Experiences with the magnetism of conducting loops: Historical instruments, experimental replications, and productive confusions

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This study investigates nineteenth century laboratory work on electromagnetism through historical accounts and experimental replications. Oersted found that when a magnetic needle was placed in varying positions around a conducting wire, its orientation changed: in moving from a spot above the wire to one below, its sense inverted. This behavior was confusing and provocative. Early experimenters such as Johann Schweigger, Johann Poggendorff, and James Cumming engaged it by bending wire into loops. These loops, which increased the magnetic effect on a compass placed within, also provided evidence of their understanding and confusion. Coiling conducting wires around iron magnetized it, but when some wires coiled oppositely from others, the effect diminished. This effect confused contemporaries of Joseph Henry who made electromagnets, and amateurs later in the century who constructed multisection induction coils. I experienced these confusions myself while working with multilayer coils and induction coils that I made to replicate the historical instruments. This study shows how confusion can be a productive element in learning, by engaging learners to ask questions and invent experiments. By providing space for learners' confusions, teachers can support the development of their students' physical understandings.
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I. INTRODUCTION

A loop is like a circle, but it is not a circle. Its two ends go to different places, breaking its symmetry, making a difference that is inherently three-dimensional. When the loop is a conducting wire, the invisible extension of magnetic field adds to this complexity. And, an opposite winding (clockwise versus counterclockwise, see Fig. 1) breaks the symmetry as well, in a way that is distinguished by a traversing current with the opposite magnetic sense.

This kind of complexity in physical phenomena can give rise to confusion as a learner tries to understand it by engaging with the physical behavior. For example, it is not so apparent to learners that a conducting winding exhibits a three-dimensional asymmetry. The confusion that learners feel in working with these phenomena also had common threads in the historical development of understanding and experimenting with electricity.

This study explores confusions inherent in working with magnetic effects of wire loops, both from the perspective of my own reconstructive experiments and from that of the historical accounts of early electrical experimenters. These stories add to our understanding, not only of the history, but also of the confusion that arises as learners become involved with these intricate phenomena.

II. LEARNING BY REPLICATING HISTORICAL EXPERIMENTS

Apparatus and demonstrations derived from historical experiments often provide a grounding for the laboratory problems adapted for physics students.[1] Although the equipment, measurement techniques, and analysis are typically updated, the historically authentic apparatus, procedures, and context may receive cursory treatment. The instructional import of these problems stems from their relation to current physics content and methods, not to the history itself.

Including historical elements into the redoing of experiments, makes it possible to investigatively access questions that integrate the physics, history, and learning. Details of the original accounts, experimental practice, and materials become relevant in ways not suspected prior to conducting the replication. Similarly, unrecorded details of the original context may emerge from problems in the replication.

Sibum's repeated redoing of Joule's landmark experimental determination of the mechanical equivalent of heat is a fascinating example of the interchange between historical and experimental inquiry.[2] Sibum's first attempt was conducted in an air-conditioned lab; the weight-driven paddle wheels used to stir water in a vat were constructed after Joule's description; the temperature readings were made with sensitive Beckmann thermometers. Anomalies immediately arose: the weights did not fall at the expected rate; it took considerable practice to read the thermometers to Joule's precision; the experimenters could not perform the physical feat of winding up the weights in the time Joule specified; the experimenters' body heat perturbed the room temperature.

These difficulties precipitated further research. Sibum measured Joule's actual preserved paddle wheels, found them different from the written description, and used these measurements in building replacement wheels. Because Joule's involvement in his father's successful brewery might have informed his experimental technique, Sibum researched contemporary brewing practices. At the time, brewers were shifting from using traditional methods to using thermometers to help regulate the brewing process; this use would explain Joule's skill in thermometry. Brewery demanded physical strength comparable to that needed to wind the weights in Joule's experiment; perhaps Joule hired an unmentioned muscular brewer's assistant to do the winding. With the benefit of this additional research, on redoing the experiment in an eighteenth-century storage cellar, Sibum produced values for the mechanical equivalent of heat

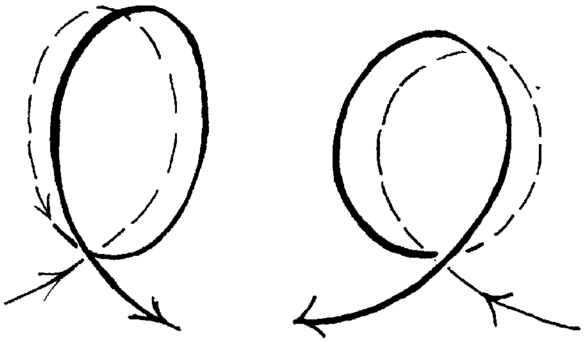

Fig. 1. The two ways of winding loops; the dashed loops are below the plane of the paper.

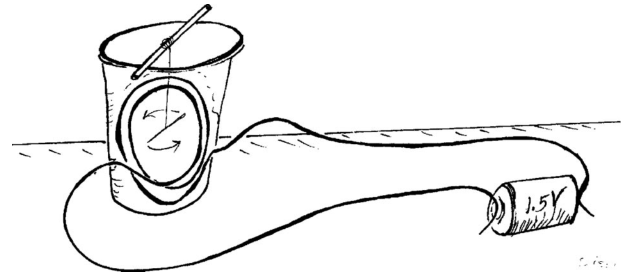

Fig. 2. The wire is bent into loops and supported by a cup to stay in the vertical plane. A magnetized needle hangs within the loop, by a thread that is tied to a straw which rests on the cup's rim. When the wire is connected to a *D* cell, the needle deflects.

(746.89 ft lb/Btu) that were consistent with each other and precise, but lower than Joule's value (772.692 ft lb/Btu) or modern determinations (776.1 ft lb/Btu). These results raised questions about how measurement, and precision without accuracy, were understood in the historical context.

Other replications have raised insightful observations about historical instruments and experiments. For example, an instrument modeled on Coulomb's eighteenth century torsion balance was so sensitive to the electrostatic charge of the observer's body as to put into doubt its role in establishing the inverse square law for electrostatic charges.[3] The color and illumination of the gas-lit artificial reference star in a nineteenth century photometer could not be replicated without finding out the chemical composition of ''town gas,'' something taken for granted in original accounts.[4] Replication studies have elucidated Galileo's motion studies,[5] Faraday's processes of thought and action in his work with magnetic rotations (1821),[6] electromagnetic induction (1831),[7] dielectrics and capacitance (1837),[8] diamagnetism (1845),[9] and colloids and gold films (1856).[10]

Including the replication of historical experiments into physics classes puts students in the position of raising these issues for themselves.[11] The intrinsic ambiguities and confusions of the historical context (that later expositions often omit) can empower students to make their own decisions about setting up the experiment and interpreting it.[12] Such experiences support students in becoming independent investigators, a valued goal for the introductory physics laboratory.[13]

In this paper, my replications are a resource both for inquiring into historical experiences, and for becoming more aware, as a learner myself, of physical complexities that a learner might encounter, as a student or as an interpreter of the historical context. The historical instruments themselves—early windings of conducting wire—are evidence of the makers' emerging, partial understanding of electromagnetism's spatial behavior. To put myself more in their place of responding directly to the electromagnetism of their wire coils, I allowed myself to experience confusion and found it productive for further experimental learning.

III. LOOPS AND ELECTRICITY

The magnetization direction of a current-bearing wire is routinely demonstrated and predicted by using a ''right-hand rule.'' One statement of it is that if the right hand thumb is oriented along the wire in the direction of (positive) current, the curling of the fingers gives the direction toward which a compass's north pole would orient. Because the magnetization circles around the wire (as represented by the fingers' curling), its direction at any point is tangential. If the wire is bent into a loop, the direction of magnetization at the loop's center points either up or down from the flat plane of the loop.[14] Working out this problem does not call for explicitly stating the winding sense (clockwise or counterclockwise); you simply apply the right hand to the direction of current flow.

