A Closer Look At Joseph Henry's Experimental Electromagnet

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Abstract

In 1830, Joseph Henry published a paper describing several experiments performed with a large experimental electromagnet. This electromagnet is highly valued from both a historical and scientific standpoint, and greatly contributed to Henry's research and the advancement of electromagnetism as a whole. Henry's experiments provide us with a tool for studying and teaching electromagnetism. We attempt to explain and match Henry's experiments with present day models of magnetic saturation, inductance, and hysteresis; using modern day equipment and a replica electromagnet. Furthermore, we have studied this electromagnet closely, and have made several conclusions about the current state that it is in today.

Contents

I.   INTRODUCTION

This study is about Joseph Henry's "experimental electromagnet" or "Albany Magnet". It was his first magnet constructed on a large scale, and at the time (1830) it was also the most powerful.[1] Joseph Henry was a great American scientist responsible for advances in electromagnetism during the 19th century that led to the development of apparatuses such as the modern telegraph, transformer, ammeter, and electric motor. Henry set out to improve the electromagnet design made by William Sturgeon, an English Physicist. Insulated wire was not available at that time, so Henry used silk or cotton to insulate his wires, drastically improving the capabilities of the electromagnet. This improvement allowed Henry to increase the strength of the electromagnet, and create many other types of electromagnetic apparatuses.

In the 1830's, many laws of electricity and magnetism had not been published to guide Henry's research. Instead, he made his own observations and inferences while experimenting with various combinations of voltage, current, and resistance in his electromagnets and batteries. Henry demonstrated several of his different scientific instruments to aid in his teaching. Specifically, his experiments with the Albany magnet are an important part of his research and teaching of electromagnetism. Henry's published Albany magnet experiments, along with the actual artifact displayed at Princeton University, is of substantial value as a teaching tool for the understanding of electromagnets.

In this study, we attempt to apply modern laws and equipment to analyze Joseph Henry's Albany magnet experiments, and use them as a teaching tool to gain a further understanding of how electromagnets function. Furthermore, we have taken a closer look at the artifact and its current state today.

II.   HOW HENRY MAXIMIZED LIFTING POWER

In 1825, William Sturgeon made an important step to advance the experiments of Franois Arago, a French physicist, who magnetized sewing needles in straight glass tubes. Sturgeon bent a piece of soft iron wire into the form of a horseshoe, insulated it with varnish, and surrounded it with a helix of loosely wound wire (Figure 1). When connected to a small battery, the soft iron became magnetic while current was flowing. When the current was interrupted, the magnetism disappeared. This was the first temporary soft iron magnet, or electromagnet. Henry set out to improve the lifting power of Sturgeon's electromagnet by experimenting with different coils, batteries, and quantity of
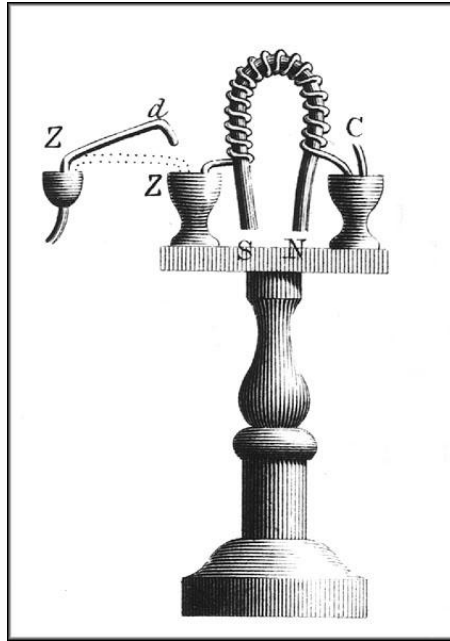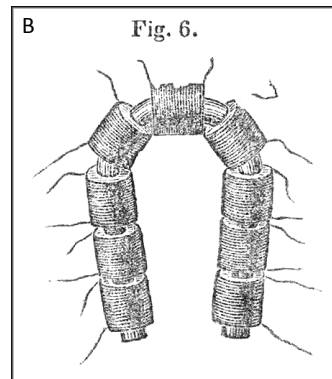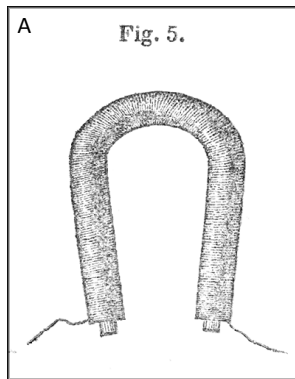
FIG. 1: Sturgeon's Electromagnet

FIG. 2: Several electromagnets made by Henry:(A) Henry's "Intensity" magnet;(B) Henry's "Quantity" magnet; (C) Henry's Big Ben magnet; (D) Henry's small experiential magnet; and (E) Henry's Yale magnet

soft iron. Here we analyze how Henry attempted to maximize the magnetic field strength, magnetic flux density, and ultimately, lifting force. Furthermore, the following subsections were primarily written as a reference for the subsequent sections, which look specifically at Henry's magnet.

A. Maximizing magnetic field strength

Instead of using bare, loose wire, Henry insulated very long strands of wire with silk to tightly wind his electromagnets; thereby increasing the number of turns. Increasing the number of turns would successfully increase the lifting power of Henry's magnets. This result can be explained by an increased external magnetic field, or the magnetic field strength. The strength of this external field is completely dependent on the number of turns of wire (N), current through each turn (I), and length of the magnetic circuit or solenoid. This relationship of magnetic field strength is designated by the letter H below.[3]

$$H = \frac{NI}{L} \tag{1}$$

By increasing the number of turns, the resistance of his coils (the load resistance) grew. Henry noticed that he got different results when wiring his coils in parallel instead of series. Under what conditions does the value of H reach a maximum? Does it occur when maximum power is transmitted to the load? We know that in an electrical circuit, when the resistance of the source and load are matched, the power transmission to the load is maximized.[?] This means that with a given internal resistance of a battery, the power transmission (I^2R or VI) to a series inductor is maximized when the resistance of the inductor equals that of the battery. Are the requirements for maximum field strength or lifting power the same as the requirements for maximum power?

Just as power is maximized through a balance between voltage and current, Henry would experiment with different combinations of voltage, current, and resistance in his coils and batteries to ultimately maximize a balance between the current and number of turns creating maximum magnetic field strength. Henry would match several galvanic cells in series to several coils in series, which he would call an "intensity" magnet (Figure 2a); and 1 galvanic cell with several coils in parallel, which he would call a "quantity" magnet (Figure 2b).[2] Matching a low resistance source with coils in parallel and a high resistance source with a long series coil seemed to maximize lifting strength of his magnets.

