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Nineteenth-Century Developments in Coiled Instruments and Experiences with Electromagnetic Induction

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Summary

Faraday demonstrated electromagnetic induction in 1831 using an iron ring wound with two wire coils; on interrupting battery current in one coil, momentary currents arose in the other. Between Faraday's ring and the induction coil, coiled instruments developed via meandering paths. This paper explores the opening phase of that work in the late 1830s, as the iron core, primary wire coil, and secondary wire coil were researched and differentiated. 'Working knowledge' (defined by Baird) gained with materials and phenomena was crucial to innovations. To understand these material-based interactions, I experimented with hand-wound coils, along with examining historical texts, drawings, and artefacts. My experience recovered the historical dead-end of two-wire coils and ensuing work with long-coiled single conductors initiated by Faraday and Henry. The shock and spark heightened in these coils provided feedback to the many instrumental configurations tested by Page, Callan, Sturgeon, Bachhoffner, and others. The continuous conductor differentiated into two segments soldered together: a thick short wire carrying battery current and a long thin wire for elevating shocks (voltage). The joined wires eventually separated, yet their transitional connection documents belief that the induced effects depend on continuity. These coiled instruments, with their intertwined histories, show experimental work and understandings in the process of developing. Seeing the nonlinear paths by which these instruments developed deepens our understanding of historical experiences, and of how people learn.

Contents

> [My] statement is not drawn from mere off-hand experiment, but is the result of many, several of which have been carried on for hours, in some cases, days together . . . G. Bachhoffner

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1. Introduction

In August 1831, Michael Faraday observed an electrical and quite transient disturbance in a coiled wire loop that was not connected to any battery at all. It came about in that loop only at the moment of closing or breaking the connection between a trough (multi-cell) battery and an entirely separate wire coil. The disturbance was evident by the deflection of a magnetic needle suspended either near that loop or within a galvanometer coil that Faraday added into the loop's circuit. In this first demonstration of his seminal finding of electromagnetic induction, Faraday used a 7/8 in. thick soft iron bar, bent and welded into a ring 6 in. across, through whose opening the two wire coils (having nearly equal total lengths) were wound (Figure 1).[1]

In the coming months, while employing various means to detect the briefly induced currents, Faraday explored many relative configurations of coils, iron, and magnets. This work extended, and reverberated with, his preceding investigations involving transitory phenomena in acoustics and vibrations, optical illusions, and magnetism.[2] The new effect showed itself visually only when the iron ring's *A* coil was connected to a huge battery assembled by putting 10 of the original troughs in series.[3] In his *Diary*, Faraday described the spark he saw between closely spaced charcoal rods attached to the *B* coil's ends:

> **46**. Got a spark with charcoal at the end of the inducing wires, very distinct though small—only at the moment of contact or disjunction ... (1 October 1831)

In the iron ring apparatus, we can now discern analogues to elements of the later induction coil—one of myriad devices making up the subsequent legacy of Faraday's researches in electromagnetic induction (Figure 2). Corresponding to the soft iron ring is the 'core', a wire bundle whose soft iron readily magnetizes, and demagnetizes, under influence from current in the coil surrounding it. The coiled wire carrying current direct from the battery became designated the 'primary'; the coiled loop having no connection to a battery provides the 'secondary' circuit. Core, primary, and secondary were cylindrically configured, each layer wound successively over the previous with insulating materials (such as Faraday's calico and twine) intervening (Figure 2, left middle). Faraday, too, had tested cylindrical arrangements on hollow bobbins, where one coil's wire was interwoven with that of the other, either side by

[1] Faraday's original iron ring is preserved at the Royal Institution, London, number RI AC 20. The battery used was a series of ten pairs of copper and zinc plates. It connected to wire made up of three 24-foot lengths that were wrapped in cloth and string and coiled about one side of the iron ring (figure 1). Around the ring's other side were two wire lengths (totalling 60 feet) that connected to a galvanometer or other means of detecting electricity (Michael Faraday, entry of 29, August 1831 in *Faraday's Diary: Being the Various Philosophical Notes of Experimental Investigation*, Thomas Martin, ed., 1 (London, 1932), and 'On the Induction of Electric Currents', First Series, read 24 November, 1831, *Experimental Researches in Electricity* (abbreviated *ERE*), vol. 1 (Sante Fe NM, 2000, reprinted from 1839), ¶27–32.

[2] Immediately preceding his discovery of electromagnetic induction, Faraday explored transient phenomena in acoustics and vibrations 'On a Peculiar Class of Acoustical Figures; and on Certain Forms Assumed by Groups of Particles Upon Vibrating Elastic Surfaces', 1831, 314–32 in *Experimental Researches in Chemistry and Physics* (London, 1991); 'On the Forms and States Assumed by Fluids in Contact with Vibrating Elastic Surfaces', 1831, 335–58 in the same volume. The relation of these studies to his subsequent work is discussed in Ryan Tweney, 'Stopping Time: Faraday and the Scientific Creation of Perceptual Order', *Physis* 29 (1992) 149–64; Elizabeth Cavicchi, 'Faraday and Piaget: Experimenting in Relation with the World', *Perspectives on Physics*, 14 (2006), 66–96.

[3] See ¶15 42, 83, 91, 157 in the *Diary* (note 1) for Faraday's unsuccessful attempts (including one on the first day of his discovery) to observe an induced spark.

