XXI. *Account of the repetition of* M. ARAGO's *experiments on the magnetism manifested by various substances during the act of rotation.* *By* C. BABBAGE, *Esq. F. R. S. and* J. F. W. HERSCHEL, *Esq. Sec. R. S.*

Read June 16, 1825.

1. THE curious experiments of M. ARAGO described by M. GAY LUSSAC during his visit to London in the spring of the present year, in which plates of copper and other substances set in rapid rotation beneath a magnetized needle, caused it to deviate from its direction, and finally dragged it round with them, naturally excited much attention, and the investigation of their various circumstances, and of their connexion with the effects observed by Mr. BARLOW in December, to be produced by the rotation of masses of iron, and described by him in a paper read to the Society,* became an object of considerable interest. Accordingly, having erected at Mr. BABBAGE's house, in Devonshire-street, an apparatus for setting a copper plate in rotation about a vertical axis by the aid of a turning lathe, we proceeded to try its effect on a magnetized needle suspended over it. The first attempt failed from the use of too small a needle; but this being replaced by a magnetic bar of considerable weight delicately suspended by a silk thread, we had the satisfaction of seeing it deviate several degrees from its point of rest in a direction

* See N°. XIV. of the present volume.

corresponding with that of the rotation of the copper plate; and on employing instead of this bar, a very delicate azimuth compass, belonging to and the invention of Captain Kater, the influence of zinc, brass, and lead was similarly rendered sensible.

2. In this first trial, having neither the command of a very rapid rotation, nor of massive metallic discs, the deviation of the compass observed did not exceed 10 or 11 degrees. In order therefore to enlarge the visible effect, and at the same time disencumber ourselves of the limit set to it by the polarity of the needle, it occurred to us to reverse the experiment, and ascertain whether discs of copper or other non-magnetic substances (in the usual acceptation of the word) might not be set in rotation if freely suspended over a revolving magnet. In order to make this experiment, we mounted a powerful compound horse-shoe magnet, capable of lifting 20 pounds, in such a manner as to receive a rapid rotation about its axis of symmetry placed vertically, the line joining the poles being horizontal and the poles upwards. A circular disc of copper, 6 inches in diameter and 0.05 inch thick, was suspended centrally over it by a silk thread without torsion, just capable of supporting it. A sheet of paper properly stretched was interposed, and no sooner was the magnet set in rotation than the copper commenced revolving in the same direction, at first slowly, but with a velocity gradually and steadily accelerating. The motion of the magnet being reversed, the velocity of the copper was gradually destroyed; it rested for an instant, and then immediately commenced revolving in the opposite direction, and so on alternately, as often as we pleased.

3. The rotation of the copper being performed with great regularity, it was evident that by noting the times of successive revolutions, we should acquire a precise and delicate measure of the intensity of the force urging it, provided we took care to neutralize the torsion of the suspending thread. To make the experiment strictly comparable proved however a matter of much delicacy, as the slightest change in the distance of the plate from the magnet was found to produce a material alteration in the time of its gyration.

4. Our first enquiry was directed to ascertain the effect of the interposition of different bodies as screens in cutting off or modifying the peculiar rotatory effect. The substances tried were, paper, glass, wood, copper, tin, zinc, lead, bismuth, antimony, and tinned iron plate. The comparative effects of these may be seen by the following tabulated observations, in making which we had the advantage of Mr. BARLOW's and Mr. CHRISTIE's presence and assistance.

TABLE I.

No. of revolut. performed.	Times of their performance.					
	Nothing interposed.	Paper interposed.	Wood interposed.	Antimony interposed. 1.	Antimony int. 2d trial.	Antimony int. 3d trial.
0	0.0	0.0	0.0	0.0	0.0	0.0
1	34	36.2	37.2	37.0	36.0	35.0
2	48	51.0	52.2	51.0	50.5	50.0
3	59	62.0	63.5	62.0	61.5	61.5
4	68	71.5	73.0	72.5	71.0	71.0
5	76.5	80.0	81.5	80.5	79.2	79.7
6	83.5	87.5	89.0	88.0	86.5	87.2
7	90.0	95.0	96.2	95.3	93.7	94.0
8	97.0	101.0	103.0	—	100.0	101.0
9	103.5	107.5	109.8	108.0	106.5	107.5
10	109.0	113.5	115.5	114.0	112.5	113.7

TABLE II.

No. of rev. performed.	Times of their performance.				
	Zinc interposed.	Bismuth interposed.	Copper interposed.	Lead interposed.	Tin interposed.
0	0.0	0.0	0.0	0.0	0.0
1	32.0	31.5	32.2	32.0	32.0
2	44.5	44.7	46.0	46.0	45.5
3	—	54.3	56.0	56.0	55.2
4	64.0	63.0	64.7	64.7	64.0
5	72.0	70.7	72.7	72.6	71.5
6	79.0	77.5	79.5	80.0	79.0
7	86.0	84.0	86.0	86.0	85.0
8	92.0	89.8	92.0	92.0	91.2
9	97.5	95.5	97.5	98.0	96.5
10	—	101.6	103.0	103.5	102.2

5. The metallic plates here interposed, as also the wooden ones, were circular discs of 10 inches in diameter and half an inch in thickness, the metals being all cast for the purpose, the wooden disc serving for a pattern. Such only are arranged together as were made under such circumstances as to be strictly comparable. It will be seen by these results that the various substances examined exert no sensible interceptive power, the slight excess of velocity in table 1. col. 1. when nothing was interposed, being evidently referable to the eddy caused in the air by the revolving magnet. Glass in like manner had no effect; but when the substance interposed was iron, the case was widely different, the magnetic influence being greatly diminished by one, and almost annihilated by two thicknesses of common tinned iron plate, as the following table will shew.