When a source resistance is much lower than the resistance of a single coil, connecting coils

in parallel lowers the equivalent coil resistance, which allows more current to be drawn to satisfy the current requirement for each coil. In addition, adding more turns increases the magnetic field strength. If the source resistance is much higher than the resistance of a single coil, adding coils in parallel will not significantly raise the total current. It will indeed increase the number of turns, but at the same time it will decrease the amount of current flow in each turn of wire, and therefore won't significantly increase magnetic field strength. When the source resistance is high compared to the load, coils can be continually added in series to increase the number of turns without significantly lowering the current in each turn of wire. We can model this behavior theoretically according to Henry's experiments. For example, let us take a coil similar to the coils Henry used in his Albany magnet experiments. One coil will have a resistance of about .6 ohms, and let's say we are using a battery with a voltage of 1 and a constant internal resistance of 0.6 ohms. Since the source and load resistances are the same, adding coils in series or parallel to the source, should equally change the magnetic field strength because the load resistance is being increased or decreased by the same ratio. Figure 3 shows the results below.
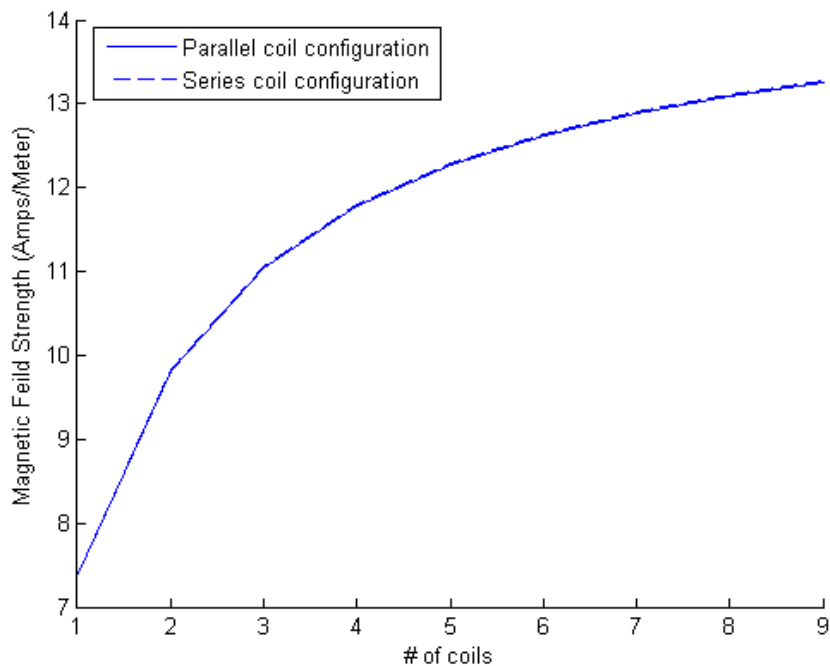

FIG. 3: Coils being connected in series and parallel with each coil's resistance equal to the source resistance

Here, the magnetic field strength for each configuration starts out equal and continues along the same path for every coil added. If the resistance of the source is lowered, let's say to 0.1 ohms, and

everything else remains constant, we can see how this change affects the magnetic field strength curves in Figure 4 below.
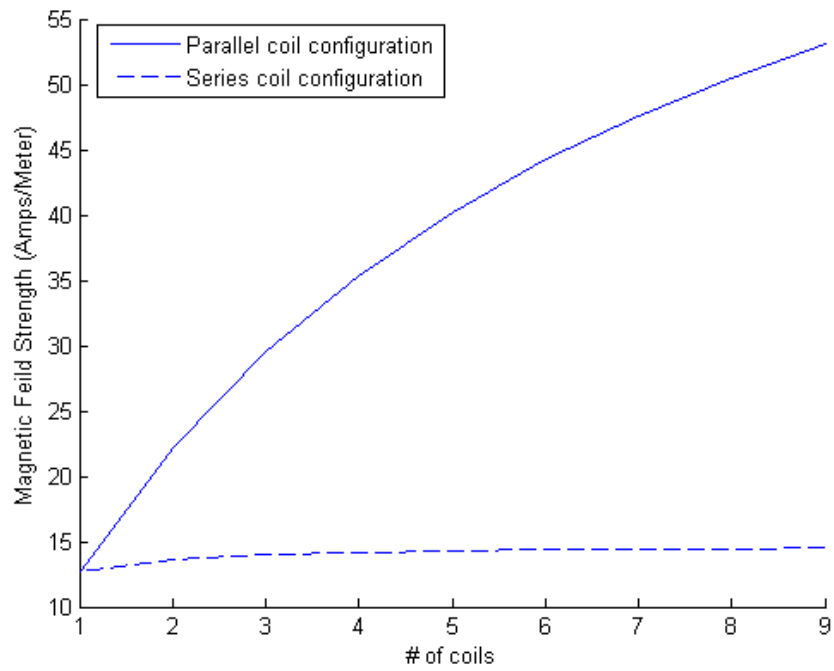

FIG. 4: Coils being connected in series and parallel with the source resistance less than a coil resistance

Here, the parallel configuration shows a far larger magnetic field strength than the series configuration. Finally, let us test a source resistance above the load resistance-let's say 5 ohms.
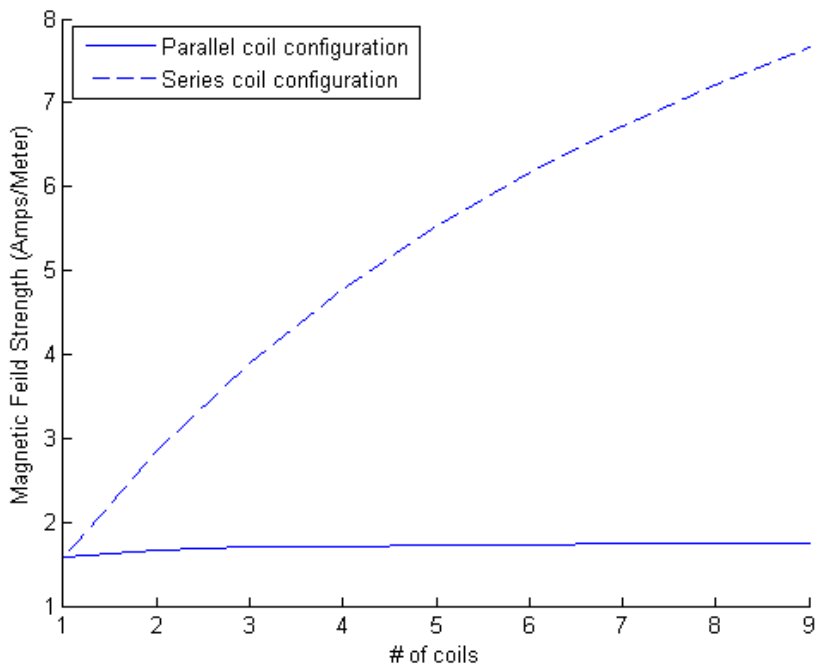
FIG. 5: Coils being connected in series and parallel with a source resistance greater than one coil resistance

As expected, with a higher source resistance, the series configuration shows the higher magnetic field strength. The results are not as extreme as the last comparison, but still significant.

From this analysis we can see that to maximize current turns with a specific source resistance, one must indeed match the load resistance to the source by adding as many turns of wire through whatever configuration is necessary. Consequently, to generate a large amount of magnetic field strength in general, one must either chose one of the two extremes: Either a source with a resistance close to zero, allowing it to simply supply as much current as possible to a low resistance (parallel) configuration; or a very high voltage, high resistance source, creating an almost constant current to supply a series load configuration.

B. Maximizing magnetic flux density

A coil wound with a core of air or vacuum, will produce a magnetic field strength or external field (equation 1). This field can have have different densities depending on the material it travels through. We call this density of magnetic field the magnetic inductance or magnetic flux density, defined by the letter B. In Franois Arago's experiments, he would wind coils around thin glass tubes to magnetize sewing needles.