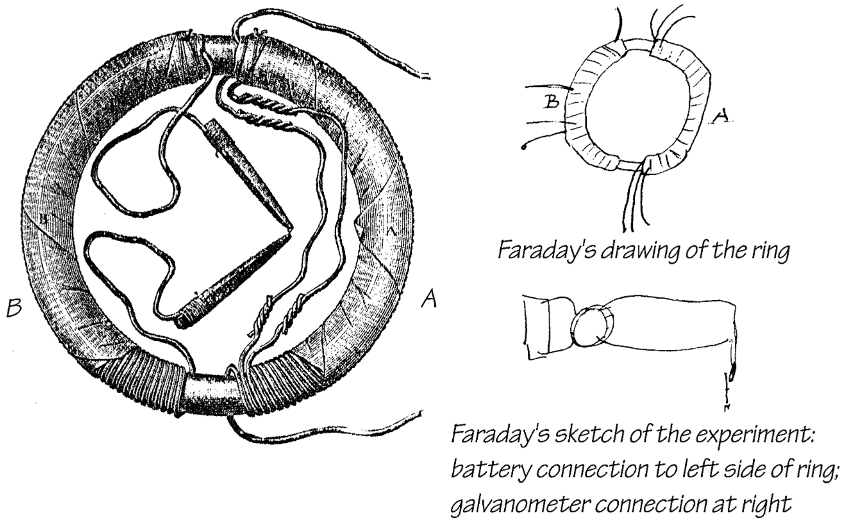

Figure 1. Left: Faraday's iron ring; when the battery current passing through coil *A* starts or stops, a brief current is induced in coil *B*, sometimes detected as a spark between the points. From Fleming (note 5). Right: Faraday's drawings on 29 August 1831, of his soft iron ring wound with two separate coils, *B* (left), and *A* (right). The *B* coil was wound in two layers; the *A* in three. The lower drawing shows the ring's connection to the battery (rectangle on left) and the galvanometer (lines at far right). From his *Diary* (note 1)¶2 and 7,367.

side or in a few alternating layers. For him, these tube constructions highlighted how the effect could be enhanced by inserting an iron rod into the hollow interior, and how it could be brought about (without a battery) simply by moving a bar magnet into the tube.[4]

But the two wire coils of the eventual induction instrument bifurcated in ways that did not originate with Faraday's prototype devices. The primary wire was thick, short, and in close proximity to the core; the secondary was long, fine, and wound over the primary circumferentially (never interleaved with it). Other features were different as well: vibrating contact breakers replaced Faraday's unspecified manual means of making battery contact; apparatus became specialized for displaying induced sparks or taking shocks; the multi-cell trough battery dwindled to a cell or two; the integrity of insulation became a major concern; and the instrument's mounting and overall design took on distinctive forms.

Between Faraday's iron ring and the mid- to late-nineteenth-century induction coil, many experimenters gained extensive experience with materials and electromagnetic effects in which people's interpretations were in continual exchange with their instrumental improvisations. Here, I explore the opening phase of that work in the late 1830s, as the elements of core, primary, and secondary emerged along meandering routes that retrospectively may seem regressive. When viewed closely, the interactive character of these investigations becomes evident in their various constructions and experimental paths.

[4] Faraday 1831, *ERE* (note 1), v. 1, ¶6,34–38.

Electromagnetic investigators of the late 1830s formed small communities engaging with each other through personal contact, overlapping acquaintances and several journals that tardily carried their work beyond local and national borders—principally one edited by investigator William Sturgeon to focus exclusively on electromagnetic undertakings.[5] Outside the Royal Institution where Faraday experimented in a well-stocked basement lab and demonstrated science to large cultured audiences in its theatre, London's science exhibition areas included the Adelaide Gallery, where both Sturgeon and chemistry lecturer George Bachhoffner performed to a broader public admitted by fee.[6] Nearby workshops, such as that of Irish-transplant instrument-maker Edward M. Clarke, produced apparatus and materials that might find their way to any of the other science venues.[7] Clarke and Sturgeon exchanged findings with Nicolas Callan, the natural philosophy professor at Maynooth College near Dublin, who put in exorbitant labour experimenting and devising stunning lecture demonstrations for the seminarians.[8] An ocean away, Joseph Henry had studiously read British and French electromagnetic writings and constructed his own load-bearing improvement on Sturgeon's inaugural electromagnet while a public school teacher in Albany, NY.[9] By the mid-1830s newly established in the role of a Princeton professor, Henry redoubled his electromagnetic research, attracting the inventive interest of Charles Grafton Page, then a similarly self-motivated student.[10] Working from home in Salem, Massachusetts, Page collaborated with Boston's philosophical instrument-makers, including Dr William King and Daniel Davis junior.[11] Spatially and socially dispersed, these investigators shared a fascination with electromagnetic phenomena, combined with ardent commitment to make apparatus that could exhibit those behaviours in new and amplified ways.

The history of electromagnetic coils in the late 1830s was appropriated and described early on by many of these same actors, each on behalf of his own priority

[5] The full title of Sturgeon's self-edited journal is *The Annals of Electricity, Magnetism, Chemistry, and Guardian of Experimental Science.* For a discussion of Sturgeon's life, experiments, and times, see Iwan Morus, *Frankenstein's Children: Electricity, Exhibition, and Experiment in Early-Nineteenth-Century London* (Princeton, 1998).

[6] The Royal Institute and the Adelaide Gallery are described and contrasted in Morus (note 4), which also excerpts contemporary remarks on Bachhoffner's science lecturing, and also in J. A. Fleming*, The Alternate Current Transformer in Theory and Practice*, 2 (London, 1892), 1.

[7] E. M. Clarke mentioned getting Dr Faraday's opinion on his invention in 'Description of E. M. Clarke's Electrepeter', *Annals of Electricity*, 1 (1837) 66. His workshop, then at 9, Agar St., West Strand, subsequently moved opposite the Adelaide Gallery, Gloria Clifton, *Directory of British Scientific Instrument Makers 1550–1851* (London, 1995), 57. Clarke, his Irish origins and association with Nicolas Callan are discussed in J. E. Burnett and A. D. Morrison-Low, *Vulgar & Mechanick: The Scientific Instrument Trade in Ireland, 1650–1921* (Dublin, 1989); Charles Mollan and John Upton, *The Scientific Apparatus of Nicholas Callan and other Historical Instruments* (Maynooth, 1994).

[8] For Callan's biography and background, see P. J. McLaughlin, *Nicholas Callan: Priest-Scientist 1799–1864* (Dublin, 1964); Niels Heathcote, 'Essay Review: N. J. Callan Inventor of the Induction Coil', *Annals of Science*, 21 (1965), 145–67; for his instruments, see Charles Mollan and John Upton, *The Scientific Apparatus of Nicholas Callan and other Historic Instruments* (Maynooth Ireland, 1994). Many of Callan's original instruments are on display at the Museum of Ecclesiology, Maynooth College, Ireland.

[9] Albert E. Moyer, *Joseph Henry: The Rise of an American Scientist* (Washington, DC, 1997).

[10] Robert Post, *Physics, Patents & Politics: A Biography of Charles Grafton Page* (New York, 1976).