TABLE III.

Revolutions performed.	Time occupied.		
	Paper interposed.	One sheet of tinned iron interposed.	Two sheets of tinned iron interposed.
0	0.0"	0.0"	0.0"
½	- -	89.7	164.7
1	22.5	128.2	—
1½	- -	159.5	—
2	31.5	186.7	—
2½	- -	211.5	—
3	38.5	234.7	—

When the poles of the revolving magnet were connected by a piece of soft iron, the rotation of the copper disc was in like manner almost entirely annihilated.

6. Resuming now the original form of the experiment, the copper disc of 10 inches diameter and $\frac{1}{2}$ inch thick, was placed on the vertical axis, and made to revolve with a velocity of 7 turns in a second, a velocity which it was found convenient to give, and easy to maintain, corresponding as it did with one stroke per second of the treadle of the lathe; and this velocity, unless the contrary is mentioned, is to be understood of all the rotations so communicated, spoken of in the remainder of this account.

7. The copper plate thus revolving, the disc of copper mentioned in Art. 2 was suspended over it; but though at first it seemed to be very slightly affected, yet on frequent and most careful repetition of the experiment, with every precaution to guard against currents of air, not the most trifling effect could be perceived. This remarkable result, while it stands opposed to any theory of magnetic vortices generated by the rotation of one body, and transferring a part of its motion to others, is, on the other hand, perfectly consonant with, and indeed a necessary consequence of the view which will be taken of the subject in the sequel.

8. In like manner a bar of hardened, but not magnetised steel, was very slightly, if at all, set in rotation by the revolving copper, not more than probably would correspond to the small degree of magnetism unavoidably developed in it in the act of hardening; but when magnetised to saturation, it was made to revolve rapidly. This experiment appears decisive as to the origin of the magnetic virtue exhibited by

the copper and other bodies in these experiments. It is obviously *induced* by the action of the magnetic bar, compass needle, &c. on their molecules.

9. Our next enquiry was directed to the degree in which this developement of magnetic virtue takes place in different metals and other bodies. For this purpose two different processes were adopted. The first consisted in securing each of the 10-inch discs already spoken of successively on the vertical axis of our machine (which was now fitted up more firmly). Giving them thus a rotation in their own planes, the azimuth compass above mentioned was placed on a convenient stand centrally over each at the same distance. The deviations observed, and the ratios of their sines to that of the deviation produced by one of them (copper) chosen as a standard, were as follows.

TABLE IV.

Name of the revolving body.	(Motion of the disc direct, or screwing.)	(Motion retrograde, or unscrewing.)	Mean.	Ratio of the force to that of copper.
	° ′	° ′	° ′	
Copper -	11 30	11 17	11 24	1.00
Zinc - -	10 7	10 15	10 11	0.90
Tin - -	5 30	5 12	5 21	0.47
Lead - -	2 50	2 55	2 53	0.25
Antimony -	1 12	1 17	1 16	0.11
Bismuth -	0 6	0 6	0 6	0.01
Wood - -	0 0	0 0	0 0	0.00

The experiment was repeated (some weeks afterwards), placing the compass (by a more advantageous adjustment of the apparatus) much nearer the revolving disc. The results were as follows.

TABLE V.

Name of the revolving substance.	Mean of deviations screwing and unscrewing.	Ratio of force to that of copper.
Copper -	28° 54′	1.00
Zinc - -	26 42	0.93
Tin - -	12 54	0.46
Lead - -	7 0	0.25
Antimony -	2 27	0.09
Bismuth - -	0 32	0.02

Agreeing as nearly as could possibly have been expected with the foregoing.

10. The extension of the same mode of examination to other simple and compound bodies, differing widely in their relations to heat, electricity, gravity, and other chemical and mechanical agents, presents an extensive and most interesting field of enquiry, and one which promises a nearer insight into the nature of magnetism, both permanent and transient, than we have yet attained. Our examination has necessarily been limited, partly from the imperfection of our apparatus, but chiefly from want of time; indeed on reperusing the present notice, it is impossible not to regard it as in many respects imperfect and hasty; and nothing certainly but the strong interest of the subject, and the uncertainty whether we shall have it in our power to prosecute it with greater assiduity in future, could induce us to present our results in their present state. Such as they are, however, we shall give them.

11. Of the other metals, silver appears to hold a high rank, and gold a very low one in the scale of magnetic energy. Indeed the latter metal rendered standard by copper was

scarcely more powerfully set in rotation than seemed fairly attributable to the quantity of its alloy.