FIG. 6: Arago's glass tube

Arago generated an external field, or magnetic field strength, with a certain magnetic flux density though the air in the tube. We can define this flux density in air, or free space, as B_0, according to the following relation.

$$B_0 = \mu_0 H \tag{2}$$

Where μ_0 is the permeability of free space, a constant equal to $4\pi * 10^{-7}$ Henries/Meter. Permeability, μ, is a property of the specific medium or material through which the H field passes and in which B is measured. For most ferromagnetic materials, μ is much larger than μ_0. Because of this, the ratio of permeability of a material to the permeability of a vacuum is commonly used in the description of the magnetic properties of solids. This ratio can be defined as the relative permeability.[3]

$$\mu_r = \frac{\mu}{\mu_0} \tag{3}$$

When a material is added to an empty solenoid, such as Arago's steel compass needles, the magnetic moments of the material tend to become aligned with the external field, creating its own magnetic field, which we can call the material's magnetization (M). We must take into consideration this additional magnetic field by adding the term μ_0M to equation 2 to obtain the following relation for a solenoid with a solid core.[3]

$$B = \mu_0 H + \mu_0 M \tag{4}$$

Now, instead of looking at the magnetization as a separate value, we can make it proportional to the applied external field H.[3]

$$M = \chi_m H = (\mu_r - 1)H \tag{5}$$

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Where χ_m is the magnetic susceptibility, a unit-less degree of magnetization of a material in response to the applied field. This can also be written as a function a permeability which is added to equation 2 below.

$$B = \mu_0 H + \mu_0(\mu_r - 1)H = \mu H \qquad (6)$$

Because the density of the magnetic field is dependent on this concept of permeability, which changes with different magnetic field strength, Henry would use a high purity iron for the material in his electromagnets. A higher purity iron allowed for two things: 1) a higher initial permeability and therefore an overall higher flux density to be produced with additional external field; and 2) his magnet only became magnetized when current was flowing. These two characteristics define a "soft" magnetic material. A comparison of a hard to soft magnetic material can be made by their respective hysteresis curves, or B vs H plots for a specific material.
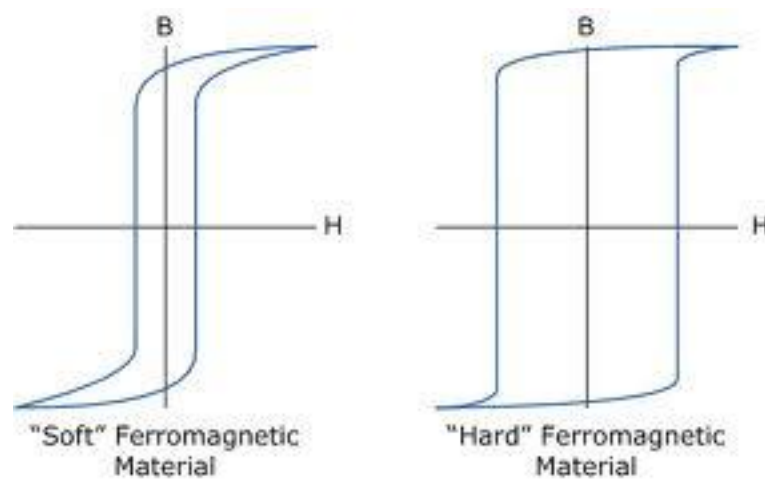
FIG. 7: A hysteresis comparison of "soft" and "hard" ferromagnetic materials

As shown above, the "soft" magnetic material saturates much faster and retains far less magnetism (usually negligible) when the external field is removed versus the saturation of the "hard" magnetic material.[?]

The non-linearity, displayed as a S-shaped curve, of the hysteresis graph is caused mainly by the interaction between magnetic dipoles. When the dipoles are acted upon by a magnetic moment created by the external field, H, the dipoles will try to align themselves with the field. When a dipole starts to be aligned, and the external field is removed, the dipoles of a "hard" magnetic

material will stay somewhat aligned, and the dipoles of a "soft" magnetic material will scramble. The greater the moment acting upon the "stiffness" of the dipoles, the more magnetic energy is required to move them further. Eventually, there is a maximum amount the dipoles can line up with one another. This maximum point is called the saturation magnetization, and can be theoretically calculated for each material, likewise for saturation flux density. For similar "soft" and "hard" magnetic materials, such as iron and steel respectively, the saturation flux density is not necessarily different. It will simply take a larger external field to saturate the material.

It is possible that the high purity iron that Henry used in his experiments allowed him to approach the saturation flux density of the material before reaching the maximum current that could be produced from his batteries, which were still evolving in the 1830's.

C.   Maximizing lifting force

How does magnetic field strength and flux density relate to lifting force? Assuming no flux leakage from the path of the solenoid, which would decrease the flux density at the point of contact, the force exerted by an electromagnet on the section of core material is defined below.[?]

$$F = \frac{B^2 A}{2\mu_0} \tag{7}$$

Where A is the surface area of the core at the point of contact. Because the lifting force is proportional to the square of the flux density, it is an important factor when creating a powerful electromagnet. However, this effect is often not seen in soft magnetic materials due to the diminishing increases to the B-field as the core material moves quickly towards saturation. This exponential increase in lifting strength for soft magnetic materials occurs at lower values of H.

Henry used increasing amounts of iron, each resulting in generally more lifting power than a smaller quantity. From equation 7 we can see that increasing the cross sectional area of the iron at the point of contact will generate a greater force on the object being lifted. But there is something missing. In all electromagnets, there is no way to have zero fringing or flux leakage. There will always be flux that flows away from the path of the core through the air. The easier the magnetic field lines can flow through a material, the less likely flux will leak from the walls of the core. This brings us to the concept of magnetic resistance or reluctance. Much like an electrical circuit dissipates energy, magnetic circuits store magnetic energy. Current in an electrical circuit will flow mostly where there is least resistance. Similarly, magnetic flux will flow through the path of

least magnetic reluctance. The reluctance of a uniform magnetic circuit can be calculated by the following.[?]

$$R = \frac{L}{\mu A} \tag{8}$$

Where L is the length of the core, A is the cross sectional area, and μ is the permeability of the core. Because the reluctance of the magnetic circuit depends on the physical dimensions of the core, using a thicker core, or a larger quantity of iron, prevents magnetic flux from leaking out into the surrounding air; increasing the flux density at the poles. Furthermore, because this relationship depends on μ, which decreases when a core moves toward saturation, the reluctance will also increase when the core is being saturated.

The Albany magnet was Henry's first "experimental magnet on a large scale." The effect of Henry using a larger (thicker) quantity of iron did two things: 1) It increased the surface area at contact, to which the force is directly proportional(equation 7); and 2) lowered the reluctance of the magnetic core, which increased the flux density because of minimal flux leakage (equation 8).

From the above sections, we can identify three main limiting factors when building an electromagnet: 1) Magnetic saturation of the core - This is a finite limit on the amount of magnetization a core can produce; 2) Battery saturation - When a source with a certain resistance is attached to an ever decreasing or increasing load resistance, the amount of magnetic field strength produced by the addition of turns will diminish; 3) Area/volume saturation - Because of magnetic reluctance and leakage, the amount of increase in flux density though a magnetic material core will diminish more rapidly in smaller cores as the the core moves towards magnetic saturation.

III. ALBANY MAGNET EXPERIMENTS

Below we look at Henry's experiments with the Albany magnet (experiments 8-20 from Silliman's American Jour. of Science, January, 1831, vol XIX, pp. 400-408), and analyze the most likely explanation for Henry's results, and later compare them to the results obtained with a replica magnet. These experiments are an important part of Henry's research and provide us with examples of source, magnetic, and volume saturation. They also display several factors that maximize magnetic lifting power. In these particular experiments, Henry sets out to display the enormous magnetic power that can be created from using a single small galvanic cell.

