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Series and Parallel Experimenting with Electromagnets

Abstract

The pull of electromagnets on weights acts through the magnetism evoked in iron by current flowing in wires coiled around that iron. Learning to work with this instrument entails engaging with how effects of current show different behavior under series and parallel connections of the wire windings. This experience was new for Joseph Henry when, around 1830, he devised electromagnets with unprecedented lifting capacity, and for me when, in following his accounts through my own experimenting with a nail electromagnet I made, I obtained results opposite to his. For him, such experimenting developed by amplifying the electromagnetic effects, not by systematically testing wiring alternatives. For me it developed through interpreting and testing how the circuital balance between internal and load resistances functioned for my wire coils and *D* cell batteries. The confusions and partial understandings arising in each investigation inform and extend our understanding of how learning happens in experimental work with materials.

A child drops a toy and then searches for it. That is experimenting. By researching children's explorations, Piaget[1] found that learning comes about through our action with things of the world. That is true for science as well as for the learning of a child. My dissertation[2], from which this study is drawn, is grounded in that finding about learning. Here I portray how two novice experimenters – Joseph Henry (1797-1878) and myself – learned by experimenting with an instrument each had made: an electromagnet.

In following the *learning* of historical experimenters with my own, I look for how experience develops through work with materials. Thus I conducted my experimenting with everyday materials from my surroundings and used my own ideas as the beginnings for what I tried. I worked at developing my experimental understanding from the evidence of my own experiments, without initially consulting the analytical and instrumental resources now available. So my concerns and method differ from those of historians who, by replicating nineteenth century instruments faithfully with the original materials, seek demonstration of physical effects and historical practices.[3,4,5]

1 PIAGET (1936).
2 CAVICCHI (1999).
3 HERRING (1994).
4 VOSKUHL (1997).

Similarities and differences hold between Henry and me. When he first made electromagnets in 1829-30, Henry was a newcomer to experimenting and not directly acquainted with other American investigators. When starting my project, I was also inexperienced in making and testing my own electrical instruments (my experience developed, as noted below). But the instruments we made differ greatly in scale. When the silk-insulated windings around Henry's 21 *lb*. horseshoe were connected to a two-cell battery, Henry's novel electromagnet could lift stupendous weights (750 *lbs*). By contrast, my 10" long iron nail attracted about 10 *gms* of magnetite sand when the enameled wire windings surrounding it were connected to four *D* cells. Yet each of us encountered confusions in interpreting our electromagnet's response when series and parallel connections were made among the several separate lengths of wire composing its windings. This paper considers those experiments with series and parallel wiring and what they reflect about learning.

1. Henry's Electromagnet

Henry's interest in devising electromagnetic instruments[6] was partly pedagogic: he wanted to impress his students at Albany Academy)[7] with dramatic class demonstrations. Thus he sought to amplify electromagnetic effects. Somewhere in reading contemporary journals, Henry noticed what he called "Prof. Schweiger's galvanometer" [*sic*].[8,9] As he understood it, that device was distinguished by "several strands of wire, each covered with silk, instead of one".[10,11] Henry regarded this innovation – to put wires in parallel – as what made his electromagnet more prodigious in action than its predecessors.

Henry's premier electromagnet was the first construction combining all these features at once: separate insulated wires wound into multilayer coils successively positioned around an iron horseshoe. The wire ends of each coil could be attached in succession (series). Alternatively, their similar ends could be "soldered" together and contacted directly to the ends of the battery, to make multiple coils (parallel). Configurations combining both types of attachment were also possible. When

[5] STAUBERMANN (1998).
[6] Previously, Henry modified the galvanometer (HENRY 1830).
[7] MOYER (1997).
[8] Perhaps while reading in the libraries at West Point and Yale during his honeymoon trip, Henry came across a reference to a galvanic coil wound from wires in parallel which he later (erroneously) called the "Schweigger Multiplier".[9]
[9] HENRY (1831a).
[10] HENRY (1831a), p. 401.
[11] I have not located a source accessible to Henry that describes a (Schweigger?) multiplier in which wires were connected in parallel. Schweigger described only a single wire"multiplier"; [29,30] Poggendorff explored parallel wiring in his "magnetic condensor".[31]

similar ends of all nine coils (fully in parallel) were connected to the zinc or copper of a small single voltaic pair, the magnetized horseshoe lifted up to 750 pounds.[9,12]

In making this instrument, Henry adapted materials at hand (as I did when experimentally following these accounts). When Henry referred to "copper bell wire", this did not denote that used in electric doorbells (as it does today). Instead, the copper wire of Henry's coils was probably imported from England,[13] where it was ordinarily used "for the bell pull of mechanical bells"![14] For the batteries, sheet copper may have come from nearby Troy,[15] but good sheet zinc had to be ordered from New York:

> there being no sheet zinc in Albany...sheet zinc is abundant in New York and I have sent for a supply.[16]