To experience the circling effect of the magnetization as a learner, I chose to make a single conducting loop and look for its magnetization. The right-hand rule became less apparent when the wire, battery, and magnetic needle were combined together in my hands. First, I dangled a magnetized sewing needle by a thread tied around its middle into a wire loop connected to a *D* cell. This assemblage was too unwieldy and lacked support. I laid a coffee stirrer across a cup's top, suspended the needle's thread from the stirrer's middle (see Fig. 2), and finally the needle's tip oriented north! Next I looped a wire around the needle in the vertical plane, and aligned the plane along the Earth's north–south meridian. Then, if the needle made any response at all to the current in the loop, it would have to turn one way or the other: east or west.

Although I distrusted my makeshift instrument, the needle immediately responded to current in the loop. The amazement recorded in my lab notebook suggests my growing vulnerability to the evolving surprises of experimenting:

> ''But there is a pronounced effect! . . . Now I can see all sorts of questions for trying.''[15]

Next, I deepened my involvement and diverged further from my assumptions about what to expect. I wanted to compare what the needle did when the turns of the loop surrounding it went clockwise, with the counterclockwise case. I tried to make one wire loop of each. But in bending the loops, I mixed up right with left, clockwise with counterclockwise. I attempted to draw a clockwise and a counterclockwise loop and followed this drawing to make two loops. Connecting a battery to each loop produced the same response from a needle hung inside it (see Fig. 3). I was confused. I wrote:

> '' . . . but it came out clockwise (or was that how I was thinking about it? not sure?)—now I see both coils as clockwise—which they are.''[15]

Working with wire loops allowed me to experience the three-dimensional relation between current and magnetism. When a conducting wire is straight, its magnetic field circles around it; when the wire is looped, its magnetic field is di-

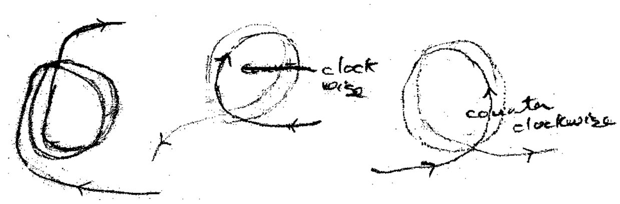

Fig. 3. I drew these sketches in my lab notebook as I was making my first loops with wire. I attempted to direct, from a two-dimensional drawing, the inherently three-dimensional property of the loops' winding. Both the loop on the left and the loop in the middle are clockwise although I had intended the one on right to be counterclockwise (notice the crossed-out label). The drawing on the right shows what I came to understand as a counterclockwise loop. From Ref. 15, April 8, 1997.

rected outward from the encircling loop. Between these two cases, the orientation of the current and magnetic field exchange places. This inversion is confusing. My awareness of it became a resource for researching historical examples. The original observers were also disarmed by magnetism's tangential circling about the conducting wire. When they went on to bend wire into loops, they were confused by the magnetic behavior.

IV. HISTORICAL BACKGROUND FOR WORKING WITH WIRES' MAGNETISM

Eighteenth century investigators who produced electricity by manually operating large friction machines had begun to notice that electricity was somehow related to magnetism. At the time, the only known sources of magnetism were mineral lodestone, needles magnetized by it, and the Earth. When electricity discharged through air with the fiery sparking either of lightning or of large electrical machines, nearby steel needles were magnetically affected. This lore was even woven into Melville's classic tale: the morning after a terrific storm whose lightning danced through the Pequod's masts and rigging, the ship was found heading opposite to the sun, not toward it as expected. As an experienced sea captain, Ahab recognized the effect, and exclaimed to his mate, Starbuck:

> ''I have it! It has happened before. Mr. Starbuck, last night's thunder turned our compasses—that's all. Thou hast before now heard of such a thing, I take it.''
>
> ''Aye; but never before has it happened to me, Sir, said the pale mate, gloomily.[16]

The crew took it as yet another sign of Ahab's infernal powers.

At the beginning of the nineteenth century, the production of electricity in a new form—as a continuous current in a circuit closed by a chemical battery—provided another access to its magnetic side-effects. But this possibility went unnoticed and untested for another twenty years, while the technology of chemical batteries or voltaic cells, was under continual development. The principle use of the electricity provided by these cells was to incite chemical separations and reactions. No one investigated the current-bearing wire itself by bending it or shaping it.

A philosophical belief in a unity inherent among all the natural forces, including electricity and magnetism, motivated John Christian Oersted to perform an experimental test of his own idea about this belief.[17] In the spring of 1820, Oersted conducted this test as a lecture demonstration for a class he was teaching. Reminding the class that lightning affects a magnetic needle, he proposed that a powerful galvanic discharge might have a similar effect. Because he suspected that this effect might be strengthened by bringing the current-bearing wire to ignition, he directed current from a large trough battery through a short length of thin platinum wire. The magnetic needle was placed directly under it at the place of ignition. All the class could see the needle deflect. Already, confusion was perceptible. Oersted later recalled in these words:

> ''Although the effect was unmistakable, it appeared to me nevertheless so confused that I deferred a minute examination of it to a period at which I hoped for more leisure.''[18]

During the summer break, Oersted experimented and made out patterns from the needle's behavior. What the needle did depended on its position around the wire, and on the direction of electricity going through that wire (determined by which end of the wire was connected to the battery's zinc end). In one experiment, the wire was above the needle and both wire and needle were aligned with earth's north–south line. When that wire was connected to the battery, the needle reoriented parallel to the east–west perpendicular direction. If, instead, the needle was above the wire and the same battery connection made, the needle oriented in the opposite sense. When needle and wire were in the same horizontal plane, the needle tipped up (on one wire side) or down (on the other). The needle's orientations reversed when the battery connection was inverted.

Taken overall, the needle's orienting showed a behavior that ''performs circles'' around the wire.[19] Oersted interpreted this behavior as evidence for a ''conflict of electricity'' occupying the space around the wire and having both an encircling and a linear, ''progressive'' component. This electric conflict was helical, a ''spiral line, bent toward the right'' like the tendril of a climbing plant. It affected the compass needle's north pole by making it reorient.[20] Within weeks of Oersted's publication of this novel phenomenon, it was further described and extended by researchers throughout Europe.[21] By suspending small magnets from cocoon silk at many locations and measuring their responses to the current-bearing wire, Jean-Baptiste Biot and Félix Savart determined the direction and magnitude of the force from the wire that acted upon the magnets.[22] After academician André-Marie Ampère showed that two wires attracted or repulsed each other (depending on the sense of their connections to the battery terminals) just like two magnets, he argued that all magnetism is produced by circulating currents, whether in a wire circuit or magnetic rock.[23] In forming this analysis, he was the first to demonstrate that electricity completes a closed path passing through both battery and wire, and that its flow (as shown by the magnetic needle) is the *same* in all parts of that circuit.

Although Ampère's sophisticated analysis has now become part of our conventional interpretation, it was not initially accessible to others at the time. Many who reacted immediately to Oersted's announcement by initiating their own experiments, experienced confusion about the magnetic needle's behavior. A year later, Michael Faraday conducted a comprehensive survey of the papers published in response to Oersted's, as a means of organizing their diverse observations and explanations. (This study launched his own findings of magnetic rotations.) Faraday detected the authors' confusions, particularly in regard to the magnetic needle's orienting:

> " . . . I have met with a great number of persons who have found it difficult to comprehend . . . "[24]

V. CONFUSIONS FROM GETTING WIRE INTO LOOPS

The following discussion follows the work of one of these early experimenters, University of Halle professor Johann Schweigger.[25] I expand the story with reflections derived from my own experiments and descriptions of multi-loop instruments made by two contemporaries of Schweigger.