12. The examination of mercury presented peculiar interest from its fluidity, and the facility with which iron might be excluded from the experiment; to make which, a flat ring of box-wood was cemented with wax between two circular glass discs, so as to form a hollow cylinder, 2 inches in internal diameter, and 0.10 in its interior height. This being suspended, empty, by a long delicate silk thread over the horse-shoe magnet, was not in the slightest visible degree affected by its rotation, however long continued. It was then detached and filled with mercury, which, from having been thrice distilled, and afterwards having stood upwards of a twelvemonth in a bottle in contact with a solution of the nitrate of that metal, might assuredly be regarded as absolutely free from iron. Being again suspended as before, it now readily, though feebly, obeyed the rotation of the magnet in either direction, being fully commanded by it, and set in motion, stopped, or reversed in its gyrations at pleasure by merely continuing or changing properly the motion of the magnet. This experiment was witnessed, among others, by our illustrious President. The place which mercury appears to hold in the scale of magnetic energy was judged to be between antimony and bismuth, certainly superior to the latter, and certainly inferior to lead.

13. In wood, glass, wax, rosin, sulphur, sulphuric acid, water, &c. we have not hitherto succeeded in obtaining unequivocal traces of magnetism. The experiment with unannealed glass succeeded no better than with annealed. In the case only of one non-metallic body (unless a minute portion

of iron present may have deceived us) a decisive result has been obtained; and, what is very singular, this body is carbon, in that peculiar state in which its density, lustre, degree of hardness, and high conducting quality, both as regards heat and electricity, seem to give it some title to a place among the metals. This is the state in which it is precipitated by a red heat from coal-gas. It is found in thick masses encrusting the interior of the retorts, gradually blocking them up, and in time rendering them useless. It is composed of coats frequently curved round a centre, and exhibiting a radiated structure, but oftener in laminæ of a fine close grain, a beautiful gray colour, and in some varieties of a shining metallic brilliancy, between that of plumbago and hardened steel; some portions yield readily to the knife, but others of a darker hue and dull earthy fracture, resist obstinately, and give copious sparks with steel. The two sorts are found alternating or intermixed in the same specimen. The magnetism developed in this singular substance is, however, too feeble to admit of precise measurement, and is only rendered barely sensible by delicate management.

14. The second process alluded to as employed by us to compare the relative magnetic forces of the different bodies examined, consists in suspending magnetised bars over revolving discs of them, and observing, not the point of equilibrium but the velocity generated, or the time required for the description of certain spaces; in other words, by measuring not the statical, but the dynamical effect. These methods, for distinction's sake, may be called he statical and dynamical methods of observation.

In the original experiment of M. Arago, a magnetic needle was made to deviate or revolve by the rotation of a plate beneath it. The motion of the needle must of course be rendered irregular by the effects of its polarity, and subject to periodical accelerations or retardations; and it is obvious, that in the case of a very weak magnetic force in the plate it can never execute an entire revolution, but must oscillate backwards and forwards till reduced to rest by the friction and resistance of the air. It occurred to us, however, that much more regular and uniform results might be obtained by this means, could the polarity of the needle be destroyed without at the same time destroying its magnetism; in other words, could the earth's action on it be so precisely neutralised as to allow of its resting indifferently in all directions. The obvious mode of doing this, by the approach of a powerful magnet acting in opposition to the earth, proved much too coarse for our purpose, which however, after a few trials, we found might be accomplished to any required degree of precision by the following simple contrivance.

If two exactly equal and similar magnets of equal strength be placed parallel to each other, but in a reverse position, and at such a distance as not mutually to affect each others' magnetism, and if in this situation they be firmly attached to a piece of wood, glass, &c. the system so formed will have no polarity, i. e. no tendency to rest in one rather than another situation, however suspended. This is clear; because whatever be the inclination (θ) of one of the magnets to the line of dip, that of the other will necessarily be ($180 + \theta$), and the directive forces being represented by the sines of these two angles will always be equal and opposite, so that each magnet urges the system with equal force, but in opposite directions. The truth of this proposition, it is no less evident, is independent of the axis of suspension, which may pass through a part of the system any how situated with respect to the magnets, in virtue of the property of a magnet whose force to turn a system of which it makes a part, round a fixed centre, is the same wherever in the system it is placed, and the same as if it were in the centre.

Hence it follows, that if two equal and similar magnets be laid parallel to each other, but in a reversed position on a horizontal glass plate freely suspended by a thread, the system will be devoid of any polar tendency, (which we shall express by calling such a system *neutral).* It is difficult however to procure two magnets exactly equal, and of equal force. But fortunately this is of no consequence, as a slight deviation from perfect neutrality may be corrected by inclining the stronger needle a little more or less to the plane of the plate. In fact the proposition is general; and by a proper adjustment of the positions of two magnets however unequal, with respect to the axis and to each other, they may be made to neutralize each other.

15. As this adjustment however is nice, and as magnets influence each other, and our object moreover called for the utmost delicacy, we adopted a more refined application of the principle just detailed. A circular glass disc was prepared, 8 inches in diameter, and suspended by three silk threads from a filament of silk, descending along the axis of a copper tube about 5 feet long, passing with stiff friction through collars in the cieling of the apartment, and serving nicely by means of an index to regulate the height of the glass disc.

At the opposite extremities of two diameters at right angles to each other, four equal small bar magnets were fixed in a vertical position, having alternately their north and south poles downwards. This position promised to present two material advantages; first, that in neutralizing the system we have not the whole polarity of the magnets to contend with, but only the small remains of directive tendency which arises from the magnetic axis in each not being precisely coincident with its axis of figure, since it is evident that an infinitely thin magnetic cylinder placed perpendicularly to the horizon, would from that cause alone be indifferent as to situation; 2dly, That in this situation their poles interfere with each other's action on the plate revolving below them, less than in any other. Instead of four we might (and as will be seen) occasionally did place a greater number of magnets round the circle, or within its area, but for the experiments now in view four were enough.