A "common spinning wheel" was used to spin silk thread around the wire.[17] The silk insulation between the layers of the coils was reportedly acquired through the "sacrifice on the part of his wife of her white silk petticoat".[18,19]

Insulating wires in coils was a new necessity of work with electromagnetism)[24] Henry's own understanding of insulation had developed through a mishap. An

[12] At the request of Yale chemist Benjamin Silliman, Henry constructed a much larger electromagnet. Under his expertise, its keeper raised a record-breaking ton[20] – but only half that weight when Silliman presented it to his classes.[21]
[13] BLAKE-COLEMAN (1992).
[14] COULSON (1950), p. 53.
[15] The Troy Iron and Nail Factory was founded in 1814 in nearby Troy NY for the "manufacturing of barr Iron, Steel ... sheet copper ..." ("Act of Incorporation of Troy Iron and Nail Factory", Jan. 15, 1814, in Mss: 596 1813-1902 vertical file collection on wire manufacturing in the Baker Historical Collection at Harvard University).
[16] November 4, 1831, HENRY (1972).
[17] Jan. 27, 1832, HENRY (1972).
[18] AMES (1900), p. 89.
[19] This tradition regarding Harriet Henry (1808-1882) relates to the experimental chronology. On December 10, 1830, Henry wrote Silliman, editor of *American Journal of Science*, urgently requesting publication of his two-year electromagnetism work which Moll's recent report)[22] had just "anticipated in part").[23] As no lab records from Henry's early career survive, the only corroboration for this two-year investigation is an Albany Institute record that on April 15, 1829 Henry demonstrated "Electro & thermo-magnetism" using "modifications of the usual Instruments").[23] This does not appear to describe a stupendous electromagnet. The Henry's wedding on May 3, 1830 was followed by a trip to Yale, New York and West Point. Harriet then returned to her family in Schenectady until mid-August when she and her family relocated to Albany. Was the great electromagnet assembled in the summer of 1830 with Harriet's "old silk"? Nothing in the couple's correspondence from that time)[23] alludes to such a project.
[20] HENRY (1831b).
[21] March 5 and April 26, 1832, HENRY (1972).
[22] MOLL (1830).
[23] HENRY (1972).

electromagnet failed to function as expected. After "considerable" perplexity, he located a cross-contact that kept "the galvanic current ... [*from*] making the entire circuit".[25] He then devoted "unnecessarily minute" (May 8, 1832) attention to redundancy in insulation: varnishing the horseshoe itself and layering silk strips and varnish between each successive layer of windings. The novelty of this practical analysis of the circulation of electricity shows Henry's understanding that constraining electricity to a specific coiled path is inherently three-dimensional.

Each of the nine coils making up Henry's electromagnet was wound as a separate four-layer unit from one 60 *ft* wire length. This arrangement conveys a different thinking from previous electromagnets)[26] by which one wire was wound continuously over the iron. With it, the strength of magnetism evolved from coils located at each different position along the horseshoe's perimeter could be measured and compared. Use of this arrangement also entails working out consistency in the clockwise or counterclockwise direction in which each coil is wound. Any inversion in winding direction will result in cancellations between the magnetization of oppositely wound segments (I encountered this with my electromagnet). Henry and other coil makers devised various schemes for ensuring consistency in their electromagnet windings.[27,28]

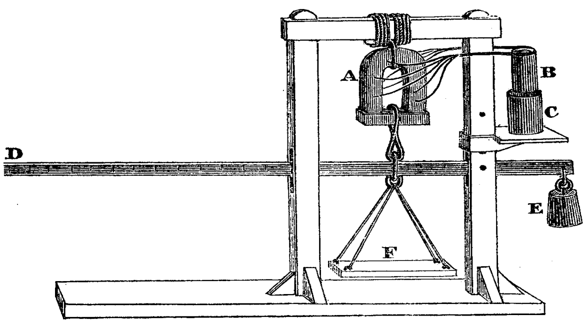

Figure 1 By adding weights to tray *F* , the maximal load capacity of Henry's electromagnet, *A*, could be determined. The galvanic plates, *B,* are depicted out of the cup, *C,* containing the acid.[9]

[24] Previously, Schweigger, Poggendorff, and Moll had used thread or wax to insulate wire in their coiled devices.[29,30,31,32]
[25] January 27, 1832, HENRY (1972).
[26] STURGEON (1825).
[27] HARE (1831).
[28] April 23, 1832, December 29, 1842, HENRY (1972).
[29] SCHWEIGGER (1821a).
[30] SCHWEIGGER (1821b).
[31] POGGENDORFF (1821).
[32] MOLL (1821).

The nine coils allowed research into what wiring combinations evoked greatest magnetic response from the electromagnet. The electromagnet's maximum load capacity could be determined by adding weights to a tray hung from its removable keeper (Figure 1). Henry tested this lift capacity under common (parallel) attachments of two, three, four, six and nine coils. With each addition, the applied load could be increased.