A. Henry's Setup

Henry describes his magnet as "a bar of soft iron, 2 inches square and 20 inches long, was bent into the form of a horse-shoe, 9 1/2 inches high." Henry explains his coil system as 9 individual coils each made from 60 feet of copper bell wire which were each wound backwards and forwards over itself over about 2 inches of core. Each one of these coils were numbered, distinguishing the first and last end of each strand so each wire could be readily combined with other wires to form longer coils. This coil system allowed Henry to easily change the load resistance of the magnet. For reference purposes let us label each coil 1-9 shown in Figure 8 below.
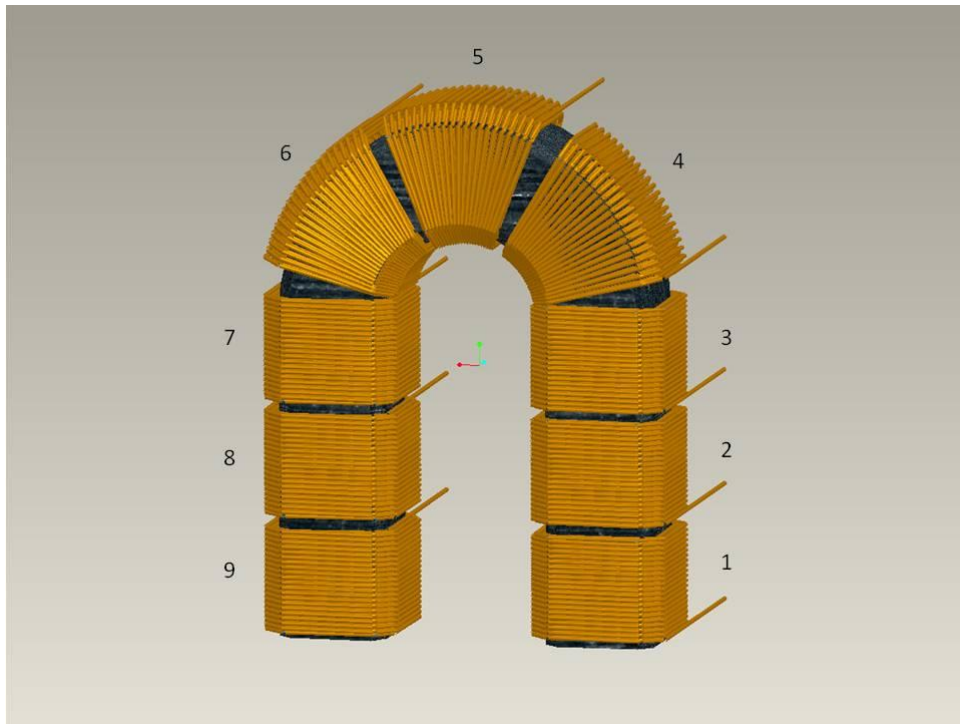

FIG. 8: Henry's Coil Configuration

Because of the amount of time and sheer tediousness of tightly winding by hand 60 feet of wire, it is unlikely that Henry would wind and unwind coils for each experiment. Instead Henry wound all the coils before experimenting.

Figure 9 below shows Henry's 3'9" X 20" frame for measuring lifting strength. With this frame Henry could add weight to the magnet's armature, allowing him to record fairly accurate magnetic force measurements.
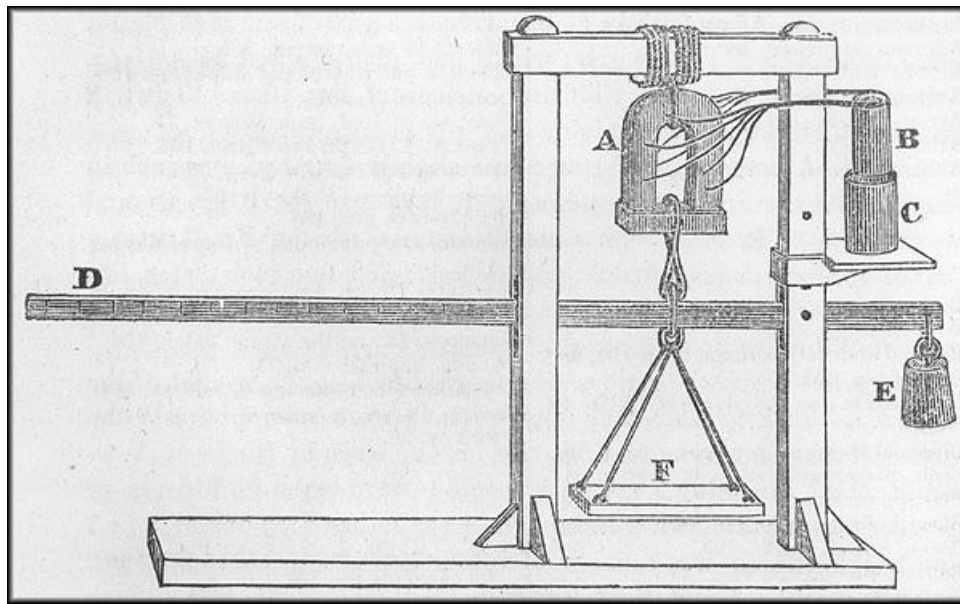
FIG. 9: Henry's frame for testing the strength of his electro-magnet

For experiments 8-14 henry uses a small single cell battery consisting of 2 concentric copper cylinders, with 2/5 a square foot of zinc between them, all submerged in a half pint of "dilute acid."

B. Experiment 8

Each 60 ft Coil - Lifted 7 lbs

Henry connects each coil (1-9) to the battery one by one. He finds that each coil by itself is only able to lift the armature, which weighs only 7 pounds.

C. Experiment 9

2, 60ft Coils in parallel - Lifted 145 lbs
100% increase in turns - 1971% increase in lifting force

When coils 4 and 6 are both connected to the battery, the lifting power is greatly increased - almost 21 times the lifting force of the last experiment. How could this be? From equation 7 we

know that the lifting force is proportional to B^2, however that would indicate a maximum lifting force of about 28 lbs. There is something missing. Something seems to be limiting the lifting power of the magnet in experiment 8. We can explore several factors that may or may not have contributed to this: 1) Even though the material he used was "soft iron," one possible explanation for these contradictory results could be some residual magnetism that developed during the forging process. All iron has some impurities in it. A likely iron that Henry would have used is Wrought Iron, which is high purity but still has some carbon content. Any amount of carbon can result in some sort of residual magnetism. When iron is heated and worked, it can develop its own magnetism. If Henry was connecting the coils in experiment 8 opposite to the residual magnetism, it may have resulted in a decrease in lifting strength. 2) It could be that the battery was acting differently under a smaller load. His galvanic cell could allow for less current to be drawn when only one coil is attached. 3) In the hysteresis curve of iron, the very first increases of magnetic field strength causes a short exponential increase in the B-Field.[3] An exponentially increasing B-field could make the lifting force increase rapidly. 4) Because the magnet was only lifting the armature in experiment 8, the net force on the magnet poles was small. The contact between the armature and the horseshoe's poles may not have been completely smooth until a greater net force was acting upon the armature (another coil was added). If a greater net force was able to produce a smoother contact, this would mean a smaller air-gap, which would result in an overall larger lifting force. Some of these ideas are more plausible than others, but it is still uncertain which, if any, account for these results.

D. Experiment 10

2, 60 ft Coils in parallel - Lifted 200 lbs
0% increase in turns - 39.9% increase in lifting force

When coils 1 and 9 are both connected to the battery, there is a significant increase in force over the last experiment. Here the magnetic field strength should be the same, however, the flux density at the point of contact increases. This is due to the fact that both coils are very close to the point of contact, minimizing flux leakage due to magnetic reluctance (equation 9) at that point. Placing the coils close to the point of contact focuses more magnetic field lines through the point of contact, thereby increasing the flux density and lifting power at that point. Because there is a certain reluctance associated with the entire magnetic circuit, there is a certain amount

of flux that should flow though the entire circuit. Consequently, the loss of flux into the air occurs primarily away form the point of contact, which provides a better lifting strength than if the coils were wound completely around the entire magnet - or a totally uniform leakage.