16. The system so constructed was found to require no after adjustment, being to all appearance perfectly neutral, so that this part of our purpose was completely accomplished, and the earth's action eliminated from the enquiry. The irregular torsion of the silk thread however still embarrassed us a good deal. But though this undoubtedly caused individual results to differ more from the mean than we had expected, it is not sufficient to account for a singular anomaly observed not only in the mean results of a great number of trials, but in all individual cases; viz. that by this mode of observation, zinc was invariably found to stand above copper in the scale of magnetic action, whereas in the determination by the statical method, where the deviation of

the compass was observed, the former metal was as invariably found to be placed below the latter, the other metals retaining their order. A possible explanation of this anomaly (should future experiments show that the fact depends on no fallacy) may be found in the principles hereafter to be explained, but we wish to be understood as speaking with reserve on this point.

17. The following table is constructed in the same way as Tables I. II. III. with the addition only of the accelerating forces deduced on the supposition of uniform acceleration from the expression $\frac{s}{t^2}$.

TABLE VI.

N° of revolutions or parts, $s =$	Times of their performance. For					Forces deduced from the expression $f = 1000000 \frac{s}{t^2}$				
	Copper $t =$	Zinc $t =$	Tin $t =$	Lead $t =$	Antimo. $t =$	Copper $f =$	Zinc $f =$	Tin $f =$	Lead $f =$	Antim. $f =$
0.25	38.3	36.1	51.7	70.9	109.6	170	192	93	42	21
0.50	54.2	51.7	74.8	102.5	157.9	170	187	89	48	20
0.75	68.5	63.9	92.8	128.0	197.4	160	184	87	46	19
1. 0	79.8	74.0	107.8	151.2	232.4	157	183	86	44	19
2. 0	110.6	106.2	156.8	221.8	351.7	164	177	81	41	16
3. 0	136.9	131.4	195.5	281.3	460.7	160	174	78	38	14
4. 0	160.0	152.8	229.5	335.0	—	156	171	76	36	—
5. 0	180.4	172.8	260.3	385.6	—	153	167	74	34	—
Mean of all - -						161	179	83	41	—
Mean of first six - -						163				18

The effect of torsion, resistance and friction, is very evident in the apparent diminution of the accelerating force in each revolution, so that only the numbers in the same horizontal lines can be regarded as comparable. Comparing accordingly the means of all for copper, zinc, tin, lead, and of the six first for copper and antimony, the proportional intensity of magnetic action for each respectively will be

Zinc - -	1.11
Copper - -	1.00
Tin - -	0.51
Lead - - -	0.25
Antimony - -	0.01

The smallness of the number for antimony is here also very remarkable. That for bismuth deduced by this means would be still more minute, so small indeed that the torsion of the thread would not allow of its magnitude being fairly determined, the suspended system merely performing extensive oscillations in very long times.

18. This method however requires us to operate on very considerable quantities of the substances under examination, a great disadvantage, as it cannot be applied to the scarcer metals, and does not admit of the use of the common ones in a state of rigorous purity. A method at once more simple and expeditious, and allowing of our acting on small quantities of matter, is to suspend portions of the different bodies we would try, similar in form and exactly equal in size, over the revolving magnet, and noting either, dynamically the times of successive revolutions, or, statically the point of equilibrium between the rotatory force and the torsion of the string. This method we pursued in a very interesting part of the enquiry, viz. in investigating (after M. ARAGO) the effect of a solution of continuity, partial or total in the mass acted on.

19. A disc of lead of 2 inches in diameter and $\frac{1}{10}$ thick, was suspended in a small thin wooden tray at a given distance from the horse-shoe magnet, revolving with the usual velo-

city, at first entire, and then successively cut with a chisel in radii nearly up to the centre, as here represented.

Fig. 1.

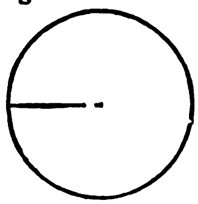


Fig. 2.

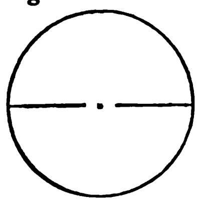


Fig. 3.

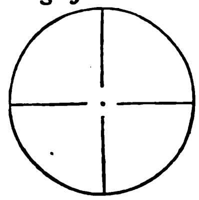


Fig. 4.

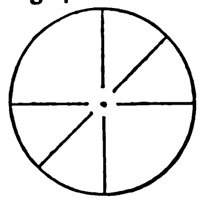
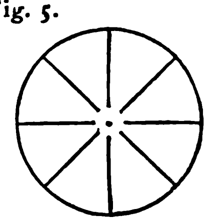


Fig. 5.