[11] For the association between Page and Davis, see Roger Sherman, 'Charles Page, Daniel Davis, and their electromagnetic apparatus', *Rittenhouse*, 2 (2) (1988), 34–47. Dr William King, electrician, is listed at 54 Cornhill St. in the *Boston City Directory*, Stimpson & Claff, from 1832–1838; in 1831, he was listed at 4 Schollay's buildings. In 1837, his former assistant Daniel Davis Jr set up a philosophical instrument-making shop at 11 Cornhill; Timothy Claxton and Joseph Wightman started theirs at 33 Cornhill in the following year. In 1840, the year after King's death, another of his assistants, William A. Orcutt, established himself as an electrician at 30 Cornhill St.

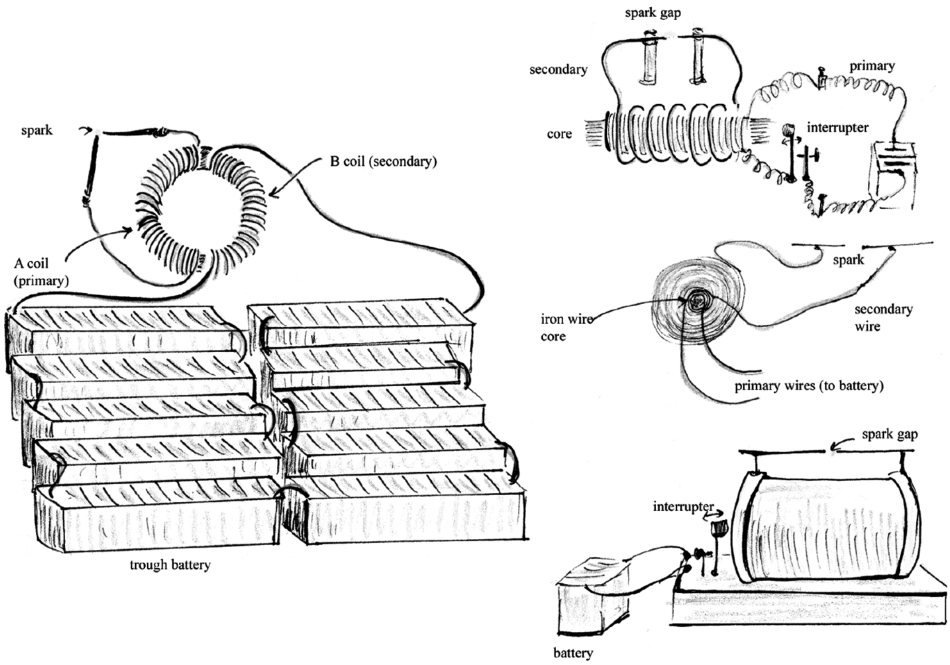

Figure 2. Comparison of the wiring of Faraday's ring with an induction coil. Left: a spark was observed between ends of the B coil of Faraday's ring when the A coil was hooked to 10 trough batteries. Top right: schematic diagram of induction coil. The iron wire core is wrapped first in the primary wire which connects to the battery through an interrupter, and then by a long secondary wire. Sparks occur between the secondary's ends. Middle right: cross-section view of an induction coil. Bottom right: outside view of the induction coil.

claims and influence, guided by subsequent results and theory. At the start of the 1857–1858 Atlantic Telegraph attempts, in which the induction coil came to play an ignominious role,[12] Callan prefaced an address to the British Association's Dublin meeting by recounting his contributions made two decades earlier.[13] A decade later, reacting in part to Napoleon III's award of the lucrative and prestigious Volta Prize in 1864 to Parisian instrument-maker Henri Ruhmkorff for inventing the induction coil, Page petitioned the US Congress with a lengthy history composed to plead his 'American claim' to the induction coil.[14] Acknowledging the roles of Page and Callan in the induction coil's origins, French contemporary DuMoncel emphasized the performance jump of the 60-cm-long sparks produced with compatriot Ruhmkorff's

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[12] Many attributed the 1858 cable's transmission failure to Wildeman Whitehouse's use of high tension from enormous induction coils to overcome the long cable's resistance. *Report of the Joint Committee Appointed by the Lords ... and the Atlantic Telegraph Company to Inquire into the construction of Submarine Telegraph Cables* (London 1861).

[13] N. J. Callan, 'On the Induction Apparatus', *Philosophical Magazine*, 14 (1857), 323–40.

[14] (Charles Grafton Page), *The American Claim to the Induction Coil and its electrostatic developments* (Washington, DC, 1867); Robert C. Post, 'Stray Sparks from the Induction Coil: The Volta Prize and the Page Patent', *Proceedings of the IEEE*, 64 (1976), 1279–86.

coil to affirm its status as a distinctive achievement.[15] Each author-inventor isolated their innovation from the others, representing it as prefiguring, or instantiating, the induction coil's subsequent outcomes.

This recasting of history became particularly explicit in J. A. Fleming's 1892 thorough narration of the induction coil's 'historical development', where the many intermediate devices were portrayed as if leading by sequential steps to the induction coil. [16] Fleming, an electrical engineer who trained under Maxwell, was a later actor in that same story, viewing himself as playing a culminating role 'to settle certain disputed questions about transformers'.[17] That personal involvement underlies his linear retelling, where each invention was taken to be an 'advance along definite lines by a process of evolution in which rudimentary forms are successively replaced by more and more completely developed machines'. Fleming compiled extensive records of these instruments' dimensions and operations but treated them uncritically as simple facts without considering how these came to be. For him, the story's merit lay less in the process of development than in its end-point. The crude prototype coils of its beginnings would be ultimately supplanted by a 'final and fully developed idea'.[18] Thus, his reconstructed story, being shaped to fit its end, was essentially different from the 'facts' embedded within.

2. Working knowledge' and experimental activity in historical instrument research

The early electromagnetic coils can sustain many possible stories beyond those already told in the protagonists' priority contests, Fleming's theory-driven progression and a recent general survey relegating the initial innovation period to random 'trial and error'.[19] The stories I research concern: the coils' wiring; experiments that provoked changes in wiring; what investigators observed sensationally; and how they interpreted their coil's behaviours. Looked at this way, any account becomes inextricably messy; no list of innovations and dates, or comparison of instrument prowess, can adequately render these many interactions among people and materials through which instruments and understanding evolved together.