A. Schweigger's doubling loops

Schweigger's work derived from Oersted's initial observations. Oersted remarked that the magnetic needle deflects one way when placed above the conducting wire, and oppositely when below it, and that it deflects oppositely when the conducting wire's attachments to the battery's ends are reversed. Schweigger used the geometry of the wire in space to relate these seemingly separate observations. In doing this, he devised a novel instrumentation—an early galvanometer—that "multiplied" the magnetic effect of the current.

Schweigger suspected that the reversals in the needle's deflection allowed for a way of increasing the overall magnetic effect.[26] He demonstrated how this increase worked by running a conducting wire so it passed over the compass, then turned around and came back below it. In this way the sense of the lower wire's effect was inverted. Now its action on the needle would be the same as that of the top wire; the two effects added, or "doubled," and the needle turned through a greater angle. On September 16, 1820 he presented this idea to the Naturforschende Gesellschaft, a natural philosophy society in Halle. Although Oersted demonstrated that a vertically oriented conducting wire affected the magnetic compass,[19] Schweigger did not consider how the loop's sides might also be contributing to the needle's deflection.

B. Reflection

Schweigger's interpretation that the looped wire provided a "doubling" intrigued me. It recalled the confusion that I had felt when the wire, which seemed only a continuous line, became three-dimensional. Perhaps when Schweigger described the single loop as a "doubling"of the magnetic effect, his thinking, too, was in transition. He had used the continuity of the wire to relate the seemingly separate observations of Oersted's wire placed above and below the compass. But following the line into its spatial contortions—thinking in the round—involved other subtleties.

C. Schweigger's figure-eight loopings

Schweigger was intrigued by how bending the wire around the needle showed that the magnetic effects "depend, not on the voltaic cell, but only on the connecting circuit."[27] Oersted had used a powerful battery of twenty pairs of plates in his classroom and his magnetic compass needle deflected through a full 90°. Apparently, Schweigger only had the use of a weak single voltaic cell. With it, he could not observe the 90° deflections—until he wound the wire in *several* loops around the needle. That the bent wire could do this suggested to him that the wire's configuration might matter more than the nature of the voltaic cell. (We now recognize the role of both these factors—the cell's electromotive force and the circuit's geometry.) And through understanding that the wire's form played a role in the magnetic effect, he became more involved in shaping how the wire went through the space between the cell's ends.

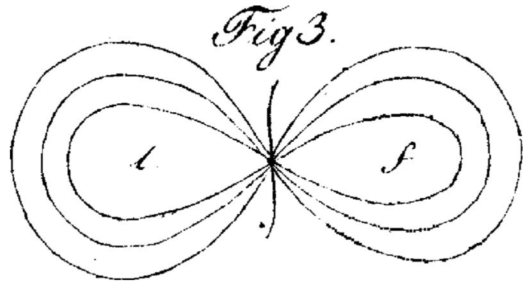

Fig. 4. Between the two halves of the figure-eight (∞), the placement of each wire's embedded top and bottom magnetizations are inverted. Thus, magnetic needles placed within the two loops will be deflected equally but oppositely. From Schweigger in Ref. 29.

At the beginning of November 1820, Schweigger presented a new instrument to the Halle philosophical society: one wax-coated wire bent into a triple figure-eight (∞), like a bow made with shoelaces (see Fig. 4). The wire's path wound back and forth from one loop to the next; successively each figure-eight had larger loops. All three paired loops were overlaid, compressed into a plane. As the paths all crossed at the middle, the wire's wax coating would have prevented shorts. The wax (and silk) coatings Schweigger used to keep electricity going throughout the looped paths are among the first instrumental uses of insulation around wires bearing voltaic currents.[28]

As a magnetic detector, Schweigger used a magnetic needle pivoted inside a small case. It could be placed within either central loop of the figure-eight. The needle responded to current by deflecting in the opposite sense when it was inside one loop in comparison to its deflection when it was inside the other loop.

The figure-eight's design is a development from Schweigger's previous single loop. What he had realized about the loop—that turning the wire back on itself reversed the sense of its magnetic effect—was applied again in making the right loop function as an inversion of the loop on the left. In the center of the figure-eight, the wire crossed over itself: the wire that was uppermost in the loop on the left, formed the bottom of the loop on the right. The crossover inverted the magnetic effect of the same wire, producing the opposing responses of the needle. This reversal is an amazing effect that anyone can demonstrate with a battery, looped wire, and magnetic compass.

In Schweigger's ways of understanding the wire by following its path at each turn and strengthening its effect by adding more turns, there was a constraint. The wire's path was constrained so that all its loops lay in one plane. In a subsequent, single loop version of the instrument, Schweigger formed a silver wire into a flat spiral (see Fig. 5). He wrote that the spiral was kept flat by fitting it in slotted wood and tying it with "silk threads in ways well known to the women when doing their cleaning work."[29]

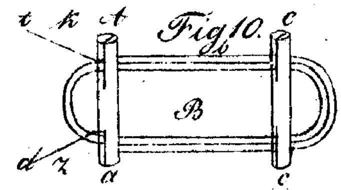

Fig. 5. Diagram of Schweigger's "multiplier," three loops of silk-coated silver wire, held by wood rods *aa* and *cc* and oriented east–west. The magnetic needle, placed within it at *B*, reversed its orientation when wire end *d* was connected to a zinc plate, and *t* to a copper plate, of a single voltaic unit. From Schweigger in Ref. 29.

D. Personal reflection

I realized how essential these means could be for holding the wires flat only when I tried making a wire loop stay flat. On its own, the wire I bent popped into a three-dimensional spring until I constrained it with tape. Perhaps, keeping the spirals planar was a constraint Schweigger chose to impose.

Schweigger's constraint of the wire loops to a plane is striking; what kept him from letting the wire loops coil into three dimensions? A clue emerges from his interpretation of an invisible structure making up the wire's magnetism. Schweigger envisioned that two opposing magnetizations were (like little fixed bar magnets) embedded within the cross section of each wire: if the wire's uppermost magnetization went $n \leftarrow s$, that at its bottom was $s \rightarrow n$ (see Fig. 6).[30] When the conducting wire was bent in a loop, the magnetizations in the loop's inner top wire and its bottom wire were oriented in the same way. Evidently, Schweigger might have seen this common orientation as what made the needle deflect more due to the wire bent around it. He did not explicitly state this, nor did he make clear how (or if) the property, that opposite magnet ends attract and likes repel, might be involved.

Another clue lies in Schweigger's use of the strange expression "unsere elektromagnetische Batterie" ("our electromagnetic battery"[31]) when referring to the wire looping itself. It suggests that he viewed the loopings' function as analogous to the plates in a voltaic pile. The magnetism of wire loopings is increased by adding on more loops, just as the tension of the voltaic pile is increased additively, by putting more plates into the pile. And, it is the *combined* action of the voltaic plates plus the wire loopings that is responsible for producing the magnetic effects. This idea relates to awareness of the field properties, in that the action of making the loops changes the field, without affecting the current.

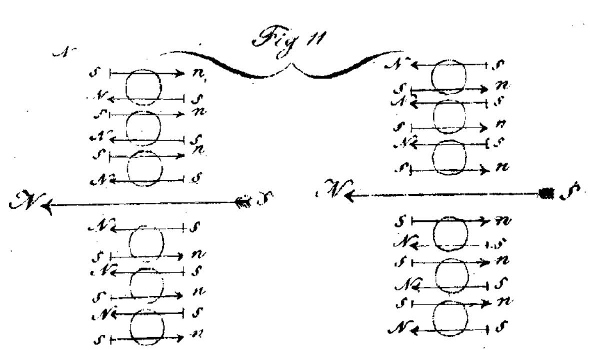

Fig. 6. The triple wires composing the two halves (left and right) of the figure eight (Fig. 4) are seen edge-on. The small arrows $s \rightarrow n$ and $\mathbf{N} \leftarrow \mathbf{S}$ indicate the opposing magnetizations Schweigger supposed were embedded within the top and bottom of each wire. The $\mathbf{N} \leftarrow \mathbf{S}$ indicates a reference direction (perhaps earth's magnetic direction). Schweigger did not specify how the magnetizations of conducting wires within the loop affected a magnetized needle within it. From Schweigger in Ref. 29.