E.   Experiment 11

3, 60 ft Coils in parallel - Lifted 300 lbs
50% increase in turns - 50% increase in lifting force

When coils 1, 5, and 9 are all connected to the battery, there is a substantial increase of lifting power due to an increase in the magnetic field strength (increasing the Ampere-Turns). Here the magnetic fields lines are slightly less focused at the poles than the last experiment because of the increase in uniformity of the leakage. Because of the significant increase in lifting force, the battery or iron seem to show very little signs of saturating.

F.   Experiment 12

4, 60ft Coils in parallel - Lifted 500 lbs
33.3% increase in turns - 66.7% increase in lifting force

When coils 1, 2, 8, and 9 are all connected to the battery, there is a an even greater increase in lifting power over the last experiment. This difference can be explained much like experiment 10, by an increase in flux density at the poles of the magnet due to the location of the coils being near the poles.

G.   Experiment 13

6, 60ft Coils in parallel - Lifted 570 lbs
50% increase in turns - 14% increase in lifting force

When 6 coils are connected to the battery (Henry does not mention the location of coils in this experiment), we can see that the increase in lifting force has suddenly diminished significantly. This is most likely caused by three reasons: 1) The flux leakage is almost completely uniform, restricting the increase of flux at the poles compared to the last experiment; 2) The resistance

of the load (the equivalent resistance of all the coils in parallel) is nearing the resistance of the cell, diminishing the increase of current being drawn; 3) It is possible that the soft iron core is nearing saturation, thereby decreasing the value of μ, which also increases the reluctance, causing increased flux leakage; 4) The batteries and coils could have been getting hot, which would increase the resistance - limiting the current flow.

H. Experiment 14

9, 60ft Coils in parallel - Lifted 650 lbs
50% increase in turns - 14% increase in lifting force

When all 9 coils are connected to the battery, we see that Henry gets an increase in lifting force similar to experiment 13. Since the battery and/or material have begun to saturate, we would expect to see a lesser increase in performance. However, with addition of coils, we see almost the same increases as the last experiment. This is due to the flux being almost as uniform as the experiment before. Experiment 13's force increase diminished dis-proportionally to experiment 12 because of a significantly different coil configuration.

I. Experiment 15

9, 60 ft Coils in parallel - Lifted 750 lbs
0% increase in turns - 15.4% increase in lifting force

When all 9 coils are connected to a larger battery composed of a single galvanic element with a plate of zinc 12in x 6in surrounded by copper, the lifting force increases. This is due to a decrease of the internal resistance of the battery, allowing even more current to flow through the coils. After the experiment, Henry mentions that the magnet is "probably, therefore, the most powerful magnet ever constructed." Henry notes that with a large calorimeter, containing 28 plates of copper and zinc (each 8 inches square), he could not succeed in making it lift as much weight as with the small battery. This is due to the fact that a battery that large will have a very high internal resistance (the sum of each cell's resistance). As discussed earlier, when the source resistance is greater than the load resistance, the addition of coils in parallel will not draw any significant additional current to increase the magnetic field strength. Only adding coils in series will noticeably increase the

strength of the magnet. Henry tests this hypothesis later in these experiments.

J. Experiment 16

9, 60 ft Coil - Lifted 85 lbs

0% increase in turns, 96% decrease in zinc surface area - 80% decrease in lifting force

To see the effect of using a very small amount of zinc and copper, Henry substitutes a very small galvanic element with a pair of plates 1 inch square. With all the coils connected, the magnet only lifts 85 pounds. We can see that by decreasing the area of zinc and copper, the internal resistance of the battery increases a significant amount, limiting current flow.

K. Experiment 17

6, 30 ft Coils in parallel - Lifted 375 lbs

0% increase in turns over experiment 11 - 25% increase in lifting force

Here Henry attaches 6, 30 foot coils, presumably cutting 3, 60 ft coils in half. This increase over experiment 11 is simple. Decreasing the resistance of each coil allows for more current to flow, in keeping with the assumption that the source resistance is still very low. This increased magnetic effect due to higher current is somewhat hidden by the increase in uniformity of flux in the magnetic circuit (assuming all the coils were connected along the circuit and not on top of each other) - but is still obviously significant.

L. Experiment 18

3, 60 ft Coils in parallel - Lifted 290 lbs

0% increase in turns over experiment 17 - 29.3% decrease in lifting force

Henry unites the 6, 30 ft coils to form 3, 60 ft coils and attaches them much like experiment 11. The results are indeed very similar to experiment 11 (300 lbs). Henry notes that the 6 shorter wires were more powerful than 3 wires of double the length. Again, this is due to the ability of 6 smaller coils to draw a larger amount of current. We still do not know, however, in what locations these coils were connected.

M.   Experiment 19

1, 120 ft Coil - Lifted 60 lbs

0% increase in turns over experiment 10 - 70% decrease in lifting force

Henry unites the 2, 60 ft coils from experiment 10 (200 lbs) to form 1, 120 ft coil. This simply allows for less current to be drawn, decreasing the magnetic field strength. This also confirms the assumption that when only 2, 60 ft coils are connected in parallel to the battery, the equivalent resistance of the load is still greater than the source.

N.   Experiment 20

1, 120 ft Coil - Lifted 110 lbs

0% increase in turns - 83.3% increase in lifting force

When Henry attaches the same long coil to a small compound battery, consisting of two plates of zinc and two of copper - containing the same quantity of zinc surface as the element in the last experiment - the lifting strength almost doubles. Henry states this configuration to have more "projectile force, and thus producing a greater effect with a long wire." By combining 2 cells in series, we understand the effect created as increases of voltage, and resistance. As mentioned earlier, a source with a higher resistance is better suited to a load of similar resistance. Here Henry was simply attempting to match resistances to maximize the lifting strength with a finite amount of turns.

O.   Henry's Conclusions

At the end of experiment 20, Henry mentions that when the single large battery was attached, the magnet was capable of lifting over 700 pounds, but only when only one pole of the magnet was in-contact, it could not support more than 5 or 6 pounds (a 99.2% decrease in strength). He claims he has never noticed such a difference between a one and two poles with smaller quantities of iron. Instinctively, one may expect the force to halve when one pole is removed from contact, but this is not true. The reason for this drastic decrease in lifting strength is due to the large air-gap produced in the magnetic circuit. If we first look at just the total magneto-motive force of the circuit, or the total Ampere-Turns, we have to take into consideration the length of both the

core material and the air-gap. The total magneto-motive force or NI is equal to the sum of the Magnetic field strength of the core (H_{core}), times the length of the core (L_{core}) and the magnetic field strength of the air-gap (H_{gap}), times the length of the gap (L_{gap}) shown below.

$$NI = H_{core}L_{core} + H_{gap}L_{gap} \tag{9}$$

We can then insert this relationship into equation 6 to solve for a new flux density.

$$B = \frac{NI}{(L_{core}/\mu + L_{gap}/\mu_0)} \tag{10}$$

As shown above, any significant value of L_{gap} will have a large decreasing effect on B. Consequently, by using only one pole of the horseshoe and creating an air-gap of only a few inches, Henry was not only halving the number of magnetic poles acting on the armature, but also greatly reducing the flux density though the magnetic path; which almost totally diminished the lifting force of his large magnet. Henry goes on to mention that he has never before witnessed such a huge difference between one and two poles. This observation is due to the reluctance of this magnetic circuit being much smaller than that of his previous magnets, which were all smaller in size. Because his other magnets were skinny, their reluctance was closer to the reluctance of the air-gap itself. A smaller quantity of iron will push more and more flux into the air more quickly than a large quantity, therefore creating less contrast between the flux density through the surrounding air and the flux density through the core.

