this very simple case requires formulæ, the knowledge of which is not generally possessed to the extent that is necessary. Also, Ampère has not given the true formula for the circular current. What he gave, namely, $\frac{n(n-1)}{2} \cdot \frac{ii'\lambda\lambda'}{r^{n+}}$ is erroneous; it should be replaced by $\frac{n^2-1}{2}\left(\frac{ii'\lambda\lambda'}{r^{n+2}}\right)$[*] For the *solenoïd* we must execute integration,

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[*] We have seen that this error produces no change in the results that Ampère drew from his formula.

by retaining several terms of the series, and then the difficulty increases enormously. I have executed it, but I am not yet sufficiently satisfied with it. This does not at all satisfy me; Newton's simple formula of $\frac{A}{r^2}$, cannot be followed into its consequences without frightful calculations. That of Ampère, in which the coefficient A is variable, presents difficulties of another kind, and even facilities, which sometimes form a striking contrast. The poles of solenoïds have no real existence, but things pass on as if they existed. When we take account of the first term alone in the expression of the force that emanates from a solenoïd, we think we see the poles at the extremity; but a more profound examination modifies this mode of viewing it."

M. Plana's own words will serve as my excuse, that I have not entered more into details on the mathematical theory of the action of electric currents; perhaps even the developments that I have given may have appeared, to many of my readers, too considerable. However, they will pardon me, if they will remark that we are concerned upon one of the most important theories of physics, as I said at the commencement of this note. Moreover, I am happy at having had an opportunity of setting forth, although very imperfectly, a portion of the labours of one of the most remarkable philosophers of our epoch; and of showing that time, far from weakening its value, seems, on the contrary, to increase it. We may say that Ampère has been the Newton of Electricity.

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