2. Series and Parallel Windings

Henry regarded his experimenting with combinations of coil connections as having "conclusively proved" that

> ...the power of the coil was materially increased by multiplying the number of wires, without increasing the length of each...[33]...in forming the coil we may either use one very long wire or several shorter ones as the circumstances may require; in the first case, our galvanic combinations must consist of a number of plates so as to give projectile force;[34] in the second, it must be formed of a single pair (p. 404).

Or, that an electromagnet's pull was greater when its windings were arranged as many wires (in parallel) than as one wire (of the same length, in series). This was the case when a single pair of plates activated the coil. However, with a trough battery consisting of many pairs of plates attached in series, greater electromagnetic effect was achieved from long windings (series).

Indications for this inference occur in Henry's paper, which was hastily assembled in response to Moll's publication about his electromagnet which lifted 75 pounds.[22] But Henry's experiments were not structured to explicitly pit multi-wire (parallel) windings against a single-wire (series) one, by keeping other conditions constant. In preliminary tests, lengths of uncoiled wire were inserted into a circuit containing a small electromagnet (*Exp*. 3-6).[9] These lengths were connected either in parallel with each other or in series. Henry found that the electromagnet lifted greater weight when the two wire strands were as one (in parallel) than when combined continuously (in series). However in these tests, the wires were not coiled around the iron form. Instead, they functioned only as resistance, admitting more (parallel) or less (series) current into the small electromagnet's windings.

With the large nine-coil electromagnet,[37] Henry did compare six coils (in parallel) directly against three parallel combinations of two coils each (a hybrid

[33] HENRY (1831a), p. 402.
[34] Henry's interpretation of `projectile force' as a property of voltaic combinations was influenced by Hare's analysis of his batteries by which many units could be put in series or in parallel.[35]
[35] HARE (1818).
[37] HENRY used a smaller electromagnet in performing some tests to compare the magnetic pull associated with different winding configurations. But he did not seem to use this smaller instrument as a model for working out the properties of the larger one, in the way that I used a nail

comparison), and two coils in parallel against the same two coils in series. Under these parallel connections, the electromagnet lifted greater weight than under series. The tests comparing two coils against one (Henry's one direct contrast between parallel and series) were done at separate times (labeled Experiments 10 and 19). The battery may have lost power (parallel was tested first). It further seems that, in his original thinking, Henry did not isolate these cases as exemplifying a principle feature of his instrument's design.

Henry never reported making a test comparing the electromagnet's pull when its nine wires were connected fully in series against the pull when its wiring was fully parallel. The absence of such direct comparison testing suggests that, while Henry credited his innovation to the electromagnet's (parallel) wiring, questioning of this was not a central concern. The (single) demonstration of parallel against series was incidental to his deeper interest in lifting weights.

Thus his investigative thinking contrasts with my responses to working with these materials and behavior. For me, it became a persistent question, to understand more about the circumstances in which either series or parallel wiring gave the more pronounced electromagnetic response. Henry seems to have accepted his initial finding (favoring parallel wiring) and adopted it into all his electromagnets, without checking its limitations.

This feeling, on my part, is reminiscent of how a teacher may feel a student has not adequately researched some inference. Yet such awareness, by me or a teacher, may not, in itself, be helpful to the learner who is engaged in working out some understanding. Each learner needs to work within and from what they deeply know. By drawing upon different questions and experiences, a learner may still get to some place (such as an electromagnet that lifts a ton) unanticipated by a teacher. What seems to be the same experiment will develop differently under the work of a student, from that of the teacher, or of Henry and me.

The arrangement of nine coils on the horseshoe made a wide search space available for analysis. However Henry did not conduct a search that was systematic for (my) question of parallel versus series windings. Instead, his experimental record followed conditions that appeared to further amplify the electromagnet's pull.

This coheres with another feature evident in the experimenting of novices such as myself and students:[38,2] systematicity in method is often partial, incomplete, or even lacking. The novices do not sort out multiple, simultaneously inhering factors by separately controlling for each, and collecting the resulting responses. Instead,

electromagnet as a model to research the effects under series and parallel connections of the windings. One of the small electromagnets held in Harvard's Historical Collection of Scientific Instruments appears to be a device constructed by Daniel Davis (0404; and modeled on Henry's electromagnet?) expressly for comparatively testing series and parallel connections among the nine coils wound around the 'U'-shaped form.

[38] CAVICCHI (1997)

their work tends to form along experimental variations that make the effect under study more perceptible. To impose controls and systematicity before an investigator's questions and experiences are ready for such structure, may unproductively limit what can be learned. Part of the novice's work at learning is in developing broad, not yet structured, experiences from which that learner's own questions can begin forming.