So, as he understood it, the planar constraint was a necessary condition for increasing the magnetic effect of the wires. In order for the loops' magnetizations to add, each successive loop had to be aligned in the same sense, and outward from the previous one. Otherwise, if the wire loops were placed side-by-side, their embedded magnetizations might interfere with each other (perhaps by repelling).

Constraining the wire loops to a plane was part of his process in observing and making sense of the needle's response. Yet controlling the instrumentation in this way might have kept him from exploring the phenomena deeply enough to notice additional confusing spatial properties. Those explorations involve moving and manipulating not only the wire, but also the needle, to see the continuous circling effect of the magnetization in space. Bending the wire into a loop was a crucial innovation. Yet Schweigger's interpretation—like his instrument—constrained him from bending the wire in other ways that might have been productive for finding the very new magnetic effects of electricity.

E. Early loopings for measurement

The same planar constraint does not figure so prominently in other contemporary loopings of conducting wire. Early on, Ampère was experimenting with conducting wires wound both in flat spirals and in hollow helices.[32] While he explored the mutual action between currents,[33] others were drawn to vary the winding of loops due to their interest in measuring the loops' magnetism.[34] The two measuring instruments discussed in the following carry on the mix of confusion and partial understanding that was associated with Schweigger's spirals. Simultaneous with Schweigger, the young student Johann Christian Poggendorff devised a multiloop hollow helical coil (that is, an air-core solenoid) from thin silk-coated copper wire; it was not flattened into the plane.[35] A pivoted magnetic compass was placed inside this closely-wound coil, but the relative orientations of the compass and coil axis were unspecified—an omission that may have confounded inexperienced contemporaries (see below). The needle's deflection was appreciable, "unmistakable," even when the coil was activated by a very weak voltaic unit. Poggendorff and other German innovators referred to this instrument as a "magnetic condenser," thus expressing through their terminology an analogy between the coil's multiple loops and the multiple plates of a condenser.[36]

In contrast with Schweigger's devices which included no provision for measurement, this instrument's deflection was read in angular degrees from the compass dial. Poggendorff experimented with different types of coils—more turns, thicker wire, different materials—and measured the needle's response. However, ambiguities worked against making definitive inferences.[37] Successive trials with multiple coils showed greater magnetic effects when the coils were all connected across the voltaic cell (parallel) than when they were attached in series.[38]

The description of this instrument became garbled in transmission into English. A diagram of Poggendorff's magnetic condenser (Fig. 7), published in a Scottish journal on the basis of a third-hand report (allegedly sent via Oersted), appears strikingly misconstrued to a modern reader.[39] Within a vertical helix, an originally unmagnetized needle was depicted as horizontally pivoted (perpendicular to the coil's

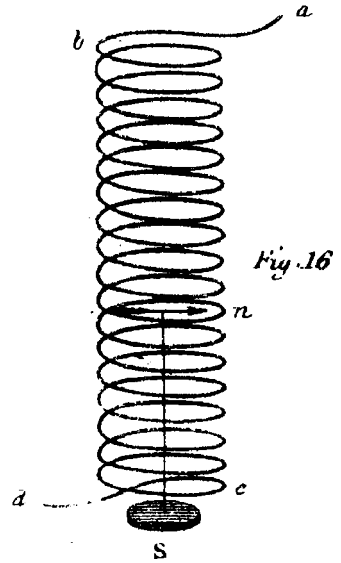

Fig. 7. Poggendorff's magnetic ''condenser,'' as reported in a Scottish journal, was a vertical spiral helix of silk coated wire with an unmagnetized steel needle supported within its axis. When the coil was connected to a pair of voltaic plates, the needle reportedly became magnetized and oriented toward earth's north. Figure from Ref. 39.

magnetic field lines). The needle was said to become magnetic and point north when the wire was conducting. Faraday addressed this drawing in his survey:

> '' . . . the needle is not in this case, as in all the previous experiments [*such as Ampère's*] in, or parallel to, the axis of the helix, but is perpendicular to it. It is probable that it becomes magnetic by some indirect action of the apparatus.''[40]

Faraday gave credence to the device, seriously trying to understand the physical behavior it might involve. Rather than simply dismissing the diagram as ''wrong,'' his response acknowledges the confusingness and realities of others' observations.

Months later, Rev. James Cumming, professor of chemistry at the University of Cambridge, made another coiled instrument, the ''galvanoscope'' (see Fig. 8), to magnify and measure the ''Galvanic force.'' This instrument consisted of a magnetic compass placed within a wire looped in ''four or five revolutions,''[41] which was configured in either of two ways. One, the ''vertical spiral,'' was planar, like Schweigger's, while the ''horizontal spiral'' was a rectangular helical coil (Fig. 8, bottom). Cumming did not report that either vertical or horizontal spiral affected the magnetic needle more (except that the vertical spiral afforded ''a better view of the needle'').[42] A measure of ''Galvanic force'' was made by observing the extent of the needles' deflection when current was passing through the coil surrounding it.

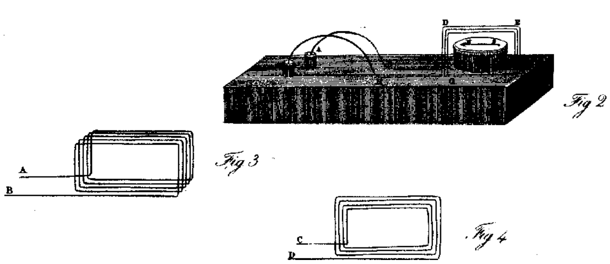

Fig. 8. Top: Cumming's ''galvanoscope:'' a magnetic compass mounted within a flat rectangular spiral of (uncoated?) wire (the lower wire segments are hidden below the support surface, as is an additional magnet). When a single pair of voltaic plates is connected to the spiral's two ends, the magnetic needle deflects; from the $N \leftarrow S$ starting orientation shown, the needle will deflect east or west(depending on the current direction). Below: Cumming's diagram of a three-dimensional (left) and a flat spiral (right), both of which increase ''Electro-magnetic intensity,'' but the flat one affords ''a better view of the needle'' (Ref. 41, p. 289). Figure from Ref. 43.

Through his experience with the wires, Cumming had come to understand their magnetic behavior in a way that supported use of either winding:

> ''From these experiments it is evident that the force exerted by the connecting wire on the magnetic needle, is in every case in the direction of a tangent to the circumference of the wire . . . imagin[e] the Galvanic fluid . . . to revolve in a close spiral line from one extremity of the connecting wire to the other.''[43]

By picturing a magnetism spiraling within the wire (instead of Schweigger's fixed bar magnets embedded at its top and bottom), Cumming could make sense of how the loop's two sides, as well as its top and bottom, ''conspire together'' to make a loop of wire influence the needle more than a straight wire. So for him, the strength of the loop's magnetic effect was ''nearly quadruple that of a single wire''[44]—and not double, as Schweigger had interpreted it. This picture also presented no obstacle to adding on the windings in a helical spiral so that adjacent loops were side-by-side with each other—an arrangement that Schweigger seemed not to associate with an increase in the wires' magnetic effect. Cumming's developments in materials and thought brought some three-dimensional qualities of magnetism and wiring into more accessible instrumental use.

VI. CONFUSIONS WITH WIRE'S WINDING SENSE

For Schweigger, Poggendorff, and Cumming, an interest in increasing the conducting wire's magnetic effect provoked them to do something with the wires themselves: bending loops and spirals. The sense of how the wire was bent—clockwise or counterclockwise—made a difference too. For them, the wire's ''winding sense'' mattered only to the direction that the needle turned within the loop; it did not affect the magnetic strength. However, this tolerance for ambiguity in winding sense changed once experimenters began winding multiple wires around soft iron bars, as they tried to amplify the ''electromagnetism'' inside the bar to increase its power to lift heavy weights. Whenever some wires were wound in a sense opposite to other wires, the magnetic effect in the iron produced by the opposing wire loops canceled, diminishing the bar's overall magnetism.