Changing the account from versions dominated by outcomes to interpretations sensitive to the vagaries of experimental process entails looking into what was happening as instruments were crafted and innovated. Davis Baird argues that these innovations constitute a form of knowledge. Baird's 'working knowledge' can be discerned in the genesis of scientific instruments like the induction coil that produce and exhibit physical phenomena.[20] In Baird's example of prototype cyclotrons, students of E. O. Lawrence modified homemade apparatus and operating conditions in response to what current output showed. Specific knowledge about materials and tools made for improvements in vacuum and beam control. Often, the evidence about

[15] Théodose DuMoncel described Page's book as 'un long panégyrique dans lequel il attribue tout à l'Amérique et à lui en particulier'; *Exposé des Applications de L'Électricité*, 2 (Paris, 1873), 243.
[16] Fleming (note 6).
[17] J. A. Fleming, *Memories of a Scientific Life* (London, 1934), 133.
[18] Fleming (note 5), 2, 1.
[19] Willem D. Hackmann collected references on improvements to the induction coil and placed these in reference to surviving artifacts in the collection of the Museum of History of Science at Oxford, 'The Induction Coil in Medicine and Physics: 1835–1877', in *Studies in the History of Scientific Instruments*, edited by C. Blondel, F. Parot, A. Turner, M. Williams (London, 1989), 235–50, quote 236.
[20] Davis Baird, *Thing Knowledge: A Philosophy of Scientific Instruments* (Berkeley, 2004), chapter 3.

what works guided innovation without a clear explanatory basis. This knowledge was built up through an integrated process of experimental and theoretical work, instrument design and performance tests, tinkering with parts and adapting outside elements, intuition-led innovations, and trial runs. Activities of making, using, modifying, and experimenting with instruments were at the same time extending and expressing understanding of physical and material behaviours. A motto by physicist Richard Feynman, 'What I cannot create I do not understand', reflects Baird's argument that knowledge inheres in the making of things and in what is created.[21]

Direct experimenting related to the bygone effects, in concert with study of texts and artefacts, is a productive tool in researching past activities and uncovering the understandings associated with innovations in instruments. David Oldroyd described an analogous role for sample preparation, site photography, and fieldwork in the history of geology.[22] Just as seeing 'the most rocks' imparts 'first-hand knowledge' to a historian's interpretation of geology in the past,[23] similarly, a historian's experimenting with old and new materials reopens observations and confusions pertaining to historical explorations of scientific phenomena.[24] Studies using experimental undertakings to augment texts and artefacts also support Baird's contention that knowledge is integrated in the workings of things.[25] For example, problems in imaging a sample flame onto the screen of his rebuilt nineteenth century photometer precipitated Staubermann's realization that the original instrument had adapted techniques from lantern slide projection.[26]

What remains of 1830s electromagnetic coils—artefacts, diagrams, experimental descriptions—is frozen in time, holding the 'working knowledge' entrained within each instrument. Along with researching the remnants to draw out their innovation history, I pursue experimental activities with hand-wound wire coils. I do not seek to replicate instruments as such, but more to gain experience with phenomena such as inductive effects of currents in coils. My interest lies in noticing experimental processes and how tentative understandings evolve while interacting with the phenomena. In the context of 'working knowledge' that Baird apprehends in things, I look for developments through which that knowledge arises and becomes expressed in materials and participant's recorded discussions.

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[21] The quote from Richard Feynman, on p. 114 of Baird (note 20) is taken from J. Gleick, *Genius: The Life and Science of Richard Feynman* (New York, 1993).

[22] David Oldroyd, 'Non-Written Sources in the Study of the History of Geology: Pros, and Cons, in the Light of the Views of Collingwood and Foucault', *Annals of Science,* 56 (1999), 395–415.

[23] Oldroyd (note 22), quotes 415, 395.

[24] Ryan Tweney, 'Discovering Discovery: How Faraday Found the First Metallic Colloid', *Perspectives on Science*, 14 (2006), 97–121; Elizabeth Cavicchi, 'Experiences with the magnetism of conducting loops: Historical instruments, experimental replications, and productive confusions', *American Journal of Physics* 71 (2003), 156–67; David Gooding, *Experiment and the Making of Meaning: Human Agency in Scientific Observation and Experiment* (Dordrecht, 1990).

[25] H. O. Sibum, 'Reworking the Mechanical Value of Heat: Instruments of Precision and Gestures of Accuracy in Early Victorian England', *Studies in the History and Philosophy of Science*, 26 (1995), 73–106; Peter Heering, 'The replication of the torsion balance experiment: the refutation of early nineteenth century German physicists', in *Restaging Coulomb: Usages, Controverses et Réplications autour de la Balance de Torsion*, edited by C. Blondel and M. Dörres (Florence, 1994), 47–66.

[26] Klaus Staubermann, 'Controlling Vision: The Photometry of Karl Friedrich Zöllner', Dissertation, Darwin College, Cambridge, UK, 1998.

3. Early inducing coils having two conductors—and one

This paper's introduction correlates Michael Faraday's 1831 induction devices with features of the eventual induction coil. However, in the mid-1830s, these two-wire coils, having one wire for battery current and another to show inductive effects, were an experimental dead end. Nothing came of them. Instead, single-wire coils were the medium of the instrumental innovations concerned with inducing sparks. While this disjuncture appears in the experimental texts and is highlighted in Fleming's history,[27] these sources do not explain why it is there.

I came to some understanding of this disjuncture by an indirect, experimental path while I was exploring Faraday's 1831 induction experiments.[28] Fascinated by Faraday's description of a tiny spark between terminations of his inducing (secondary) wire (quoted in section 1), I strove daily and unsuccessfully for over a month to reproduce this effect myself.

Through the opening of a closed horseshoe (similar in size to Faraday's ring), I wound lengths of wire. To the windings on one side of my ring (like Faraday's *A* coil, later termed 'primary'), I connected D cell batteries (Figure 3, left). The ends of the much longer windings on the ring's other side (like Faraday's *B* coil, or 'secondary') connected to a small homemade coil having a magnetized sewing needle hung by a long hair within it—my version of his galvanometer (Figure 3, right). When I closed the primary circuit, the suspended needle turned one way, then it reoriented north. On opening the circuit, the needle turned briefly the other way. My needle's deflection recreated Faraday's. One circuit from the past, the other configured by interpretation, both exhibiting the momentary inductive effect, give evidence of a 'working knowledge' formed interactively with materials, similar to what Baird identifies.