The times observed and forces deduced in the several cases were as follows:

Rev.	Disc uncut.		Disc cut as in Fig. 1.		Disc cut as in Fig. 2.		Disc cut as in Fig. 3.		Disc cut as in Fig. 4.		Disc cut as in Fig. 5.	
	$t=$	$f=$	$t=$	$f=$	$t=$	$f=$	$t=$	$f=$	$t=$	$f=$	$t=$	$f=$
1	28.2	1258	30.9	1047	33.1	913	42.1	564	48.1	432	55.6	324
2	41.2	1178	44.5		47.4		59.8		69.0		81.4	302
3	50.6	1172	55.0		59.0		74.7		86.6		103.3	281
4	58.7	1161	63.9		68.3		88.3		102.1		124.5	258
5	66.4	1134	72.0		77.2		100.0		115.8		145.9	235

Similar effects were observed in other metals, but in different degrees. For instance, in the case of soft tinned iron, the same number of cuts, made in the same manner, produced a very slight diminution of force, while in copper the effect of the same operation was to reduce the force in the ratio of 1 to 0.20.

20. A thin disc of copper suspended at a given distance over the revolving magnet, performed 6 revolutions from rest in 54ˢ. 8. It was then cut in 8 places in the direction of radii nearly up to the centre and 45° asunder, by which operation its magnetic virtue was so weakened, that it now required 121ˢ.3 to execute the same number of revolutions. The cuts were now soldered up *with tin*, and the magnetic action was now found to be so far restored as to enable it to

perform its six revolutions in $57^s.3$, that is to say, very nearly in the same time as when entire. This is the more remarkable, since tin, as we have seen, is not above half so energetic as copper when acting directly. This indirect mode of action therefore affords us a means of magnifying small magnetic susceptibilities which may hereafter prove very valuable.

21. To illustrate this more strongly, we suspended a brass disc of $2^{in}.25$ in diameter, and $0^{in}.15$ in thickness, as in the last case, and noted the time of its performing successive revolutions, as follows:

1 rev.	2 rev.	3 rev.	4 rev.	5 rev.
$20^s.2$	29.1	35.2	40.8	45.7

It was now cut, as in the last case but it being necessary for this purpose to use a saw, the abraded portions, which were pretty copious, were strewed over it with the intervention of a piece of thin paper, to obviate the effect of loss of weight, as nearly as might be. The times were now found increased as follows:

1 rev.	2 rev.	3 rev.	4 rev.	5 rev.
41.1	57.9	71.0	83.0	93.7

being almost exactly doubled, and of course the force was reduced in the ratio of about 4 to 1.

The cuts were now cleanly soldered with bismuth; and though, as we have seen, the direct force of bismuth is so small as to be scarce perceptible, yet its indirect effect in restoring the magnetism of the brass was such as to cause the same arcs to be described in the following numbers of seconds.

1 rev.	2 rev.	3 rev.	4 rev.	5 rev.
28.2	39.7	48.4	56.3	63.0

which require the exertion of an accelerating force more than double of that developed in the last trial.

The bismuth was now melted out, and the cuts being carefully washed with melted tin, were filled with fresh tin, which was allowed to fix, and the disc being trimmed, and replaced, the times were now found to be

21.7	30.8	38.0	43.5	48.7

The restoration of energy, as in the case of the copper disc is here very manifest, the times of rotation being nearly reduced to their original magnitude. The comparison of these, reduced by the formula $f = 1000000 \frac{s}{t^2}$, and the means of the five results taken in each case, gives for the accelerating forces

Brass, uncut	1.00	Copper uncut		1.00
cut	0.24		cut	0.20
soldered with bismuth	0.53		soldered with tin	0.91
soldered with tin	0.88			

The effects of soldering with lead and with fusible metal were also tried, and found to be both represented on the same scale by the same fraction, viz. 0.85, being but very little inferior to tin.

22. When the soldering is imperfect, the effect in restoring the magnetic action is proportionally weaker, but the influence of ever so small a free metallic communication is sensible.

23. A disc of lead cut in 8 radii as above was found to make one revolution in 58^s.3. It was then wetted so as to fill the cuts with sulphuric acid, and the time of revolution was found to be 57.3; so that the influence of sulphuric acid,

even when thus magnified, is still equivocal; and its magnetism, if it exist, can hardly be estimated at a thousandth part of that of copper, and is probably still lower.

24. The reduction of the metals to filings or to powder, was found to produce a still more striking diminution of their magnetic energy; and a class of experiments of great interest, as to the effect of the agglutination of these powders by metallic and non-metallic cements and liquids, immediately presents itself, into which want of leisure only has hitherto prevented our entering, as well as on the important subject of the magnetism of metallic alloys and atomic combinations, with which this branch of the enquiry is essentially connected.

25. When we come to reason on the above facts, much caution is doubtless necessary to avoid over-hasty generalization. Whoever has considered the progress of our knowledge respecting the magnetic virtue, which, first supposed to belong only to iron and its compounds, was at length reluctantly conceded to nickel and cobalt, though in a much weaker degree—then suspected to belong to titanium, and now extended, apparently with an extraordinary range of degrees of intensity to all the metals—will hardly be inclined to stop short here, but will readily admit, at least the probability, of all bodies in nature participating in it more or less. Yet if the electro-dynamical theory of magnetism be well founded, it is difficult to conceive how that internal circulation of electricity, which has been regarded as necessary for the production of magnetism, can be excited or maintained in non-conducting bodies. Without pretending to draw a line however, in what is perhaps at last only a question of degree, one thing is certain, that all the unequivocal cases of mag-

netic action observed by us, lie among the best conductors of electricity.* Another feature, no less striking, is the extreme feebleness of this species of action compared with that which takes place in cases of sensible attraction and polarity. This will appear more evidently, if we consider the mode of action which probably obtains in these experiments, and the mechanism, if we may so express it, by which the effects of such almost infinitesimal forces are rendered perceptible in them.