A. Historical confusions with electromagnet windings

The Albany, NY schoolteacher, Joseph Henry, was the first to use multiple wires and layers[45] in making the coils of his enormous 1831 electromagnet (Fig. 9).[46] Like Schweigger, Henry viewed the coiled loopings as a ''magnifier'' of electromagnetic action, and he devoted attention to improving their windings and magnetic effect. Just as one winds thread on a bobbin, he built multilayer coils by winding a wire ''several times backward and forward over itself.''[47] Henry found that the electromagnet's strength was greater when its windings were made from separate wire coils (in parallel)

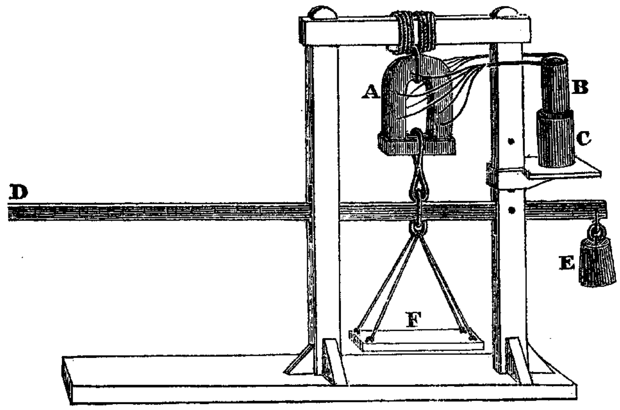

Fig. 9. Joseph Henry's electromagnet, *A*, was installed in a frame so that weights could be added to tray *F* to determine its maximal load capacity. The cylindrically arranged galvanic plates *B* are depicted out of the cup *C* which contains the activating acid. Figure from Ref. 46.

than from one long continuous wire.[48] In adding on these separate wire coils, it became critical to ensure that all wires were wound in the same consistent way. Henry described this in the following private letter:

> " . . . much caution is required in arranging the several wires so that the galvanic current shall pass through none in an adverse direction . . . "[49]

However, in his published report,[46] Henry did not say anything about this issue. So the Americans, who followed Henry's paper, encountered a new unexpected confusion. Soon after Henry's paper appeared, Edward Hitchcock, a professor at Amherst College, started making an electromagnet. After completing it, but before testing it with a battery, he wrote to Henry for advice:

> "In coiling . . . so as to make several thicknesses of the same strand I understand it that it should be always wound in the same direction around the magnet whether the coil advance forward or backward. If not so I should like to be set right."[50]

Hitchcock's question suggests his confusion about something he had not yet experienced directly. However, rather than working with that confusion, he seems to want to circumvent it by asking Henry for the rule about how windings "should" go.

In contrast to Hitchcock, who asked for advice before proceeding, another instrument-maker, James Chilton, wrote to Henry only after he had worked through the confusion of his electromagnet, when it did not perform as expected:

> " . . . I found I had made a great mistake in arranging the extremities of the wires . . . the consequence of which was that I had currents running in contrary directions. This error I could not easily correct, for I had omitted marking and numbering the ends, and so I had the vexatious job of taking the whole off, and commencing anew. But . . . it now works well."[51]

Philadelphia medical professor Robert Hare took a different tactic when he blithely claimed, "It is of no importance how the wires are wound."[52] To avoid having to redo improper windings, he made his coils by using a lathe to spin separate hollow coils units like spools. These prefab coils could then be slipped on or off the iron bar. He first checked how each coil affected a needle when current was traversing its windings. In that way he could orient all the coils to produce the same magnetic effect when they were on the bar—and if one when on wrong, he could just slip it off and turn it around.

B. Confusions in replicating windings

These historical confusions in the making and testing of coils became alive for me too as I undertook to make a galvanometer—a more sensitive version of the instrument whose origins date to Schweigger's looping of wire around a magnetic compass. The coil of my instrument was made of two separate layers. The first layer was wound on a plastic spool; the second was wound directly over it, from a separate wire. A crosswise slit in the spool admitted the suspension of the magnetized sewing needles, which served as the instrument's detector. The needles were rigidly attached to each other and suspended by a single long straight human hair. The upper needle was positioned so that it pivoted freely within the wire coil; the lower needle was outside and below the coil. The lower needle's shadow projected onto a graduated dial, providing a means of reading its angular deflections. The instrument was sensitive to currents in the range 0.7–12 mA.

The coil's two separate wire layers introduced an unexpected complexity. I first tested the instrument by connecting one wire layer to the battery and observing the needle. I did this for each layer separately; each time, the needle's tip swung east, aside from its customary northern heading. Then I joined together the same ends of the two layers to make one continuous serial length. When I connected the opposite ends of this two-layer coil to a *D* cell, the needle did not move.

I had expected the needle's eastward turning would be even stronger when the two layers were combined. I started over: I crossed the ends of the two layers to make a serial length in which the current went through the two layers in the sense opposite from that of my first trial. When I tested this, the needle turned east, very strongly. I then realized what must have happened. I wrote "the windings in opposition; this gives cancellation."[53]

Still, I was confused. In winding the coil, I had been careful to put each layer on in the same way: each layer started from the same end and was wound on in the same direction. By examining the coil more closely, I discerned the problem. The two layers did have the same handed sense—provided the current entered into each from the same direction, the same end of the coil. But, when I connected together the wire ends that came out from the same end of the coil, the sense of the current in the coil's outer layer was now opposite that in the inner layer (Fig. 10). I checked this idea by connecting the coils' two layers in *parallel*—same layer ends to same battery ends. When I did this, the needle went steadily east, just as for the crossed serial connection (and for each layer separately).

This experience opened my awareness to a subtle aspect of making multilayer coils (such as induction coils). When one single wire is wound back and forth over itself like thread on a bobbin, the winding sense inverts between successive layers. For example, if the wire is being wound clockwise from left to right, it will come back counterclockwise from right to left. This inversion in winding sense would also invert the magnetic direction, except that it is accompanied by a second—opposing—inversion which cancels it, resulting in

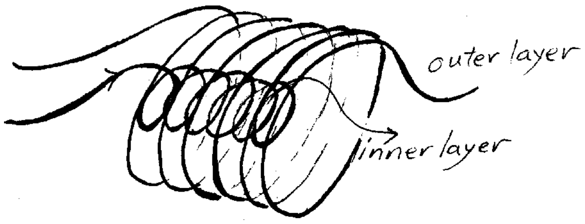

Fig. 10. The inner coil and the outer coil are wound in the same sense. When current traverses both coils from left to right, the magnetic sense of both coils is the same, and adds. When the same (right) ends of each coil are connected, the current goes through the inner coil from left to right, and the outer from right to left, and the magnetic effects of the two coils cancel.

no net change in magnetic direction (see Fig. 11). This second inversion is the one that Schweigger recognized when he bent one wire back over itself. At the bend, the direction of flow switches from being left-to-right to right-to-left. That bend flips the wire's magnetic effect. Because the combination of two inversions cancels, the magnetic effect of the second layer of windings adds to that of the first, resulting in increased magnetization within the coil.

I wondered if those who made the early coils thought about the complexity of winding sense. Was the confusion of putting wire onto iron so that when current went in it, the iron's magnetism would be consistent, underlying Hitchcock's inquiry to Henry or the misfigured windings of Chilton? The question remains open.