In response to the needle's swinging, I reconfigured my apparatus, adding a switch to the primary circuit, putting more wire on the ring, and improving the needle's suspension. On activating and deactivating the circuit after making these changes, the needle swung further, echoing Faraday's description:

> 44 . . . very powerful, pulling the needle quite round, but still it was only momentary. The needle settled as at first though contact continued, and when contact was broken the needle was pulled for the moment in the opposite direction with equal force. (1 October 1831)[29]

I next proceeded to look for the sparking that Faraday observed between his *B* coil's ends. I disconnected my galvanometer and instead attached sewing needles to the ends of my ring's longer coil. I taped these needles onto glass so as to mount them in very close proximity, making a tiny air gap through which the spark might pass. Then, looking closely at the needles in low light, I closed and opened the switch on the primary. No spark appeared.

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[27] Joseph Henry's single-conductor spirals are hailed as 'chiefs of the clan and true ancestors of our modern coil' in Fleming (note 6) 2, 1.

[28] For a fuller discussion of my efforts with the iron ring, see my dissertation, 'Experimenting with Wires, Batteries, Bulbs and the Induction Coil: Narratives of Teaching and Learning Physics in the Electrical Investigations of Laura, David, Jamie, Myself and the Nineteenth Century Experimenters—Our Developments and Instruments' (Harvard University, 1999), Chapter 19.

[29] Faraday, *Diary* (note 1).

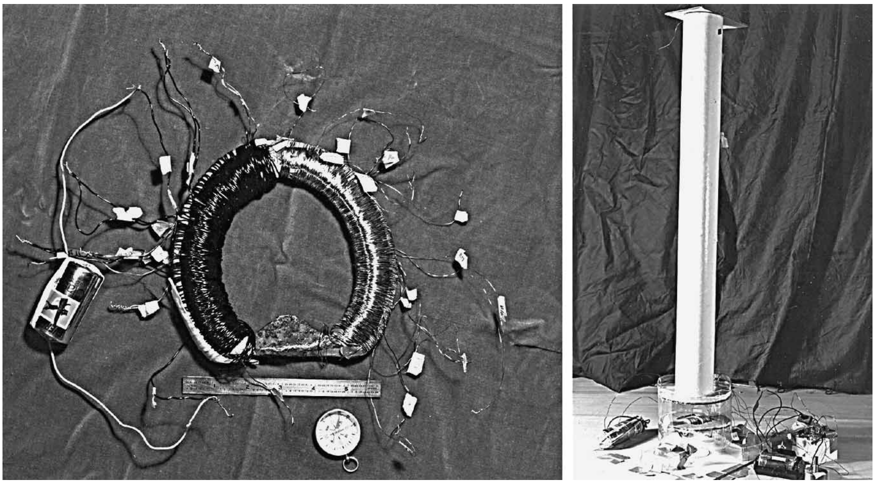

Figure 3. Left: my horsehoe ring, wound with wire coils. The dark coiled wire (on the left side of the ring) connect to a D cell to carry battery current; when the current changes, currents are induced in the light coloured coil and detected with a galvanometer. Right: the white tube of my galvanometer shields a hair hanging within. The hair suspends a magnetized needle inside a wire coil (visible at through clear shield at bottom. When current passes in the coil, the needle turns. It swings back when the current stops. Photos by Joe Peidle.

I thought I knew what to do on the basis of subsequent expressions of 'Faraday's Law', by which more wire loops on the *B* coil, and greater current changes in the primary, contribute to increasing induced voltage.[30] I added winds onto the induced side by the thousands[31] and increased the applied current, from the output of two D cells, to several amperes from a power supply. Again, there were no sparks. Pursuing trial after sparkless trial across many lab sessions, I modified the circuit and power source, and compiled all these variations in a table. Without getting feedback from the circuit, and relying only on formal analysis while my own experience (or working knowledge) of inductive phenomena was still rudimentary, my experimenting kept flailing. On retrospect, this passage in my work re-enacts that of the historical case where experimentation with two-wire coils apparently fizzled out after 1831.

One day, this stalemate shifted. Unlike Faraday's high currents, the currents delivered by my D cells were low.[32] To work around this limitation, I set up to deliver a higher current (maximal 15 A at 2.5 V) from a lab power supply into my ring's primary (Figure 4). With black cloth draped over my head and the apparatus

[30] In the special case of electromagnetic induction between a primary circuit 1 and secondary 2, Faraday's Law can be expressed as: $\epsilon_{21} = -M_{21}(\mathrm{d}I_1 / \mathrm{d}t)$, where e_{21} is the electromotive force (V) induced in circuit 2 by circuit 1, M_{21} is the mutual inductance between the two circuits, and $\mathrm{d}I_1 / \mathrm{d}t$ is the change in current (A) in circuit 1. The mutual inductance depends on such features as the number of loops in the two circuits, their geometries, and the magnetic permeability of the surroundings. See J. D. Jackson, *Classical Electrodynamics* (New York, 1975), Edward Purcell, *Electricity and Magnetism* (New York, 1965).

[31] My ring's final windings had a total of 3690 turns of wire. Of these, 400 turns on the primary, and 2164 on the secondary, were usable; Cavicchi (note 28), chapter 19.

[32] Faraday's low-resistance sources delivered high currents into his low-resistance windings. The resistance of my sources and windings were unmatched, and currents were typically low.

Figure 4. Sketch from my lab notebook showing the induction ring, its primary wires connected to a power supply (far right) by way of a knife switch. The secondary wire terminates in sewing needles, viewed under a magnifier loupe (middle). A spark was observed when the switch disconnected the primary circuit (from Cavicchi note 28).

(another innovation of this trial), I switched the current on and off. No sparks appeared at the needles, but I glimpsed a flash elsewhere and recorded:

> . . . I found the spark—at the switch—on the primary pretty sizable—hadn't noticed spark at switch at lower settings, but wasn't looking for it in the dark either. (7 May 1997)[33]

Then, replacing power supply with D cells, I observed in the dark what the room lights hid: 'a spark at the switch!'