IV. THEORETICAL COMPARISON

Through equation 7, we can attempt to convert the lifting force that Henry obtained in each experiment to different values of flux density. To then estimate the magnetic field strength, we must estimate the internal resistance of Henry's galvanic cell that he used in his experiments by first estimating the point where the source resistance was matched with the load resistance (i.e. the point at which a higher increase in magnetic field strength is produced by adding a coil in series instead of in parallel). Once we have this point, we can then estimate the load resistance by the length, diameter, and resistivity of the copper wire that was used. After we have this resistance, we can then estimate the current that would have flowed through each turn of wire (assuming the cell's internal resistance remained constant). We can also easily get a fairly accurate estimate for

the number of turns in each coil and the length of the magnetic circuit. Once all this information is obtained we can give a decent estimate of the magnetic field strength generated when each coil is added. We can then plot B vs H curve which can be compared to other B-H or hysteresis curves of different magnetic materials. As mentioned before, the material Henry used was a "soft" iron, which means it was most likely wrought iron, or an iron of equal or higher purity. Looking back at experiments 10, 19, and 20, in all of which Henry uses 120 feet of wire and approximately the same amount of turns, we can identify that with a parallel configuration the magnet lifts the most weight - which suggests the highest current. The theoretical resistance of 120 feet of copper wire .05 inches in diameter at room temperature is .48 ohms. From the measurements taken on Henry's apparatuses, we found that the resistance of the copper he used was approximately double that of pure copper. Consequently, we estimate the resistance of 120 feet of Henry's wire to be about .96 ohms. Because the parallel configuration of 120 ft of wire had the greatest lifting force and current - more than the series configuration with two galvanic cells (double the source resistance and twice the voltage) - we can suggest that the resistance of a single cell has to be less than .96 ohms. Because Henry got such a drastic increase in lifting power by putting the coils in parallel, it is likely that the resistance of the cell was closer to one quarter ohm. Using this estimate of internal resistance we can calculate the theoretical values of the magnetic field strength (H). The following is the Matlab code used to generate the B-H plot:

```
coils=[0,1,2,2,3,4,6,9];
weight=[0,7,145,200,300,500,570,650];
F=(weight*4.44822162);
u0=4*pi*10^-7;
A=(2*0.0254)*2;
B=sqrt(2*F*u0*A)*10000
Rs=.25
Rl=.24./coils;
I=(1.2./(Rl+Rs));
N=coils.*80;
L=20*0.0254;
H=(I.*N./L);
plot(H, B)
xlabel('H (Amplure-Turns/Meter)')
```

```
ylabel('B (Gauss)')
```

A plot of Henry's B-H curve is shown in Figure 10 below.
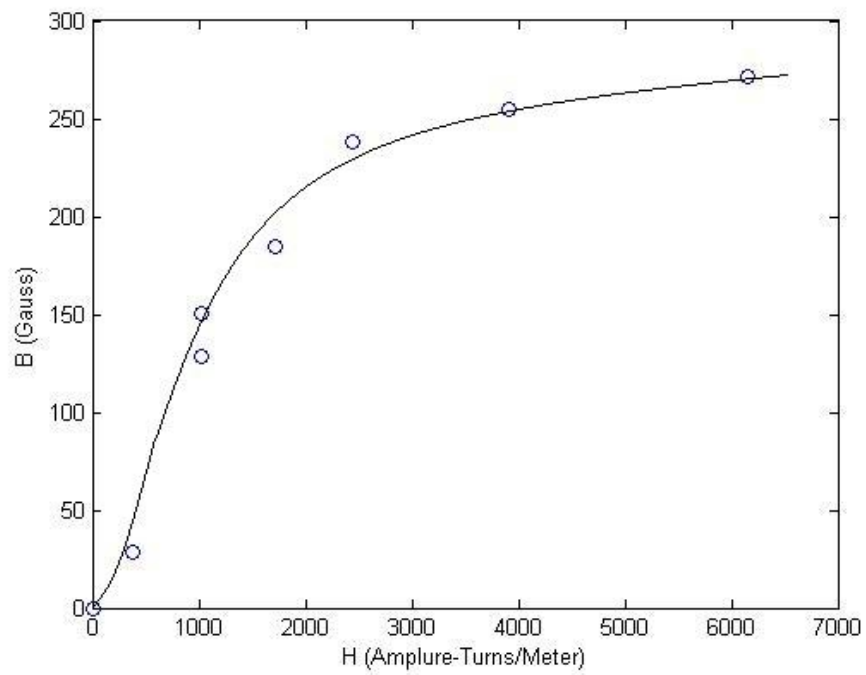

FIG. 10: Plot of Flux Density vs. approximate Magnetic Field strength for Henry's magnet

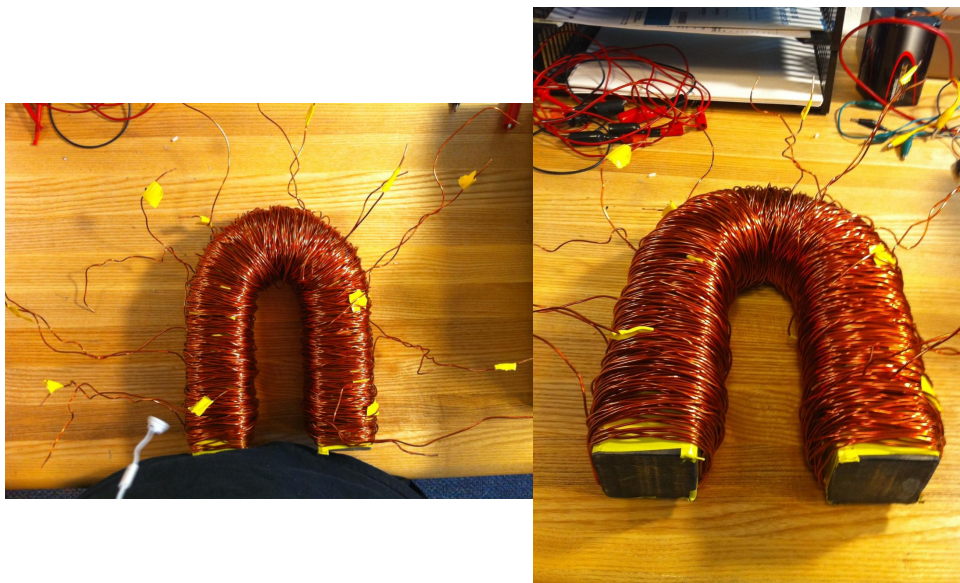## V.   EXPERIMENTAL COMPARISON

FIG. 11: Our Replica Electromagnet

To confirm some of the suggestions made about Henry's experiments, we constructed a replica of Henry's Albany magnet, shown in Figure 11 above. Each coil was wound in the same way as experiments 8-16. There are a couple of main differences between our magnet and Henry's: 1) Our magnet was forged from a mild steel, which has a higher carbon content than wrought iron, giving it some residual magnetism after the external field is removed. Mild steel also takes much longer to reach saturation, and has a smaller initial permeability; 2) We used 9, 60 ft strands of high purity enameled copper wire, which has a much thinner insulation than Henry's silk, allowing for a greater number of turns, and has a lower resistivity than the copper wire used by Henry. These two differences, especially using a different magnetic material, can be shown to have a large effect on our results. Nevertheless, all the data collected below should be consistent enough to establish certain comparisons with Henry's results.

When measuring the B-field at different areas on the poles, it was observed that the B-Field increased when the probe was brought towards the inner edge of the pole. Furthermore, the B-field was at a maximum at the inner corners of each pole (about double that of the center). Even though the reading was higher at the corners, it was difficult to get consistent measurements there, so these results were discarded.

To test the idea of flux leakage though a magnetic circuit, each coil was attached to a constant current of 5 Amps and the B-Field was measured at the center of each pole. The results are shown below in Table I.