C. Sectional windings in induction coils

By the second half of the nineteenth century, electromagnetic instruments had developed much beyond the early loopings of Schweigger, Poggendorff, and Cumming. Yet the possibilities for confusion in working with magnetism's handed sense persisted, especially for amateurs intent on winding their own induction coils. For example, the winding sense of the instrument's long outer secondary coil had to be consistent with that of its inner primary winding. Otherwise, the induced and inducing effects would counter each other, annulling the effect. Nicholas Callan (1799–1864), the teacher-priest at Maynooth College, Ireland, who devised early prototype inductive coils in 1836 (and shocked unwary students with them), was aware of the importance of keeping winding sense consistent. He discussed winding sense in describing how he combined the thin secondary wires of two test induction coils:

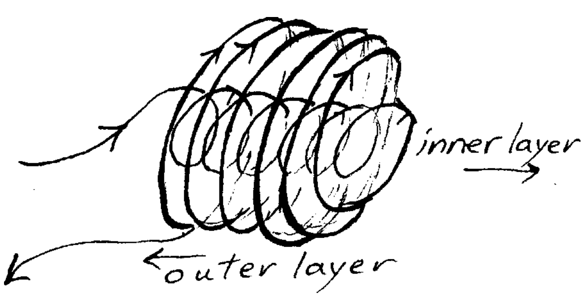

Fig. 11. The inner coil is wound in the opposite sense from the outer coil's windings, from one continuous coil. When current enters the outer layer, both its direction and its winding sense are inverted. As a result, the magnetic sense of the current in the outer coil is the same as that in the inner, and the magnetizations due to the two layers add.

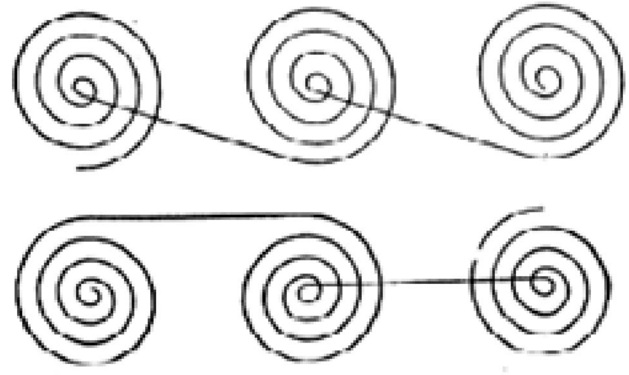

Fig. 12. Two ways of combining sections to make up an induction coil's secondary are shown. Top: sections are all wound in the same handed sense; connections are made from one section's inner wire to the next's outer. Bottom: alternate sections are wound in the opposite handed sense; connections are made only between inner wires, and between outer wires. Figure from Ref. 57.

> "Care must be taken to unite the thin wires in such a manner that the electric current excited in the helix of each magnet on breaking battery communication, may all flow in the same direction; otherwise, the current produced in the helix of one magnet may neutralize the current excited in the helix of another."[54]

Some late nineteenth century guidebooks written for making one's own electrical instruments also warned the novices about the problems arising when the windings of coils are opposing.[55]

Under the experimenters' efforts to make induction coils spark dramatically through wider air gaps, they strained the instruments. The voltages induced inside large secondary coils were high enough to permit discharges between successive layers. To prevent this, experimenters began winding their secondaries in what they called "sections;" separate narrow coils that were connected sequentially with an insulating wall between them and slipped over the primary coil. The sections were flat spiraled discs, reminiscent of Schweigger's spirals. Within any one section, the difference in potential was not great enough to risk internal electrical discharge, and the insulation between sections prevented breakdown across the coil.

In preparing sections, it was crucial to keep track of the winding sense, so that when successive sections' wire ends were soldered together, the direction of the induced current would be consistent throughout.[56] Some coils were constructed so that all the sections were wound in the same sense, and the innermost wire of one section was soldered to the outermost wire of the next (Fig. 12). However, this introduced the risk of bringing wires at differing potentials into proximity. Another practice sought to reduce this by soldering the joints only between sections' inner or outer wires. This meant winding every other section (or "pie") in the opposite sense. One later manual described how this was to be done, but without providing an analysis of the underlying physical behavior:

> " . . . winding the pies in the same direction and reversing each alternate one . . . makes the first pie a right-handed helix and the second a left-handed helix (Fig. 12) . . . Each pair of pies, that

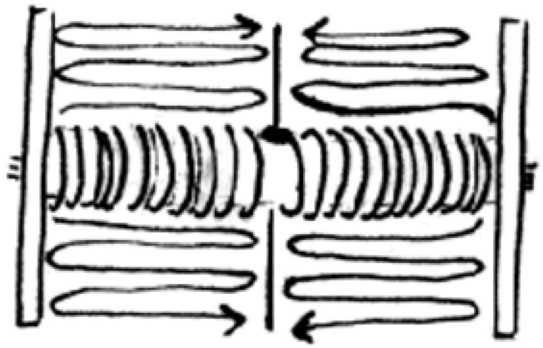

Fig. 13. Diagram of the windings in the two sections of my induction coil. The section's ends meet in the middle and winding sense is consistent through the middle.

> is a right and a left-handed one, should be connected together as they are wound . . . so that when all the disks are finished, there will be no confusion as to the direction of their windings."[57]

D. Reflections from winding a two-section coil

To experience the complexity of large coils, I followed nineteenth century manuals (including those referenced above)[58] in winding an induction coil of my own. I wound the coil's fine wire secondary (1 km of No. 34 gauge wire) sometimes in my hands, sometimes with a hand-turned spindle. At ten hours a day, it took five days to complete the secondary.

Through laying on the winds, my hands became sensitive to guiding the fine wire, feeling for irregularities, and monitoring the winding sense. Sometimes the loops slid to one side or caught on an unevenness from the layer below, crossed over previous winds, or kinked. Practice in winding improved its evenness and by adopting the rhythm of back and forth layering, secured consistency in the winding sense.

I constructed the secondary in two sections of fourteen layers each. To start the first section, I anchored the wire's free end at the midpoint in the coil's axis, and from there, wound the wire out and back, layering it in the half opposite the spindle attachment (Fig. 13). To start the second section, I flipped the coil so the spindle held its other end, soldered the new wire's end to the first section at the midpoint. I laid the windings so that the second section continued with the winding sense of the first.

According to the quote above,[57] alternate sections are wound in the opposite handed sense. This instruction identified a difference between the historical winding practice, and mine. The historical instrument-maker always began each section by anchoring the wire's free inner end against the spindle, and proceeded to wind out and back from there. To preserve the same winding sense between two sections, the second section would be wound on the spindle in the opposite handed sense (Fig. 14). One section had to be flipped around to join the other. By being flipped, the two mirror-image sections had the same winding sense. In contrast, I had performed that flipping operation prior to winding by inverting the spindle mounting (Fig. 15).

Thinking through how both the historical practice and mine worked to yield a consistent magnetic effect, was both confusing and productive. Going beyond the descriptions involved retracing the actual process. It allowed me to recover an inversion step that might be overlooked; an inversion similar to the double inversion made between layers of thread wound on a spool. Doing the instrumental replication brought me to immediately experience the subtle confusions inherent in winding coils, and to improvise my own ways of working with these confusions. Even when historical accounts differ from replications, such as where the inversion step was made, those differences can be productive. The differences may make evident the diversity in the experimenter's practice.

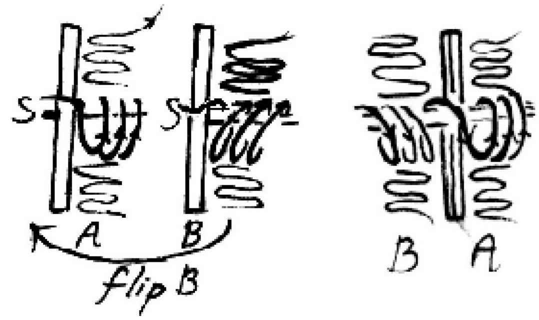

Fig. 14. The instrument-maker's sections were wound in mirror-image pairs, *A* and *B*, winding out from the spindle *S*. To join the sections at the middle meant flipping one section, so that the two were consistent.