Similarly, there is another incompleteness of systematicity in the experimenting upon which Henry based his inference relating battery type to electromagnetic performance. He inferred that when a trough battery was used, greater electromagnetic effect was obtained with one long wire (series), whereas when a "single pair" of plates were used, multiple wires (parallel) gave greater effect[39]. As mentioned above, that wire was uncoiled and functioned only as a resistor. And, Henry did not use the same length of wire in each case contrasting the trough battery against the single pair. Further tests of this were never attempted: the room containing this apparatus was needed "for public exercises" (p. 403). By its structure, this test, along with Henry's other experiments, loosely associates battery type (single pair or trough) with a load (parallel or series) under which circuits including that battery will produce greater electromagnetism. But it is not expressed as an understanding of balance between battery and load or of how coils differently affect that balance by being connected either in parallel or in series.

Gerrit Moll, the other contemporary investigator of large electromagnets, was thoroughly perplexed by Henry's accomplishment in electromagnetically lifting great weights. Moll appealed to Faraday for advice[40] regarding his inability to procure comparable magnetic strength:

> I have been toiling very much these days, in endeavouring to repeat the American electro-magnetic experiments, but without success. I could not convince myself that by increasing the number of coils the power of the temporary magnet was increased in the least degree... I shall be very happy to learn whether you have been more successful in repeating the American experiments...[41]

It seems likely to me that Moll did not have access to Henry's actual paper[9] but only to a Royal Institution abstract[42] of it (edited by Faraday (Moyer [43])?). While that abstract ascribed the electromagnet's "extraordinary effect" to "an increase in the number of coils without increasing the length of the wire"[44,45] the sense of this

[39] HENRY (1831a), pp. 403-4.
[40] Researchers have observed that Faraday must have been aware of Henry's electromagnet[23, 43, 46] and speculated that it may have contributed to Faraday's early electromagnetic induction work,[43] but have not identified any replications of it in Faraday's records.
[41] Moll to Faraday, June 7, 1831, HENRY (1972).
[42] *J.R.I.* (1830-1).
[43] MOYER (1997).
[44] *J.R.I.* (1830-1), p. 609.

expression was lost as the abstract did not fully specify how Henry wound coils, or how he connected their ends. Thus, the confused and confusing distinctions between parallel and series connections, that Henry was engaged with, were not communicated. In fact, the abstract misrepresented Henry's "Experiment 9" as a test of all (nine) coils "united as to form a continuous wire";[44] a series test which Henry never reported doing.

Moll's vagueness, in describing his efforts to Faraday, suggests what confused and concerned him. He left blank spaces that omit key dimensions (size of battery plates, number of turns in coils). He did not specify the kind of connections (series, parallel) he made between a single cell and the five coiled layers wound over an iron horseshoe. The reasoning by which he came to feel ``foiled in this attempt''[47] is unclear; he did not seem to have construed his own experiments as tests of (parallel) methods of wiring. As with Henry, his testing appears to have been grounded upon – and guided by – what maximal weight an electromagnet will support.

The configurations of wiring and the underlying means by which circuital electricity divides and balances were not explicit within the community investigating electromagnetic effects. Although it was known that electricity branched along multiple paths, a new, different and still-unspecified understanding of this was developing in more systematic methods of insulating wire, and in the observations that electromagnetic responses are affected when the wire coiling is split to allow multiple paths.

What the electromagnetic phenomena were showing about circuits was more complex than those investigators had means to grasp. While the investigators' confused or vague efforts were caught in that complexity, they implicitly acknowledged it when directly reporting what they noticed. This quality, by which complex effects sustain both confusion and further inquiry, is diminished when the work is reduced to an over-simplified account, as happened with the abstracting of Henry's paper and so commonly recurs in our textbook summaries. Yet understanding and holding on to that quality is essential for developing teaching and learning as an interactive researching of our thinking and the physical world.

3. My Experiments Comparing Series and Parallel

Throughout my experimenting with improvised electromagnetic instruments during my dissertation study,[2] it continually puzzled me that Henry associated his electromagnet's prodigious performance with the parallel connections of coils in its windings. I observed only the opposite: the electromagnetic effect was always enhanced when coils were connected in series, not in parallel. Series outdid parallel both when the coils had an air

[45] This expression, which appeared in Moll's letter (quoted above), was differently expressed in Henry's own paper.[9]
[47] Moll to Faraday, June 7, 1831, HENRY (1972).

core and their magnetism was detected by how much a magnetic needle deflected (a galvanometer) and when the coils were wound over iron and their magnetism was demonstrated by the weight of magnetite sand that iron attracted.

It was this confusion about series, parallel, and how the historic instruments performed differently from mine, that I followed with my own investigating. And it was by holding that confusion deeply in my thinking, and exploring it through available materials, that my experience connected with that of historical learners.

To further understand this, I modeled the electromagnet circuit. The magnitude of the current, I, flowing through the resistive coils wound around the iron form determines the magnetic field within the iron and the strength of its pull. The coils – either in series or in parallel – constituted the load resistance, R_l, in my circuit, through which current flowed. There was one other element in my circuit: the *D* cell providing its voltage (1.5V).