26. The rationale of these phænomena, as well as of those observed by Mr. Barlow in the rotation of iron, which form only a particular case (though certainly the most prominent of any) of the class in question, seems to depend on a principle which, whether it has or has not been before entertained or distinctly stated in words, it may be as well, once for all, to assume here as a *postulatum*, viz. that *in the induction of magnetism, time enters as an essential element*, and that *no finite degree of magnetic polarity can be communicated to, or taken from any body whatever susceptible of magnetism, in an instant.*†

* The meagre statements and imperfect reports which have hitherto reached us of M. Arago's researches, had prepared us to expect a much more appreciable amount of magnetic force in non-metallic bodies than we have observed. Glass, wood, water, ice, and indeed every description of substance, have been included in the list of bodies capable of producing a notable deviation from the magnetic meridian in a suspended bar, by their rotation. This naturally renders us desirous of seeing that eminent philosopher's own account of the means employed by him to render sensible such very minute forces, which must have been unusually delicate. This may perhaps be the proper place to mention, that the numerical estimates in this paper are merely intended to be received as gross approximations, valuable only in the absence of all other information of the kind. The metals used were those of commerce, no pains having been taken to free them from iron. Much refinement would have been thrown away on such materials.

† It is now some years since one of the authors of this account (Mr. Babbage)

27. This principle will, if we mistake not, be found to afford at least a plausible explanation of most, if not all the phænomena above described, without the necessity of calling in any additional hypothesis, or new doctrine in magnetism. For the other principle we shall have occasion to employ, that magnetic bodies differ exceedingly, both in *susceptibility* of this quality and in the degree of the pertinacity with which they retain it (which may be called their *retentive* power), is not an hypothesis, but an acknowledged fact. It is only in the mode of its extension to new cases of *magnetics* that we can be led into any fallacies. Whether these two qualities (susceptibility and retentive power) be, or be not mutually dependent, this is not the place to enquire. Probably they are not so, at least directly: and the new facts almost convert this probability into certainty; at all events, at present we shall for greater generality suppose them independent.

observed the following facts, which set the principle stated in the text in a very clear light. A natural magnet, armed with soft iron, terminating in a cylindrical surface, was made to support a load hooked on to another piece of soft iron, terminating also in a cylindrical surface, so that its contact with the former was limited to a physical line. The weight it would usually support varied from 27 to 33 lbs., according to the caution used in increasing the load. On loading it with 30 lbs. it became necessary to add the remaining weight by degrees, a quarter of a pound at a time, and to wait a short time after each addition. At about 32½ lbs. the weights usually fell from the magnet, and it was observed on replacing them, that it would no longer support more than 30, and that some minutes must be suffered to elapse before it could be brought to its former load. It was thus evident that the magnet required time for the developement of its full virtue. Again, having loaded the magnet by degrees up to 32 lbs., if the contact was broken for an instant by seizing the iron to which the load was suspended with both hands, detaching it suddenly and instantly restoring it, the magnet now continued to suspend 32 lbs., though, had the separation been of longer duration, 30 only would have been suspended. Time therefore is required to lose, as well as to gain magnetism.

28. Conceive now a plate of any thickness, and of indefinite superficial extent, of a metal or other magnetic, whose retentive power is very small. If either pole (suppose the north) of a magnet be brought vertically over a point in its surface, it will there produce a pole of the contrary name in the plate, the maximum of polarity being immediately under the magnet. Now let the magnet be moved horizontally along the surface, preserving the same distance from it. The points over which in succession it becomes vertical, not *instantly* receiving all the magnetism of which they are susceptible, will not have reached their maximum of polarity at the precise moment of nearest appulse, but will continue to receive fresh accessions during the whole of that certain small portion of time when the distance (being at or near its minimum) undergoes no change, or only a certain very minute one. In like manner, the points which have attained their maximum of polarity, being left behind by the magnet, will by degrees lose their magnetism; but the loss not being sudden, they will continue near their maximum for a certain finite time, during the whole of which the magnet continues receding from them, and leaving them farther and farther behind. Thus from both causes, there will be always in arrear of the magnet a space both more extensive and more strongly impregnated with the opposite polarity, than in advance of it; and as the magnet moves forward, the point of actual maximum (or the pole) of the plate, instead of keeping pace with it and being always precisely under it, will lag behind. There will thus arise an oblique action between the pole of the magnet and the opposite pole of the plate so lagging behind it; and were the plate free to move in its own plane, the resolved portion

of this action parallel to its surface, would continually urge it in the direction of the magnet's motion.

29. But besides the attracting pole of the opposite name (south) produced by the (north) pole of the magnet at the spot immediately under it, there will also be developed a corresponding repulsion or north polarity in the plate. This however will not, like the attractive, be concentrated nearly in one spot immediately below the magnet, but must of necessity be diffused round it in a much less intense and more uniform state throughout the more distant parts of the mass, and may be conceived as arranged in spherical or other concave strata about the point vertically under the magnet as a centre. Now when the magnet by its motion is carried out of the axis of these strata, it is obvious that the resultant force of each of them will be less and less oblique to the surface as its radius is greater. The general resultant therefore of all the repulsive forces exerted throughout the whole extent of the plate is necessarily less oblique to the surface than that of the attractive ones, whose influence, from this cause alone, must therefore preponderate, and must necessarily produce a *dragging* or oblique action, such as above described. This force, however minute, acting constantly, must at length produce a finite and sensible velocity, provided the whole mass of the plate to be set in motion be finite, and the force of the magnet sufficient to overcome friction, resistance, &c.