Coil	Right side B-Field (Gauss)	Left Side B-Field (Gauss)	Total B-Field (Gauss)
1	140	29	169
2	117	49	166
3	98	53	151
4	87	68	155
5	78	78	156
6	58	97	155
7	48	107	155
8	39	112	151
9	29	136	165

TABLE I: B- Field measurements taken for each coil supplied with a constant current

As expected, when coils move from the right side to the left, the flux density starts out strong at the right, then shifts to the left.

Next we test some of the coils in similar configurations to Henry's experiments. Because the current is constant, the magnetic field strength should not change when coils are added or subtracted in parallel. Here we should be able to see the effect of the flux density changing at the poles with different coil configurations.

Coil	Right side B-Field (Gauss)	Left Side B-Field (Gauss)	Total B-Field (Gauss)
4,6	78	78	156
1,9	78	92	170
1,5,9	73	83	156
1,2,8,9	73	87	160
1,2,4,6,8,9	78	78	156
All	78	78	156

TABLE II: B- Field measurements taken with coils wired in parallel supplied with a constant current

Our results seem to agree with Henry's. When the coils are moved from the arc of the magnet to the extremities, there is an increase in flux density at the poles. When another coil is added to the top, the flux density is made more uniform, and therefore decreases at the poles.

To see how the additional magnetic field strength effects the flux density at the poles, a constant current was run though the same current configurations in series.

Coil	Right side B-Field (Gauss)	Left Side B-Field (Gauss)	Total B-Field (Gauss)
4,6	156	161	317
1,9	166	175	341
1,5,9	244	250	494
1,2,8,9	322	338	660
1,2,4,6,8,9	488	502	990
All	732	737	1459

TABLE III: B- Field measurements taken with coils wired in series supplied with a constant current
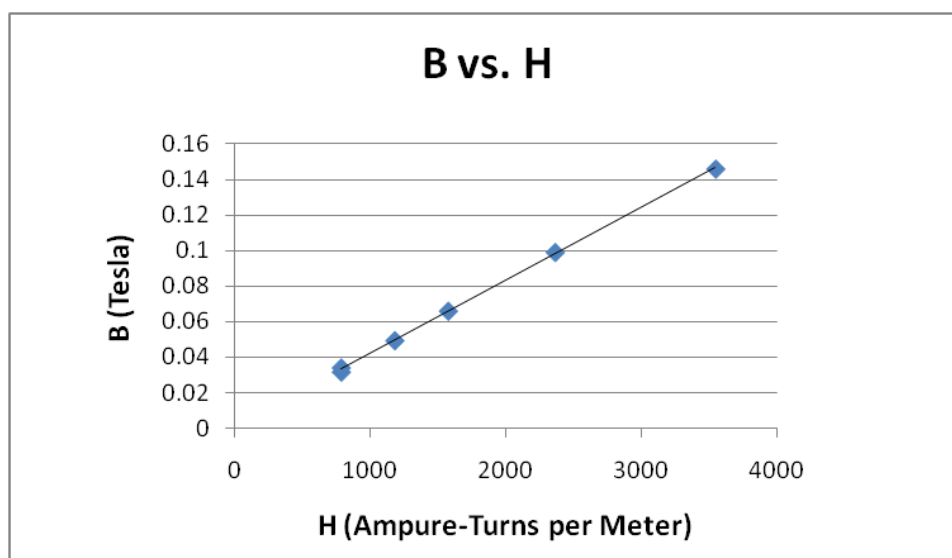
FIG. 12: Plot of magnetic permeability for our replica magnet

When this data is plotted above, we can see that the permeability is pretty much constant though these experiments. Because our setup was not limited by a battery's resistance or voltage, the curve shows no sign of leveling off. Also, because the material used in our magnet is a mild steel, it is likely that the amount of magnetic field strength does not have as much of a distinct or quick magnetic saturation effect as soft iron - in other words, compared to Henry's soft iron, the plot is a relatively small section of the steel hysteresis curve. As we can see from our experimental results, the idea of magnetic reluctance is a very important aspect in the understanding and design of electromagnets.

When the magnet, in any configuration, was attached to a galvanic cell that contained similar surface area of copper and zinc to the cells in Henry's experiments, the lifting force of the magnet was extremely low. We could barely make the magnet lift a few pounds. This is most likely due to two main factors: 1) The initial permeability of Henry's iron was much larger than our mild steel, which would make our magnet require a much higher magnetic field strength to obtain similar results; and 2) The batteries that were constructed did not output a significant amount of current and had a large internal resistance. We believe this is due to a different concentration of sulfuric acid. Henry only mentions the acid that he uses as simply "dilute acid."
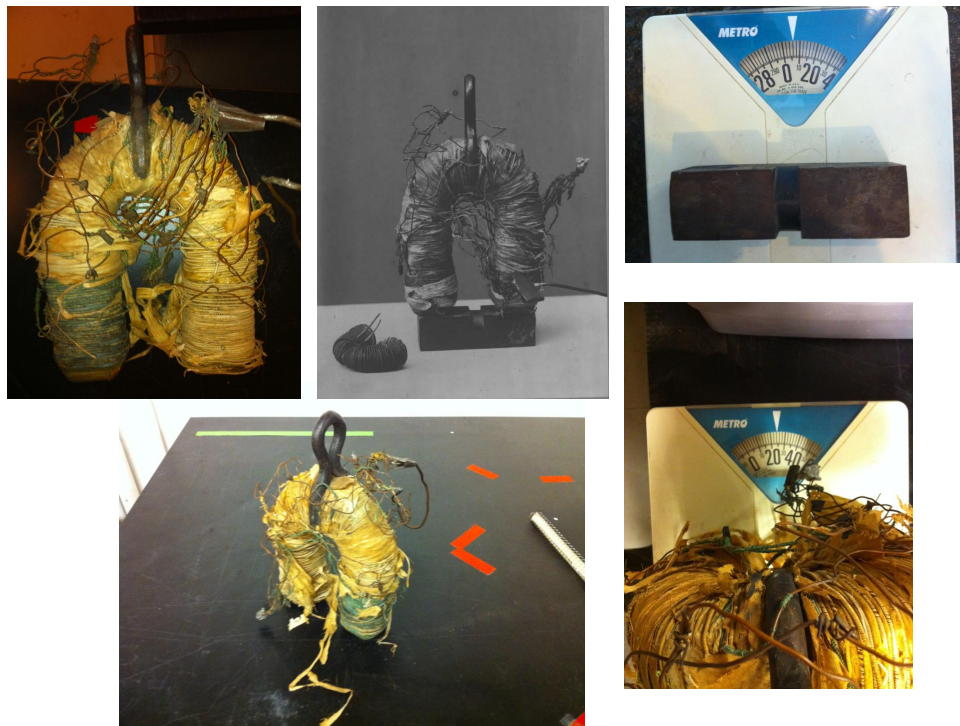
VI. HENRY'S MAGNET TODAY

FIG. 13: Henry's Albany Magnet and armature at Princeton

The Magnet at Princeton weighs 24 pounds and is about 9 1/4 to 9 1/2 inches tall. This seems about right when you factor in the weight of silk insulation and 9, 60 ft copper coils. The armature was found in the Jadwin Hall display case, sitting on the shelf below the Magnet behind a large galvanic battery, almost completely out of sight. It weighs 7 pounds, measuring 2 inch square by 6 3/4 inches long, which matches the description in Henry's paper. The magnet shows two large solder connections, each made with 9 strands of wire coming in/out. These 9 strands can easily correspond to Henry originally having 9 separate 60 ft coils. However, there is a 3rd, smaller, solder connection made with 6 strands of wire. How was the magnet really wound?