The only circuit description of a battery familiar to me was the standard Thévenin model of introductory textbooks. It represents a battery's output voltage as the sum of an "ideal" voltage (the battery's voltage when unconnected, V_i) and a resistor. That resistor, or "internal resistance", R_i, stands for the battery's collective resistance to circulation of electric charge.

Following the textbooks, I assumed that a battery, such as the *D* cell, had a unique internal resistance. I linearly added that to the load resistance and computed the current flowing through that combined resistance, due to the ideal voltage. I did this for two cases of the load: when two equal resistors were connected in series, and when the same resistors were connected in parallel. In each case, the calculated current was different. The value of current depended on the relative magnitudes of internal resistance and load resistance. Thus it was that ratio (of internal to load resistance) that determined whether the electromagnet lifted more weight when its coils were in series, or in parallel. If the battery's internal resistance exceeded the resistance of one coil, then coils connected in *series* should result in stronger pull for the electromagnet. This argument also suggests that connecting many cells in parallel will reduce internal resistance.[48]

Yet this analysis was remote from what I understood through my beginning experimental experiences. The difference in effect seemed so big to me. Unlike the historic reports, my coils were always more magnetic when connected in series. I was further confused by finding that circuital current was greater when several *D*s were in series, than when in parallel. I lacked experimental strategies and trust in my work, that were eventually needed for analyzing these discrepancies. When my findings differed from texts, I assumed my circuits or interpretations were faulty.

A year later, after my experimental experience had developed, I resumed this question. I discussed this work in the lab with Wolf Rueckner and Joe Peidle;

[48] See my dissertation[49] for my derivation, discussed in this passage.

[49] CAVICCHI (1999), p. 800.

outside it with Phil Morrison and Tom Cavicchi. Through all these interactions – with materials, people and ideas – connections across the models (and their limits) and behavior of materials (and their complexities) gradually emerged for me. By wondering about how some historic experiments could have happened as described, I became aware of complexities in everyday materials.

By the model, stronger electromagnetism under series connection of its coils occurs when the battery is more resistive than one coil. One coil's resistance was a fraction of an ohm. What was the internal resistance of a *D*? I had assumed it was low – and lower than historic cell resistances. However, my doubts about these assumptions grew.

To characterize *D* cell, I connected a load resistance, R_l, across the *D* and used meters to record the voltage, V, across it, and the current, I, through that resistance. I applied loads of successively lower resistance, starting with kilo-ohms and decreasing to fractions of ohms. As I diminished the load resistance, the current increased across four orders of magnitude. In working to supply these greater currents, the battery became hot and the voltage across its terminals dropped. This drop was small but steady until the circuit's resistance was about 1Ω (Figure 2). Then the battery's voltage plummeted well below 1V. In calculating internal resistance from this data, I obtained a range of values.[50] These calculations did not yield one number, one answer, the singular value of "the internal resistance of a battery" (for example, Giancoli[51]. In repeated improvements to the experiment, the *D*'s internal resistance was never one number. It was nonlinear,[52] having a different value for each load, varying from 9Ω under 2-1kΩ loads, to .2Ω under low (3Ω) loads. These analyses suggested that the *D* ranged in internal resistance values that were greater than my coil's resistance. This was consistent with my observations that, when multiple coils are connected in series, their magnetic effects are enhanced.

[50] Under the Thévenin: model, a battery's internal resistance can be calculated as: R_i=(V_i-V_1)/{V_l})R_l. I later found this method was recommended to amateurs in *Electrician and Mechanic*, 19 (1909), p. 441.
[51] GIANCOLI (1991), p. 484.
[52] I used linear regression procedures and logarithmic models to analyze the data and infer the nonlinear behavior of the *D*'s internal resistance.

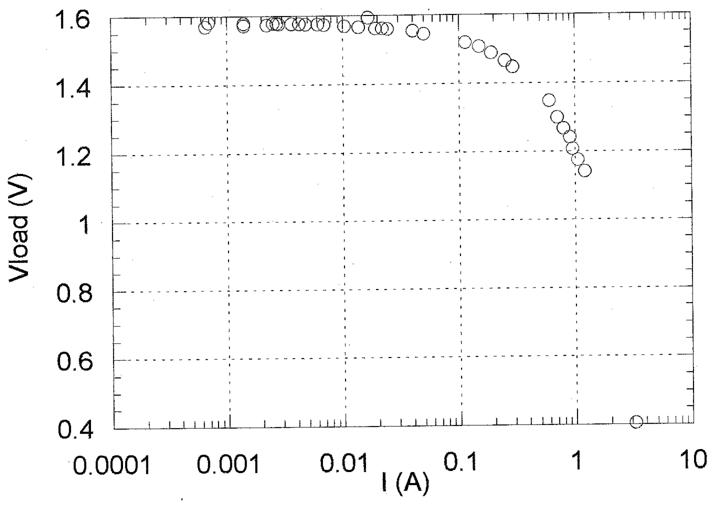

Figure 2 A semi-log plot of my data of voltage across a *D* cell, against current through a resistance that was reduced in successive trials.