VII. LEARNING FROM CONFUSION

This study's interpretations and replications suggest how past experimenters responded to the spatial asymmetric properties of the magnetism of conducting wire loopings. Along with identifying such details as the role of Schweigger's ties in keeping spirals flat, these replication activities also connected with more intangible features of experimenting. The instrumental loopings reflected what the makers understood. When these loopings were tested, the resulting physical behavior sometimes revealed inadequacies in the windings and in the makers' understandings. This observable demonstration of the unexpected (or overlooked) sense of the physical behavior evoked their confusion in the specific setting of an instrument which they could modify and test, and thus change their understandings.

Confusion recurred across the century-long span of developments in instrumental work with conducting windings: from early wire coils, to electromagnet windings, to induction coils and sectioning. Learners today continue to find that confusion emerges as an ongoing part of their experimental work. This evidence of historical learning with physical effects is related to other studies of physics learners that docu-

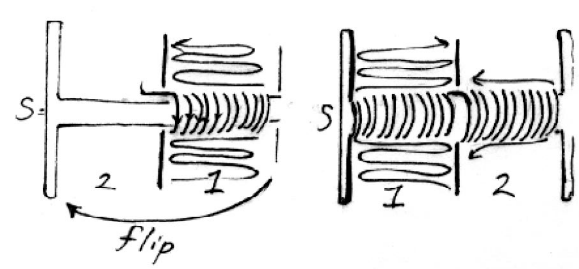

Fig. 15. By contrast, I flipped the end of the coil held by the spindle, and wound both sections on in the same winding sense.

ment how resourcefulness, resurgence, and development are built up in learners' intuitions about physical phenomena that they have experienced directly (particularly motion).[59]

In the examples developed here, the interactions among learners' confusions and inferences offer evidence of the intrinsic complexity of responding to asymmetry, handedness, and inversion in natural phenomena. Physics students today are given the right-hand rule as an already worked-out remedy for that complexity. Yet the rule is particularly susceptible to being made rote. It can be utterly daunting to a learner, disjoint as it is from the phenomena under study—unlike Schweigger's figure-eight loop which so aptly evokes the ways magnetic sense relates to wires' windings. And, also unlike Schweigger, Poggendorff, and the others, most students today lack experience with real wires that they have bent themselves and tested magnetically, which is essential for developing both confusion and understanding.

That confusingly evocative quality of nature is evident in how the twist of a loop takes our thinking from one place, one sense, to another. With the twist, the physical effects invert, and as our minds trace those twists and inversions, our perspective changes too. Learning involves both making that passage and working out how all these orientations and senses hold together at once: in and out, up and down, right and left, clockwise and counterclockwise, north and south. It is a process of connecting each bend we make in a wire and each magnetic reversal we observe, with the continuity of the loop's form and of its magnetic field in space.

These experiences with confusion, opened through historical experiments and replications, connect with pedagogical concerns for students' learning through experimenting. The historical studies are resources for interpreting the depth in learners' responses to a physical behavior and for recognizing how that behavior is made visible by the instruments or experiments that they invent. As they explore complex phenomena, their experimental paths become diverse and responsive to what they observe empirically.[60] Seemingly small actions, such as the orientation by which learners bend wire into a loop or connect loops together, may both express and extend their emerging understandings, such as of magnetism's asymmetry.

Confusion is integral to that development, as it is through confusion that learners become aware of something in nature that is not quite what they expect. For them to move on in this awareness, they must take their own confusions seriously enough to try something out, make and test an instrument, and think about it.[61] For us, as teachers, to act on these findings means that we need to become involved with the learners, supporting the developments that arise through their explorations: fostering confusion as a productive space for learning physics.

ACKNOWLEDGMENTS

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[18]Quote on pp. 322–3 in John Christian Oerstead, ''On electro-magnetism,'' Ann. Phil. **2**, 321–337 (November 1821).

[19]John Christian Oerested, ''Experiments on the effect of a current of electricity on the magnetic needle,'' Ann. Phil. **16**, 273–276 (July–December 1820), see p. 276.

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[21]First privately printed on July 21, 1820 and circulated among friends, Oersted's brief Latin tract was immediately translated and reprinted in all the leading European science journals. See Bern Dibner, *Oersted and the Discovery of Electromagnetism* (Blaisdell, New York, 1962).

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[26]I. S. C. Schweigger, ''Zusätze au Oersteds elektromagnetischen Versuchen,'' J. Chemie Physik **31**, 1–17 (1821). Translated excerpt on p. 129 of Robert A. Chipman, ''The earliest electromagnetic instruments,'' U.S. Natl. Mus. Bull. **240**, 122–136 (1966).

[27]Translated quote on p. 130 of R. A. Chipman; original in Schweigger, Ref. 26.

[28]Earlier, glass was used to insulate the sides of current carrying wires that were immersed in electrolyte solutions; see John George Children, ''An account of some experiments, performed with a view to ascertain the most advantageous method of constructing a voltaic apparatus, for the purposes of chemical research,'' Philos. Trans. R. Soc. London **99**, 32–38 (1809).

[29]Translation by Petra Lucht on December 16, 1997; original quote on p. 35 of I. S. C. Schweigger, ''Noch einige Worte über diese neueu elektromagnetischen Phänomene,'' J. Chemie Physik **31**, 35–41 (1821).

[30]*N* and *n* designate north magnetic polarity; *S* and *s* designate south.

[31]Translation by Petra Lucht on December 16, 1997; original quote on p. 38 of Schweigger, Ref. 29.

[32]Ampère observed that when coils were wound in the opposite handed sense, their magnetic polarities were opposite. Using his theory that all magnetism was due to circulating current loops, he worked out a rule relating the direction of current circulation to the polarity of the magnetism it produces (Ref. 14). See ''Expériences relatives á l'aimantation du fer et de l'acier par l'action du courant voltaïque,'' Ann. Chim. Phys. **15**, 93 102 (1821) (no author given but probably the editor, Gay-Lussac); and L. Pearce Williams, ''What were Ampère's earliest discoveries in electrodynamics?,'' Isis **74**, 492–508 (1983).

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[34]For a historical survey of electrical measurement instruments, see Joseph Keithley, *The Story of Electrical and Magnetic Measurements: From 500 B.C. to the 1940s* (IEEE Press, New York, 1999).

[35]Johann Christian Poggendorff was trained in pharmacy, but being too poor to own a store, he commenced university studies in science in 1820. Later he was a physics professor at the University of Berlin and editor of Annalen der Physik and of a bibliographic reference comprehensive of all scientific publications; see *Dictionary of Scientific Biography*, edited by C. Gillispie (Charles Scribners' Sons, New York, 1970–1980).

[36]Poggendorff's professor, Paul Erman, first reported on his ''magnetic condensor'' in ''Ein electrisch-magnetischer Condensator,'' Ann. Phys. (Leipzig) **67**, 422–426 (1821); sections are excerpted and translated in Wilhelm Ostwald, *Electrochemistry: History and Theory* (Smithsonian Institute, Washington, DC, 1980). Poggendorff's own subsequent publication is in Gothic font, J. C. Poggendorff, ''Physisch-chemisch Untersuchungen zur näheren Kenntniss des Magnetismus der voltaischen Säule,'' Isis von Oken **8**, 687–710 (1821), and partially translated by R. A. Chipman in Ref. 26.

[37]Using a coil's needle as a detector, Poggendorff first showed that graphite and other nonmetals would carry a voltaic current. He termed them ''semi-conductors'' (''halb-Leiter''); Ref. 26, p. 133.

[38]Parallel wiring's enhanced electromagnetism was exploited by Henry's electromagnet (see Ref. 46). However, because it is an outcome of the relative balance between the internal resistance of the voltaic unit and the external resistance of coil and circuit, it was not observed when other voltaic combinations were used; see Cavicchi in Ref. 7.

[39]D. B. [David Brewster], ''Account of the new galvano-magnetic condenser invented by M. Poggendorf of Berlin,'' Edin. Phil. J. **5**, 112–113 (1821), see fig on p. 821.

[40]Faraday in Ref. 24, pp. 289–290.