FIG. 14: Connections made on Henry's Magnet

At first glance, the windings seem disorganized, but upon further examination, several identification tags can be seen attached along each strand. These tags are all different. Each tag seems to be paired with another, being different only by a single dot or hole in the center of the tag. This suggests that Henry labeled one end of each strand with a symbol or dash, and the other end with the same symbol or dash plus a dot or hole in the middle of the label.

FIG. 15: Different tags on Henry's magnet

Each strand of wire seems to be wrapped in either tan or green linen. There are 5 green wires and 4 tan wires coming from the first large solder connection. Let us call this connection the blue connection. There are also 5 green wires and 4 tan wires coming from the other large solder connection. Let us call this connection the orange connection. There are only 2 green wires and 4 tan wires coming from the small solder connection, let's call this connection the black connection. It is possible that Henry alternated between green and tan linen. Furthermore, most of the tan wires are wrapped around the left side of the horseshoe, and most of the green wires around to the right.

Originally, Henry documents that "540 feet of copper bell wire were wound in 9 coils of 60 feet each". Let us assume Henry insulated 5 of the 9 wires in green linen and the remaining 4 with tan linen. In experiment 17, there were "wires, each 30 feet long, attached to the galvanic element, the weight lifted was 375 Ibs." This suggests that he would have cut 3 of the 60 ft strands of wire in half, creating 6, 30 ft strands. Let's assume that 2 of the 3 60 ft wires that he cut were wrapped in tan linen, and the remaining strand was wrapped in green linen. If this is accurate, it would agree with the black connection having 4 tan wires and 2 green wires.

A closer observation of every strand of wire coming out of each solder connection was made. Each strand was followed from each connection to the point of entry into the windings along the horseshoe.
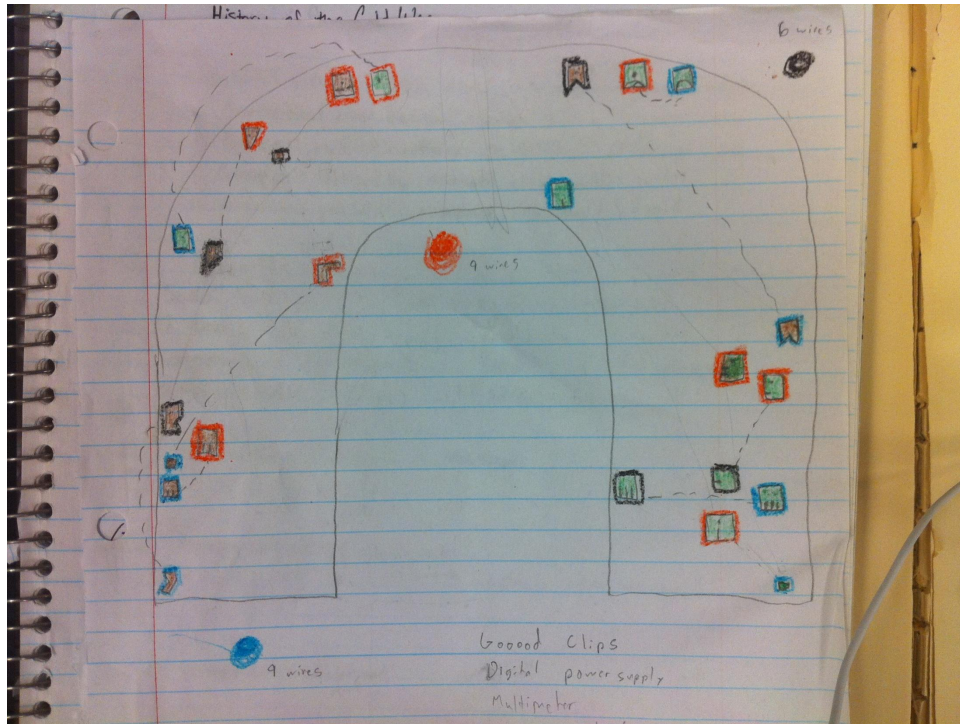
FIG. 16: A outlined map of each connection, insulation, and tag

These locations were recorded on the drawing above, along with a sketch of each tag associated with each wire. Each tag was colored tan or green - identifying what color linen was used for insulation. They were outlined with either blue, orange, or black - identifying which solder connection it was from. The tags that were bent together and unreadable were marked as a small square.

From this outline, we can suggest that 2 tan and 1 green wire from the black connection are connected through coils to the blue connection, and another 2 tan and 1 green wire are connected through coils to the orange connection.

The resulting circuit consists of 6, 60 ft coils in parallel with 3 pair of 30 ft coils in series (A total of 12 wires). The suggested circuit diagram is shown below.
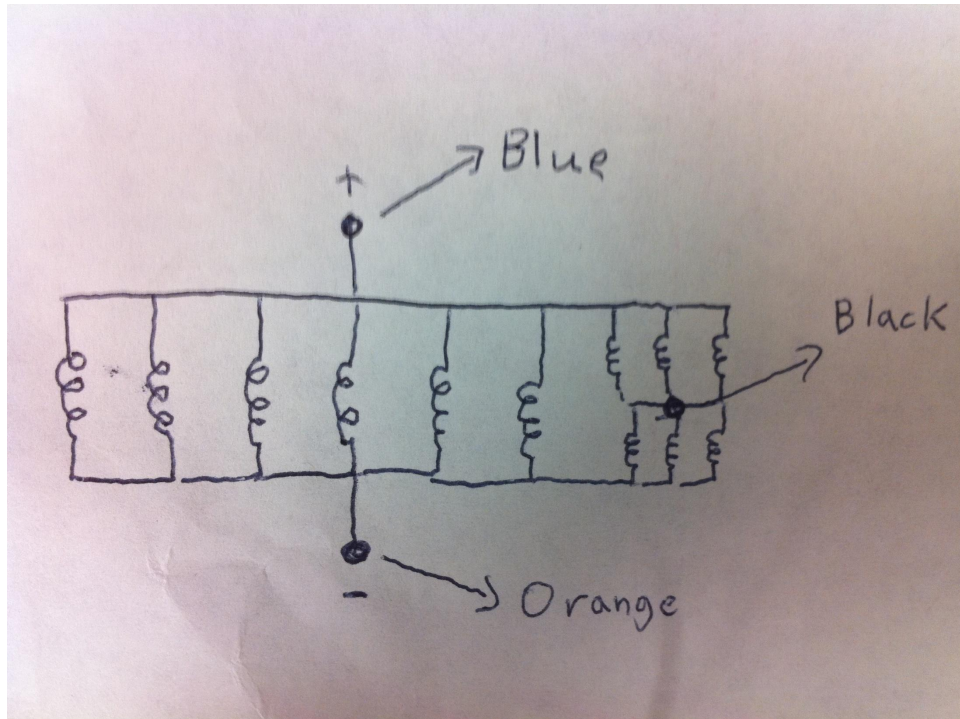
FIG. 17: Suggested Circuit diagram of Henry's magnet

VII. CONCLUSIONS

From this study, we see the importance of Henry's Albany magnet experiments, and how they demonstrate the many factors used to increase the lifting power of electromagnets. Our experiments and analysis puts magnetic field strength, flux density, and magnetic reluctance into perspective. We can see the true importance of each factor and how each relates to the other. These different properties can be used to aid us in learning and teaching electromagnetism. I hope we have solved many of the mysteries about how Henry obtained the results that he did, as well as provided significant insight into the current state of his magnet today.

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questions which led to a deeper understanding of the magnet. We also thank the Lounsbery Foundation for its support.

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[1] Scientific Writings of Joseph Henry. Volume 1

[2] Scientific Writings of Joseph Henry. Volume 2

[3] Materials Science and Engineering

[4] Elements of Electrical Engineering: A Textbook of Principles and Practice