My further explorations[53] provoked my interest in using the materials available to me – copper wire, iron nail, *Eveready D*s – to produce what historic investigators observed: greater magnetic pull when an electromagnet's coils are connected in parallel, than in series. I combined these materials in rough instrumental analogy to Henry's electromagnet and tray of weights. I weighed the amount of magnetite sand attracted to the head of a 10" long iron nail when it became electromagnetic as current flowed in its windings. The four layers of the nail's windings could be connected in parallel or in series. As with my previous experiments, when the coil's layers were in parallel, the nail electromagnet lifted only half as much sand as that lifted under the series configuration (Figure 3). These trials deepened my awareness of what measurements and model seemed to entail: the *D*'s higher internal resistance determined the stronger electromagnetism of coils in series.

[53] Many of my experiments with magnetic effects of coils and electromagnets in series and parallel connection are omitted from this account. See my dissertation[54] for details.
[54] CAVICCHI (1999), pp. 485-503.

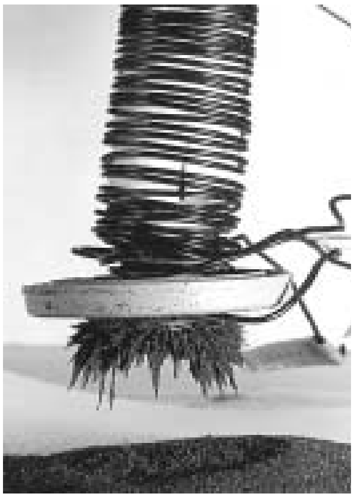

Figure 3 My electromagnet: a long nail that lifts magnetite sand from a pile when its coiled wires are connected to *D* cells. Photo by Joe Peidle.

I wanted to see if reducing the battery's internal resistance would bring the coil's response over to the other regime (greater effect under parallel connections). I computed that putting many *D*s in parallel would reduce the net internal resistance. I had tried this several times and never noticed the current increasing. But my internal resistance studies suggested that the *D*'s internal resistance might be high and variable. Perhaps it would take putting many *D*s in parallel to observe any change in the outcome of comparisons between series and parallel.

Connecting many *D*s in parallel involved cutting wire lengths, stripping their ends, duct taping the wire ends against each cell end, and compressing the tape with rubber bands. Aligning *D*s and their wires in the same orientation was tricky. More than once, I felt a cell suddenly heat up: it had been inserted opposite all the others, providing them with a complete electrical path! Between the two copper strips making endpoints for this complex array of *D*s and wires, the voltage was still 1.5V, just as for a single cell. Connecting the nail's coil across these copper strips would complete the circuit, making the nail into an electromagnet.

I started with one *D* cell, and successively added fresh *D*s in parallel with it. At each addition (from one to twenty *D*s), I used a balance to weigh magnetite sand attracted by the nail, when its windings were configured in series, and in parallel. In practice, this measurement was full of uncertainty. The nail retained sand when the source was disconnected. To prevent this residual magnetism from successively accumulating, I inverted the battery connections (and the magnetic polarity within the nail) between each test. Imperceptible irregularities affected the geometry and amount of sand attracted; my nail's rough head was unlike the historically polished surfaces between magnet and keeper. As more *D*s were added, the nail did not hold more sand well and sometimes released it.

With under ten *D*s in parallel, the familiar consistency was repeated: the nail was more electromagnetic for series connections (Figure 4). With more *D*s in parallel, the data became too widely scattered to suggest a trend. Sometimes, the nail attracted more sand in the parallel configuration; such observations were too limited (perhaps involving other physical complexities) to indicate that the circuit balance had changed.

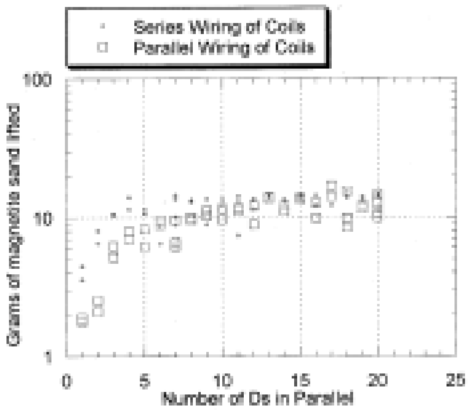

Figure 4 A plot of weight of sand (gm) lifted by my electromagnet against number of fresh *D* cells connected in parallel as the source. The nail's windings were connected both in series and parallel.

To circumvent the many experimental ambiguities, I switched to contemporary apparatus. I replaced the *D*s with a power supply and measured the magnetic field at one spot with a gaussmeter. These instruments allowed for canceling, or `zeroing' the nail's residual magnetism (read from the gaussmeter) by sending oppositely directed currents through the nail's windings.