30. Vice versa, if the plate be drawn along in its own plane, and the magnet be free to move in a horizontal direction, the former ought to drag the latter along in the same

direction with a velocity continually accelerating, till they move on together with equal velocities.

31. It is manifest that, cæteris paribus, the greater the relative velocity, the more will the pole developed in the plate lag behind the magnet, or the magnet (in the reverse case) behind the pole. The more oblique therefore will be the action, and the greater the resolved part of the force, and the velocity produced by it dato tempore. The same effect must also be produced by an increase in the absolute force, or lifting power of the magnet; so that in such experiments there is an advantage in using large magnets which have great lifting powers, over small ones with intense directive forces, and this is perfectly consonant to experience.

32. Hitherto we have only considered the case of rectilinear motion. If we regard the magnetism of the plate as very transient, and the velocity moderate, the whole space occupied by the magnetised portion of the plate will still be small, and confined to the immediate neighbourhood of the point vertically under the magnet. If the motion of the latter change its direction, the momentary pull communicated to the plate will always be in the direction of a tangent to the curve described. If therefore it describe a circle, it will tend at every instant to impress a gyratory motion on the plate about a centre vertically under the centre of its own motion, and vice versâ, if the plate be made to revolve about a centre, it will tend to drag the magnet round with a continually accelerated motion, provided its rectilinear recess from the centre of motion (or its centrifugal force) be prevented by a proper mechanism. The former is the case of a disc of copper suspended by its centre, and set in rotation by a

magnet revolving beneath it. The latter is that of a compass needle, or of our neutralised system of vertical magnets suspended over a revolving disc of copper. A very pretty illustration of the direction of these forces is obtained by suspending a circular disc of zinc or copper from the end of a counterbalanced arm, which is itself suspended by its middle, thus constituting a kind of double balance of torsion. If the length of the arm be so adjusted, that the circumference of the disc shall be an exterior tangent to the circle described by the poles of a revolving magnet, the whole disc will be swept round in an orbit concentric with the motion of the magnet, while it at the same time acquires a rotatory motion on its own centre in the contrary sense. The centrifugal force is here overcome by the arm and the weight of the disc, and the velocity goes on accelerating till the increase of resistance puts a stop to further accessions.

33. In Mr. BARLOW'S experiments, the earth is our inducing magnet; its two poles both act on every particle of the revolving shell employed in that gentleman's experiments, and their action when complete produces two poles, a north and a south, at opposite extremities of the diameter parallel to the dip. This is the case when the shell is at rest. Let it now be set in motion about any axis, anyhow inclined to the dip. If the communication and loss of magnetism were instantaneous, the places of the poles (i. e. the points of maximum polarity) would be unaffected by the rotation; but as that is not the case, these points, in virtue of the principles already stated, will shift their places, and decline from the direction of the dip in the same direction as the shell's motion, that is to say, in the direction of a tangent to a small

circle, whose axis is the axis of rotation, and whose circumference passes through the extremities of the diameter parallel to the dip. The extent of this declination will depend on the velocity of rotation and the diameter of this small circle, and will be proportional to both, that is, to the velocity of rotation multiplied into the sine of the angle made by the axis of rotation with the direction of the dip. It will therefore be a maximum when the axis of rotation is perpendicular to the magnetic meridian, and vanish when the shell is made to revolve on an axis parallel to the line of dip. These consequences are perfectly consonant to the results obtained by Mr. BARLOW in his paper; and in fact, the general result announced by him in (page 326 of this volume) comes to the very same thing as above stated; for it is obvious, that the new axis of polarization there spoken of, acting in combination with the original, or, as we may call it, the primary axis developed in the quiescent state of the shell, will exert a compound force on the needle, such as would be exerted by a single equivalent axis situated intermediately between them, but much nearer to the more intense than to the more feeble one. The position of this equivalent axis will necessarily be in the great circle passing through the two component ones. Now the small circle described by the point which was first the pole of the stronger or primary axis about the axis of rotation is a tangent to this great circle, and the equivalent axis (being but little removed from the primary one, by reason of the small intensity of the other), will therefore have its pole situate indifferently in either circle. Or conversely, the single axis produced in our view of the subject being resolved into two; one of which is that corresponding to the quiescent state of the shell, and the other 90° removed from it in the same place, this latter will be identical with Mr. BARLOW'S secondary axis.