The spark in the primary circuit gave me something to explore, whereas the spark on the secondary circuit remained elusive. There was a difference between seeking something expected but unseen, and working with something observable. Only in that process did I discover that the spark was significantly brighter on opening the switch—historically termed 'break'—than on closing it—termed 'make'. This asymmetry between make and break—so strikingly exhibited by the phenomena—is typically omitted by physics texts, and historical uses of the words 'make' and 'break' had little meaning for me before.[34]

Again, experience with materials was essential to comprehending the phenomena and historical experiments. Under the power supply's high currents, my switch often sparked at both make and break; this led to my initial spark observation, quoted above. With the D cells, sparking occurred only at break, and this circumstance brought me to realize that make differs from break. The brighter spark at break involves induction; the lesser spark at make is due to direct current. I then noticed that Faraday, working routinely with high currents, explicitly contrasted his new observation of brightened sparking at break from ordinary sparking at circuit

33 Cavicchi (note 28), chapter 19.

34 The rate of change in current within a wire is involved in inducing voltage in that same wire or in separate wires (note 30). When a circuit is closed, on 'make', current starts gradually. When the switch opens, at 'break', the current stops abruptly. Its more sudden change induces a higher voltage.

closure. [35] Henry, who preceded Faraday in observing a spark when he disconnected long coiled wire from a small battery, did not make this distinction. [36]

Faraday and Henry demonstrated that this new electrical effect, arising momentarily in the same conductor through which battery current had just passed (i.e. the primary), differed from ordinary battery current. They detected this effect, now termed 'self-induction', not only as a spark, but also as a bodily shock of a kind that they did not experience in routine work with battery current. While grasping a long coiled wire with one end in each hand, a shock passed through their body whenever that wire broke its connection across the battery's terminals (Figure 5). If the wire was short, there was no shock (or associated spark); if the coiled length was entirely straightened, the shock diminished. Faraday interpreted the relation between non-shocking battery current and the new shocking effect as transformative; he called it: 'one of the very few modes we have at command of converting quantity into intensity as respects electricity in currents'.[37] Both investigators explored conductors to see which enhanced these effects, and found different optimal configurations. For Faraday, an electromagnet—a wire coiled around iron—gave the greatest effect, whereas Henry's best device was a wide copper ribbon, insulated in fabric and tightly spiralled.[38]

From Faraday's 1831 two-coil ring to the one-conductor coils and spirals investigated by Faraday and Henry around 1835, both the experimental instrument, and its observable effects, underwent changes. The wire coils carrying battery current through Faraday's ring were separate from those in which electricity was induced and detected. The new form of induced electricity that shocked Faraday and Henry traversed the same path in a coiled conductor as that taken by the battery current (Figure 6). The enhanced spark and bodily shock—effects that were not notable with the 1831 two-coil devices—provoked Faraday and Henry to explore wiring geometries having a conductor shared between direct and induced electricity. My unproductive efforts to get sparks with the second coil on a ring (or helix) corroborate the historical 'dead end' that waylaid work with this seemingly prescient device. Two features of the electricity induced in single-conductor coils were not apparent in Faraday's 1831 observations of electromagnetic induction: elevated intensity (or 'tension' or voltage), and occurrence on a 'break' in the battery (primary) circuit. [39] These features were characteristic of the eventual two-wire

[35] Faraday discussed these cases in 'On the Magneto-electric Spark and Sock, and on a Peculiar Condition of Electric and Magneto-electric Induction', *Philosophical Magazine*, 5 (1834), 349–354.

[36] Joseph Henry, 'On the Production of Currents and Sparks of Electricity from Magnetism', *American Journal of Science* 22 (1832), 403–408; reprinted in *The Scientific Writings of Joseph Henry*, 1 (Washington, DC, 1886). No mention of sparking at make appears in Henry's later study, 'Contributions to Electricity and Magnetism, No. II, "On the Influence of a Spiral Conductor in increasing the Intensity of Electricity from a Galvanic Arrangement of a Single Pair" (read 6 February 1835), *American Philosophical Society Transactions* (1837), 223–31.

[37] Faraday, 1834 (note 35) 351. 'Quantity' refers to the property we associate with high current at low voltage; 'intensity' to high voltage with low current.

[38] Faraday contrasted conductor configurations in 'On the influence by induction of an Electric Current on itself ..., Ninth Series', read 20 January 1835, in *ERE* 1839/2000 (note 1); he also showed that this new induced effect had a different direction from that of the battery current. Henry's efforts are detailed in his paper of 1837 (note 36). His preliminary results were published earlier, 'Facts in reference to the Spark, &c. from a long conductor uniting the poles of a Galvanic Battery', *Journal of the Franklin Institute* (1835) 169–70, and *American Journal of Science*, 28 (1835) 327–29, Appendix to the above, 329–31. Telegraph engineer W.T. Henley cited Faraday's experiment contrasting sparks from a coiled wire, with those from a straight one in his testimony on the failure of the 1858 Atlantic Telegraph, in the *Report* (note 11),¶ 2432, 109.

[39] There was a lesser effect in the same conductor, on starting the battery current.

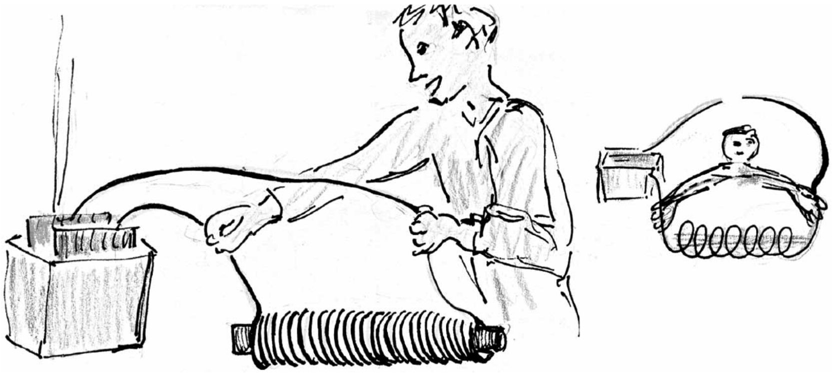

Figure 5. Left: an experimenter grasps with each hand the ends of a conducting coil. Right: when the battery is unconnected from the coil, the person completes that circuit and experiences a shock.

induction coils. One, elevated intensity/voltage, shows graduated increase and thus allowed cross-comparison between the instruments differing in spatial and material constitution. The other, coincidence with circuit 'break', is temporal and could be made repetitive and recurrent.

The investigators used what they understood about these features of space, materials, and time, in devising new instruments. Conversely, their evolving instruments manifested more about the inductive effects, giving rise to further instrumental improvisation. This experimental process was interactive without being either sequential or random. In the context of an earlier phase of Faraday's work, David Gooding perceives 'the emergence of a reflexive understanding of the parameters and outcomes of [Faraday's] own agency in a changing experimental situation'.[40] If Gooding's analysis is applied to this early work with induction devices, 'parameters' corresponds to coil lengths or shapes and 'outcomes' to shocks. The emergent understanding so closely enmeshed with these instruments that they simultaneously documented its developments and produced the experimental changes.