With these instruments, the multidimensional nature of electrical properties could be constrained. With the power supply configured as a current source, by setting the current and leaving the voltage free to take on any value, the nail's magnetism was lower under parallel connection of the coils. By selecting another power supply with very low internal resistance (0.0003Ω; Kepco KS60-10M) and configuring it as a voltage source (by specifying voltage and leaving current to take any value up to the instrument's maximum), the nail's magnetism was equivalent under both series and parallel (Figure 5).[55]

[55] This result did not occur when the first power supply was tested as a voltage source; it could not supply sufficient current to the low resistance coils to enable it to maintain constant voltage.

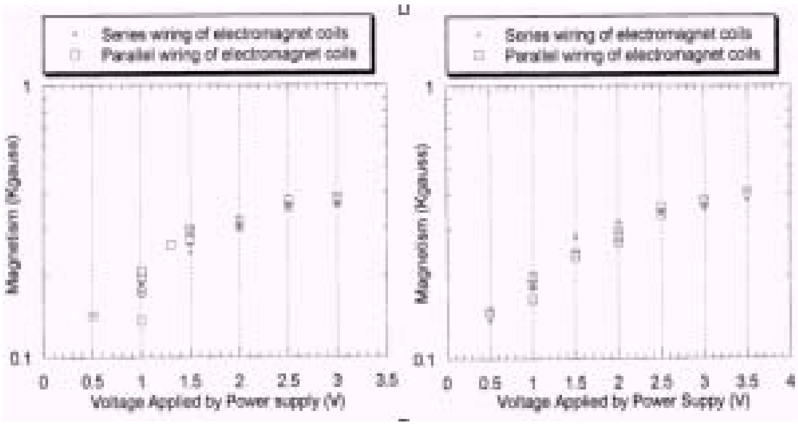

Figure 5 Readings (in kilogauss) of the magnetic field produced by a nail electromagnet activated by a power supply operating at fixed values of voltage (but variable current). For this very low resistance supply, the nail's electromagnetism is nearly the same under series (dot) and parallel (box) connections of the coils.

At any specified value of voltage, the parallel windings drew twice the current (up to 17A at 3.5V) as the series windings.[56] Now, the nail's electromagnetism conformed to the modeled rules for what electricity does in series and parallel.

4. Connections to Instruction and Historic Investigations

This comparative exploration, of electromagnetic effects under series and parallel connections, brought me to closely examine relative balances between internal and external resistance. The standard model's predictions had not settled my questions. Rather, so much ambiguity remained in my test circuits, observations of responses, and in *D* cells' behavior, that it was not clear to me – without working through many alternatives – what experimental changes might facilitate the observations I hoped to make.

The power supply tests rendered into material effects what the model described analytically. The regulation and simplicity of those tests and the model contrasted against my battery-nail circuit with many overlaid complications. In staying with that complex circuit, I developed my awareness of electricity's behavior and the ways (initially subtle and obscure to me) by which the model's abstract terms (such as internal resistance) became apparent through what my materials did. These extended trials brought me in some ways closer, not to the specific paths of historic

[56] This data approximated the model's depiction of equivalence between magnetic effect under parallel and series when the source's internal resistance is negligible. In this mode, the power supply mimicked an ideal battery.

investigators, but to qualities of confusion and incomplete clues from phenomena, by which their learning and noticing happened.

The clean consistency of the data from power supply tests (Figure 5) was unlike that of my data of weights of sand lifted under circuits with *D*s in parallel (Figure 4). Even with all their complex internal design, the power supply and gaussmeter brought about simplicity in what electricity did and how that was observed, which everyday batteries, with their many chemical variations, could not provide. Comparison of these two graphs suggests how, with the isolation of physical properties in their delivery, detection and analysis, the behavior of the physical world – and our interpretations of them – manifest an orderliness not otherwise apparent.

The nature of what historic investigators – and our students – notice and experience with materials and physical phenomena is closer to my trials with the many *D*s in parallel than to power supply tests. For them, even the idea that one phenomenon is different from another, having boundaries between behavior and responses, has not been worked out: these physical qualities remain co-concurrent in everything that happens. In learning from these physical phenomena, the investigators first developed ways of engaging this full complexity. By that exploration, they began to know what made effect and magnitude, and the nature of what constitutes a physical distinction or boundaries. Until a learner works out these distinctions and relationships, the learner will not see them in the phenomena at all and cannot be (productively) told about them. However, academic courses are usually founded on the inverse premise – that a learner can be told. Thus courses open with assertions of definitions, boundaries, and laws established by others that are unrelated to students' experiences.

For novice investigators such as Henry, and me, experimental or instrumental changes that alter physical effect may take on value or meaning that seems incompletely scoped under more systematic analysis of the phenomena. Thus what Henry experienced as "a very material improvement in the formation of the coil"[10] by wiring his electromagnets in parallel, does not – in our view – derive from a fundamental feature of "galvanism". Instead, the parallel configuration, by which Henry electromagnetically lifted stupendous weights, indicates details about the materials constituting his electromagnet and battery which were not then identified in measurable ways. Evidently, with what was then considered a small cell "containing only 2/5 of a square foot of zinc surface, and requiring only half a pint of diluted acid"[57], the internal resistance was much less than the .3Ω of one 60' length of that electromagnet's coils. It must have been much less resistive than our *D* cells.