34. In what has been said, the velocity of rotation has been supposed commensurate to the velocity with which magnetism is propagated through the iron of the shell. But if we conceive in this, or in the general case, either the retentive power of the shell, disc, or lamina great, or the velocity of motion excessive, it may be instructive to consider the modifications thus introduced into the effect. It is evident that the induced pole will lag farther and farther behind the magnet in proportion as either of these conditions obtains. In the case of rectilinear motion, this will, up to a certain point, increase the oblique action, and the dragging effect will be strengthened; but if the velocity be excessive, or the retentive force considerable, as in steel, the pole may lag so far behind as to carry it altogether out of the sphere of the magnet's attraction; and the magnetised portion, remaining within its limits, may have not had time enough to acquire a high degree of polarity. From both causes the drag (the expression, though uncouth, is convenient) should be weakened. In the case of circular motion this effect may go so far, that a complete circumference shall have been described before the polarity of any one point shall have been either completely induced, or completely destroyed. In this case the effect observed will be a general weakening of the total polarity of the disc or sphere; and (supposing the latter of iron, or soft steel) a directive virtue on a small compass needle placed near it, not probably towards any particular place, but to a resultant imaginary point depending on the

situation of the compass, the dip, and the axis of rotation, by laws not very easy to assign. This will explain some expressions quoted by Mr. BARLOW from his correspondence with one of the authors of this paper, which may appear otherwise to militate against the general view here taken.

35. This diminution of the total effect by a more general distribution of the magnetism, was imitated by sticking a great number of needles vertically through a light cork circle, all being strongly magnetised, and having their north poles downwards, so as to form a circle, or, as it were, a coronet of magnets. This apparatus suspended centrally over a revolving copper disc, was not sensibly set in rotation. In this case, when at rest, the south polarity induced in the plate would be disposed in spots accumulated under each needle; but these spots, elongated and blended by the effect of rotation, must produce a nearly uniform circle of south polarity, whose equal and contrary actions on all the needles would keep up the equilibrium, and prevent the coronet from acquiring a tendency either way.

36. One consequence of this reasoning, which deserves trial, is this—that if the axis of rotation of an iron shell be situated in the direction of the dip, the spots occupied by its poles will not change their places by rotation, and consequently no deviation of the compass ought to take place from that cause. The experiment however is very delicate; and care must be taken to remove any magnetised bodies whose influence might induce subordinate poles in the shell, whose places would shift by rotation. The compass therefore in this case cannot be neutralized by a magnet;* but we must

* In Mr. BARLOW'S experiments, the large and powerful bar magnets used to

have recourse to some neutral system, such as that described in the foregoing pages, in its place, or it may be left unneutralized. It ought too to be so small, or so remote, as not to produce induced polarity in the shell, which would react on itself when the sphere is set in motion, and destroy the success of the experiment.

37. The effect of a solution of continuity in the revolving bodies comes next to be considered. It is difficult; but the difficulty is not a consequence of our principles of explanation, but of our ignorance of the very complicated laws which regulate the distribution and communication of magnetism in bodies of irregular figure. So far however as the operation of the general principle can be traced, its results are consonant to observation.

38. In the first place, it is obvious that where one or more slits are cut in a metallic plate, over which the pole of a magnet is revolving, that immediate and free communication between particle and particle, on which probably the rapid, and certainly the intense developement of magnetism depends, is destroyed. The induced pole (by which we mean now the whole of that space in which sensible magnetism is developed, and which is, of course, a spot of sensible, and probably considerable magnitude—of a figure more or less elongated according to the velocity of the motion)—instead of travelling regularly round, retaining a constant magnetism and force, will now be in a perpetual state of change. Instead of being carried uniformly across the slit, it will die away in intensity, and shrink into a point in dimension on the hinder

neutralize the earth's action on the compass needle, cannot be without some disturbing influence of this kind.

side, and be again renewed on the side in advance, but at first not in its full intensity; so that it is not merely the diminution of surface arising from the abstraction of a part of the metal, but a much more considerable defalcation of magnetic force which takes place on either side of the slit, that operates. Now this operation is always to weaken the drag between the magnet and the disc, and no reason, a priori, can be assigned why this effect should not take place to any extent.

39 The validity of this reasoning is shown by taking the extreme case in which the substance acted on is in the state of powder. Each particle of this becomes necessarily a feeble magnet, and its north and south poles, being at the same distance (almost precisely) from the pole of the magnet, counteract each other's action. The extreme feebleness of their magnetism prevents the particles from affecting each other by induction across the intervals which separate them; so that each acts as an individual, and destroys in great measure its own effect. The moment however a *metallic*, i. e. *a magnetic contact* is established between them, their mutual induction acts, and the result is a general developement of one polarity in the region adjacent to the magnet; and of the other, feebler and more diffused, in the parts of the mass remote from it. This is probably the rationale of the restoration of virtue which takes place when a cut disc is soldered up. And it is not difficult to conceive that a weak magnetism may be thus very faithfully transmitted through substances, such as bismuth and lead, whose direct action is very small, because, as we have seen, the intensity of their direct action depends, for one of its causes, on the retentive

power of the substance, which is out of question in the indirect mode of action here considered. In fact, if the retentive power of the solder were reduced to nothing, i. e. if it gained and lost magnetism instantaneously, it would still act as a conductor, and probably the better for this quality; so that the communication between opposite sides of a slit, or contiguous portions of two adjacent particles of a powder, would still be kept up by it, provided it were susceptible of magnetism at all. The observed and very striking fact then of the powerful action of bismuth as a conductor, while its action as a magnet is so extremely feeble, is in itself a strong argument for the independence of these two qualities, which we have designated by the expressions—*susceptibility*, and *retentive power*, and may possibly be made the foundation of a mode of distinguishing and measuring their degrees in different substances.

C. B.

J. F. W. H.