4. The single conductor differentiates to two paths—and relapses to one path

The US medical student Charles Grafton Page followed up on Henry's preliminary, incomplete report about the shocking spiral by constructing a much larger one, with which he expanded the experimental possibilities and produced new findings.[41] Whereas both Faraday and Henry sensed shock (or spark) only while conducting battery current through the entire coil (or spiral), Page directed battery current through only a portion of the spiral, and took the shock across that same portion, or any other part (Figure 7). To flexibly administer current to the spiral, and take shocks from it, he soldered connector cups at different radial positions along its length. By this system of

[40] Gooding (note 24), 159.

[41] C. G. Page, 'Method of increasing shocks, and experiments, with Prof. Henry's apparatus for obtaining sparks and shocks from the Calorimotor', *American Journal of Science* 31 (January 1837), 137–41.

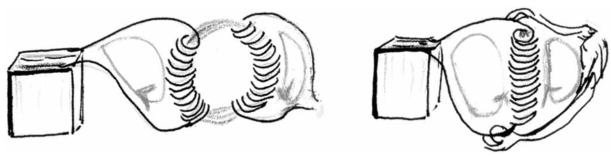

Figure 6. Left: battery current passed through left coil on Faraday's ring; when it stopped, an induced current or spark arose in the separate wire coiled on the right side of the ring. Right: the coil through which battery current passed was also part of the shock circuit.(right loop).

variable-length paths for current and shock, 'shocks of all grades' could be produced, making the spiral instrument suitable for therapeutic shocks.[42]

Page noticed an additional trend. If the battery current traversed a short section of the spiral, while his hands spanned more of it, the shock (felt on stopping battery current) was greater than if his hands grasped the battery connection points. Including more of the spiral between his hands increased the shock more.[43] Page reported this finding as 'curious ... difficult to explain'.[44] In his retrospective suit to the US Congress, Page described his spiral (when used in this way) as the first apparatus producing 'electricity of high intensity ... from a *secondary coil*—that is a coil not induced within the battery circuit'.[45]

News of Page's shocking device made its way across the Atlantic through the garbled account of a US traveller and acquaintance of Page in Salem MA. Sturgeon encountered the traveller, Francis Peabody, in the company of London electrician E. M. Clarke at the Adelaide Gallery (see section 1). [46] Sturgeon's imagination was fired by the American claim of a device that 'convert[s] *quantity* of the electric fluid into intensity', or in our terms, turns high current to high voltage.[47] Many details of Page's spiral—including his name as its inventor—were lost in the verbal transmission. The informant described a copper spiral, coiled like a 'watch spring' and carrying battery current through half its length while the shock was taken across its entirety. Complaining 'I was not told its length or breadth', Sturgeon did not bother cutting

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[42] Page (note 41), 141; Page, 'Medical Application of Galvanism', *Boston Medical and Surgical Journal*, June 22, 1836, 333.

[43] Page's observation, that shock increases as it is taken across more non-current bearing winds, is problematic to reproduce. See Elizabeth Cavicchi, 'Opening the Circuit to the Body, more Options, and Ambiguity: Charles Grafton Page's Experiment with a Spiral Conductor', *Technology and Culture*, in preparation 2006; 'Sparks, Shocks and Voltage Traces as Windows into Experience: The Spiraled Conductor and Star Wheel Interrupter of Charles Grafton Page', *Archives des Sciences*, in preparation 2006.

[44] Page (note 41), 139.

[45] Page 1867 (note 14), 3.

[46] Sturgeon's encounter with 'a Mr. Peaboddy, a scientific American gentleman whom I accidentally met with in the Adelaide Gallery of Practical Science' is described on p. 67 in William Sturgeon, 'On the Electric Shock from a single Pair of Voltaic Plates, by Professor Henry, of Yale College, Unites States: Repeated, and new Experiments' (28 September 1836), *Annals of Electricity*, 1 (1837), 67–75, reprinted in William Sturgeon, *Scientific Researches, Experimental and Theoretical in Electricity, Magnetism, Galvanism, Electro-Magnetism and Electrochemistry* (Bury 1850), 282–89. It is critiqued in (Charles Grafton Page) (note 14), footnote p. 11. Francis Peabody (1801–1867) established White Lead manufactories in Salem in 1826 and 1832; Joseph Felt, *Annals of Salem*, II (Salem 1849). Interested in science, particularly photography, Peabody contributed financially and personally to the Harvard College Observatory and other related projects. Harvard University Archives.

[47] Sturgeon 1837 (note 46), 67.

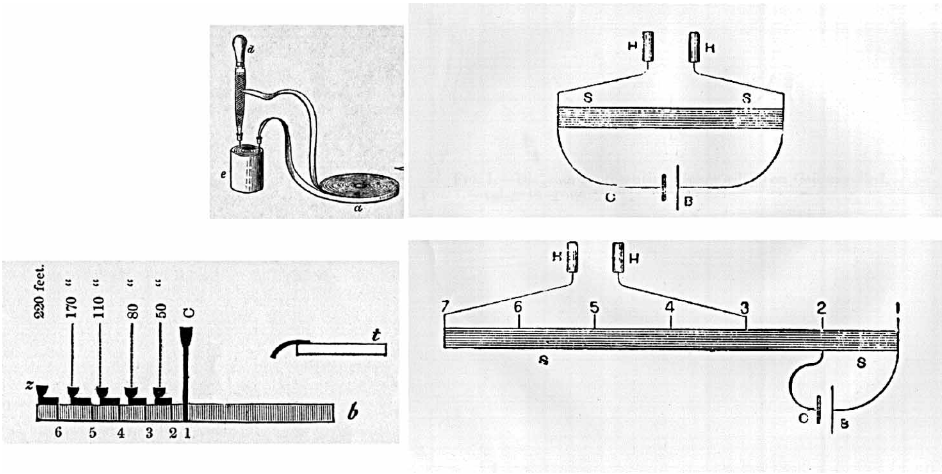

Figure 7. Top left: Henry's sketch of his spiral, battery, and rasp interrupter (from his 'Contributions to Electricity and Magnetism: On Electro-Dynamic Induction' No. III, *Transactions of the American Philosophical Society*, 6 (1839), 303–37.) Top right: Henry's spiral unwound; the shock is taken across the handles *HH*, while the battery is applied across the same span. From Fleming (note 6). Bottom left: side view of Page's spiral showing connector cups spaced across its length. Bottom right: Page's spiral unwound; the shock may be taken across parts of the spiral that may differ from the segment carrying the battery current (from Fleming note 6).

up copper sheet to make a spiral. He figured that the wire coils (removed from a magneto-electric machine) that were already 'at hand . . . might answer the purpose just as well'.[48] Sturgeon conjoined two hollow helical coils of insulated wire (in series, using our terms), sent battery current through just the first coil (A in Figure 8), and took the shock across both coil A and additional coil (B in Figure 8).