[41]Quote on p. 289 of James Cumming, ''Description of the galvanoscope,'' Ann. Phil. **6**, 288–289 (1823).

[42]Quote on p. 289 of Ref. 41.

[43]Quote on p. 273 of James Cumming, ''On the connexion of galvanism and magnetism,'' Trans. Cambridge Philos. Soc. **1/2**, 269–279 (1821); ''On the application of magnetism as a measure of electricity,'' *ibid.*, **1/2**, 281–286 (1821).

[44]Reference 43, p. 275.

[45]Joseph Ames, ''Certain aspects of Henry's experiments on electromagnetic induction,'' Science **75**, 87–92 (1932).

[46]Joseph Henry, ''On the application of the principle of the galvanic multiplier to electro-magnetic apparatus, and also to the developement [*sic.*] of great magnetic power in soft iron, with a small galvanic element,'' Am. J. Sci. **19**, 400–408 (1831). Also in Joseph Henry, *The Scientific Writings of Joseph Henry* (Smithsonian Institution, Washington, DC, 1886), Vol. 1.

[47]Reference 46, Am. J. Sci., p. 404.

[48]Henry attributed to Schweigger the precedent in this finding that a conducting wire's magnetism was greater when it was composed of several separate wire coils in parallel, than of one long series length. However, it appears that Poggendorff, not Schweigger, made those prior observations. This was not a general result (as Henry supposed) but dependent on the specific balance between internal and external resistance in the circuit. If the battery's internal resistance is lower than that of an individual wire coil, the magnetic effect will be greater when several wire coils are connected in parallel, than when they are in series. For my investigations of these properties in Henry's electromagnet and mine, see Cavicchi, Ref. 7.

[49]Letter of May 8, 1832, in Joseph Henry, *The Papers of Joseph Henry*, edited by Nathan Reingold (Smithsonian Institution Press, Washington, DC, 1972), Vol. 1, December 1797–October 1832.

[50]Letter of April 23, 1832 in Ref. 49.

[51]James Chilton to Henry, Letter of December 29, 1834, in Joseph Henry, *The Papers of Joseph Henry*, edited by Nathan Reingold (Smithsonian Institution Press, Washington, DC, 1975), Vol. 2, November 1832–December 1835.

[52]Quote on p. 145 of Robert Hare, letter to editor, Am. J. Sci. **20**, 144–147 (1831).

[53]Quote on p. 23 of Ref. 15.

[54]Quote on p. 492 in Nicholas Callan's paper, ''On a method of connecting electro-magnets so as to combine their electric powers and on the application of electro-magnetism to the working of machines,'' Annals of Electricity, Magnetism and Chem. **1**, 491–494 (1837). I have replicated Callan's experiment to combine the primaries and secondaries of two similar hand-wound induction coils. Using an oscilloscope as a detector of the induced voltages, I observed that when the coils' winding sense is opposing, the induced voltage is substantially diminished, like the effect Callan mentioned in this quote.

[55]Advice to keep the winding sense of the secondary consistent with that of the primary is given in such manuals as John Sprague, *Electricity: Its Theory, Sources, and Applications* (Spon, London, 1875); F. C. Allsop, *Induction Coils and Coil-Making* (Spon, London, 1894); Charles Seaver, *American Boy's Book of Electricity* (McKay, Philadelphia, PA, 1921).

[56]For advice on keeping the current sense consistent between sections, see H. S. Norrie, *Ruhmkorff Induction-Coils* (Spon, London, 1896), p. 14; James Hobart, ''Construction of a jump spark ignition coil and condenser,'' Am. Electrician **14** (12), 576–577 (1902).

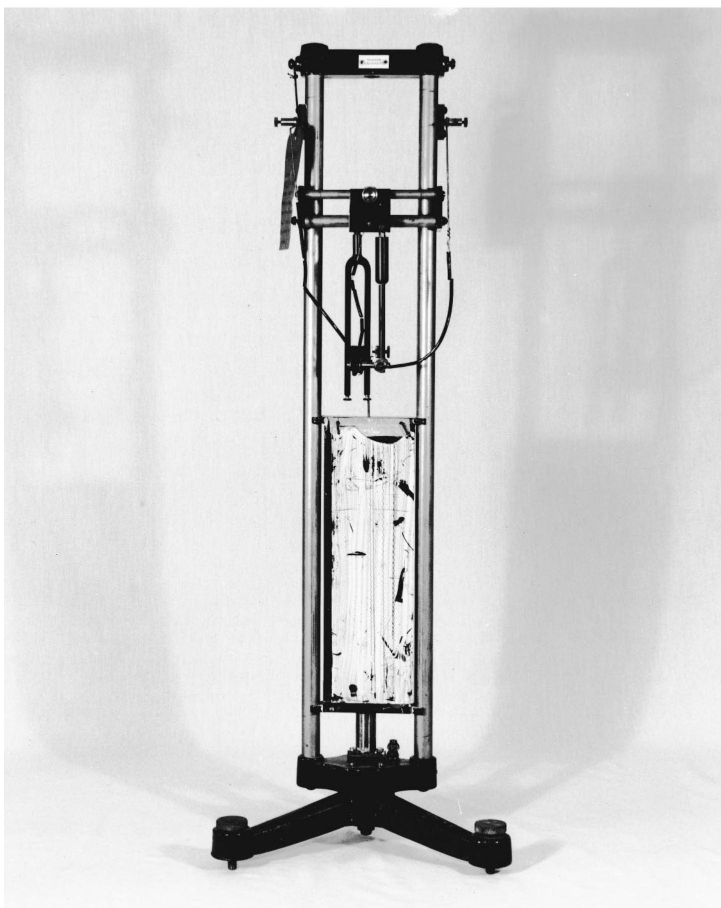
[57]A. Frederick Collins, *The Design and Construction of Induction Coils* (Munn, New York, 1909), pp. 75–77.

[58]The secondary of my induction coil is about 1 km long, having a total resistance of 1.1 kΩ; with a single *D* cell input to its primary, its secondary induced signals of 6–8 kV. For a fuller account of my induction coil replication and its operation, see Chap. 20 of Ref. 7.

[59]For research and analysis of learners' physical intuitions as resources for learning physics, see John P. Smith III, Andrea A. diSessa, and Jeremy Roschelle, ''Misconceptions reconceived: A constructivist analysis of knowledge in transition,'' J. Learn. Sci. **3** (2), 115–163 (1993); David Hammer, ''Student resources for learning introductory physics,'' Am J. Phys., Phys. Ed. Res. Suppl. **68** (S1), S52–S59 (2000); Andrea diSessa, *Changing Minds: Computers, Learning, and Literacy* (MIT, Cambridge, MA, 2000).

[60]See the discussion of historical explorations in Neil Ribe and Friedrich Steinle, ''Exploratory experimentation: Goethe, Land, and color theory,'' Phys. Today **55** (7), 43–49 (2002).

[61]For examples of learners' and teachers' developments through taking their confusions seriously, see Eleanor Duckworth, ''Learning with breadth and depth,'' in *The Having of Wonderful Ideas and Other Essays on Teaching and Learning* (Teachers' College Press, NY, 1996); and the essays in *Tell Me More: Listening to Learners Explain*, edited by E. Duckworth (Teachers' College Press, New York, 2001).



Free-Fall Apparatus. The problem in measuring the constant acceleration of a freely-falling body is always one of timing. If you can locate the body in space at regular time intervals, finding the acceleration requires only the application of the appropriate kinematic equation. In this apparatus the falling body is the frame containing the glass plate that is lightly coated with white shoe polish. This falls down in front of the electrically-driven turning fork that scratches an oscillatory track in the polish. If the frequency of the tuning fork is known, data for the position as a function of elapsed time are obtained. This apparatus is in the Greenslade collection, and was made by Gaertner of Chicago, better known for optical apparatus. (Photograph and notes by Thomas B. Greenslade, Jr., Kenyon College)