Henry so consistently – and committedly – ascribed enhanced magnetism to parallel wiring, that later evidence of the other (series-dominant) behavior was startling to read. Several years after his concentrated period of constructing great electromagnets, one day's isolated trial showed something different. A thin current-

[57] HENRY (1831a), p. 405

bearing wire exerted more magnetic pull on a pile of iron filings, than a thick one (acting like many wires in parallel). Unfortunately, the comparative value of this experiment cannot be judged. Its record leaves unspecified the of the wires relative lengths and the state of the battery.[58] Whatever the details, the wires did not act as Henry expected. This provoked him to question the inferences guiding his prior magnet constructions:[59]

> Transmitted a current through a thick wire from the small circular battery, lifted small quantity of filings.
>
> Transmitted same current through thin wire, quantity much greater. Does not this principle operate in electromagnetic magnets – may we not in some cases have too many wires?[60]

Perhaps this question expresses a tentative awareness that electricity's consistency is not shown through conformancy to one single rule of behavior, but by what comes out under many "cases".

Intriguingly, a decade after Henry's electromagnet building, a blind experimenter contrived a unique "magnetometer" which allowed direct comparison of an electromagnet's pull under series and parallel wiring of its coils.[61] Hearder[62] wound a cable of 24 separately insulated wires around a U-shaped iron bar (Figure 6). When activated by either of two standard cells,[63] this electromagnet lifted more than twice the weight when its 24 coils were in series than when in parallel. But with a lower voltage cell[64] the parallel configuration outdid the series.[65] While this is coherent with my observations and appears strikingly analogous to my interest in comparing effects under series and parallel wiring and relations between internal and external resistance, Hearder's interpretation was different. His investigation was to explore ways of

[58] This appears to be the same type of "circular battery" that Henry had used to activate his electromagnets. Was it unusually resistive on that day in 1835?

[59] In the following quote, Henry cannot be using the expression "same current" in the terms we understand that today. Perhaps Henry meant that both wires were attached to the same battery in the same way.

[60] March 19, 1835, HENRY (1975).

[61] HEARDER (1844).

[62] Jonathan HEARDER (1810-1877) became involved in investigating and teaching electricity in his early teens. After a gunpowder explosion blinded him, students no longer attended his school, but he continued inventing such electromagnetic devices as induction coils)[66] and became a popular public lecturer.[67]

[63] These were the Grove's cell and Daniels cell.[65] Later, the Grove's cell was described as exhibiting 1.7-1.9V and .25Ω internal resistance; the Daniels as 1.08V, 4-10Ω.[6].

[64] This was the Smee's cell.[65]

[65] NOAD (1857).

[66] HEARDER (1856).

[67] HARPLEY (1877).

[68] BOTTONE (1902).

distinguishing and quantifying electrical properties ("intensity" and "quantity") of the three cells while lacking a direct means of measuring those properties.

An interesting feature of this study is how the differently scaled balance between source and wire material linked to the interpreting of each investigator. This is an experience not so easy to come by when working with the meters and power supplies of today. Our analysis, meters and instruments make it possible to describe and use electricity without being overwhelmed in this confusion of many materially contingent effects.

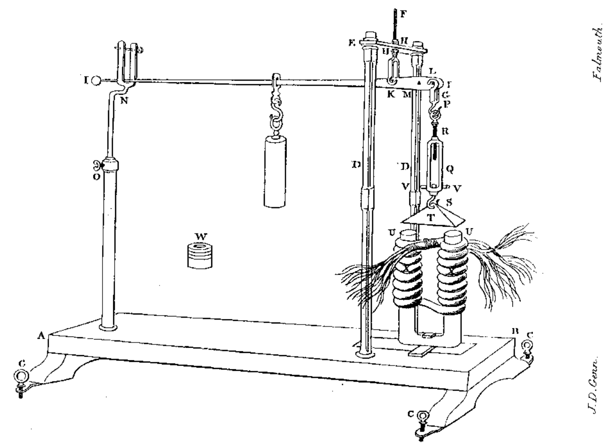

Figure 6 Hearder's "magnetometer'' is wound with 24 wires which may be connected in parallel or series.[61]

But it was just such confusion that I felt would be productive to explore, for understanding more about how the historic investigators – and my students – encountered and thought about electrical phenomena. In this exploring, electricity's divisions and circuiting become evident through specific instances of materials and their patterns remain uncertainly tied to features (like internal resistance) whose character is still concealed. Working through the relationships embedded in such confusion may be more a making of many connections among experiments, observations and ideas, than of fitting them to the rule. Any understanding of orderly behavior emerging through this work will be grounded in many instances; this experience can suggest other particular cases and what order they will show.

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