Unlike Page, who did not presume to know or explain what made his spiral work, Sturgeon set up his experiments with a conjecture in mind, and this idea is reflected in his original two-coil arrangement. He viewed the shared coil A as substantive to the effect and supposed that the battery current in that coil was the very same fluid that caused the shocks. While the battery connected to A, this fluid had low intensity. When that connection broke, the fluid was 'transferred suddenly to a new channel' in coil B, and this transfer—he surmised—boosted the fluid's intensity to the point where it gave good shocks. However, this idea failed when Sturgeon tested it. Putting his hands across both coils A and B made the shocks 'lessen, rather than increase' in severity, as compared with shocks taken only across coil A![49] Sturgeon abandoned the 'worse than useless' second coil (B).[50] Instead, he sought out configurations of the first coil (A) that improved its shock. Taking wire of various lengths, he wound compact layered coils whose design derived from Sturgeon's further ideas about how a wire's magnetism affects its shock (see below). He took the shock on breaking a coil's battery connection, then uncoiled it, and felt no shock. Elated by this discovery,

[48] Sturgeon (note 46), 69.
[49] Sturgeon (note 46), 69.
[50] Sturgeon (note 46), 70.

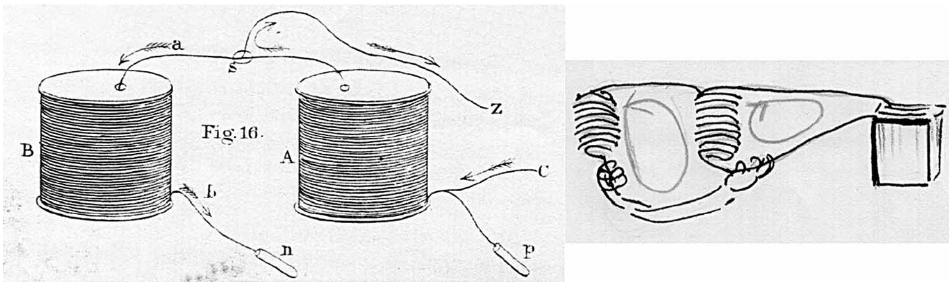

Figure 8. Left: Sturgeon's shocking coils; battery current is applied to coil *A* (through C and Z), and the shock is taken across both coils *A* and *B* by the handles *n* and *P*. From Sturgeon, note 47. Right: diagram showing battery loop (right) and shock loop through both *A* and *B* (left).

and its clear (to him) instantiation of his idea, Sturgeon announced that it brought 'to light a novel principle . . . till this day, unregistered in the pages of philosophy'.[51]

Of course, Sturgeon's 'discovery' that coils gave strong shocks, unlike uncoiled wire, was not the first observation of this (self-inductive) behaviour. Three months later, he became aware of Faraday's work, perhaps through Charles Barker (a contributor to his own journal), who correlated the shocking devices of Faraday, Callan, and Sturgeon, and described one of his own (Figure 21). Sturgeon conceded the discovery, but not its explanation, and reprinted Faraday's Ninth Series in full in his journal.[52] However, Sturgeon remained uninformed about Page's spiral and the inadequacy of his interpretation of coil *B* until Page's paper became available to him that spring. Then, he admitted that the problem with coil *B* was its distance from coil *A*; these two were not 'within the influence of each other'.[53] In our perspective, they were not sufficiently coupled for the changing magnetic field of *A* to induce a significant electromotive response in *B*. For example, Faraday's iron ring provided coupling between his distinct, non-overlapping *A* and *B* coils of 1831. With Page's spiral, and subsequent induction devices, the current-bearing conductor and the conductor delivering shocks are closely arranged, often concentrically, and show in their structure an increasing attention to proximity and related issues.

Page's experimental development contrasts with Sturgeon's. Both reacted to an incomplete report about a shocking spiral powered only by a single-pair battery (which was well known not to be capable of delivering shocks). Page responded to Henry by constructing his own longer spiral from cut-up copper sheet, along which he inserted connectors so that current could be sent through various lengths, and let

[51] Sturgeon (note 46), 75.

[52] Sturgeon, 'On the production of Electric Shocks from a single Voltaic pair', *Annals of Electricity*, 1 (1837), 159–60. In Sturgeon's 1850 reprint volume containing many of his papers, he commented that his neglect of contemporary literature allowed him to duplicate Faraday's results. This was 'no little mortification, because of an *apparent* plagiary, which I most abominably detested'; Sturgeon 1850 (note 46) p. 45. On the preceding page of the Annals publication, contributor Charles Barker cited Faraday's Ninth Series (reproduced on pages 160–62 and 169–86 of *Annals of Electricity*, 1 (1837)), and perhaps this tip led Sturgeon to Faraday's work. Morus (note 5), 61–67 treats Sturgeon's work with self-induction phenomena only from Sturgeon's stance, and does not identify the transmission error by which Sturgeon attributed Page's spiral to Joseph Henry.

[53] Sturgeon, 'Explanation of the Phenomena, &c.' *Annals of Electricity*, 1 (1837), 294–95.

the shock be taken across different spans. Page's spiral with tabs accommodated questions that he had not imagined in advance; the instrument itself stimulated new research and questions.[54] By contrast, instead of replicating the 'watch spring' design of Page's instrument, Sturgeon started off from the reputed finding that high 'quantity' electricity converted to high 'intensity'. Being framed by his ideas about how electric fluid could be made to do this, Sturgeon's two-coil work floundered. Adverting toward the single-conductor whose shocks provided feedback to its coiled or uncoiled state, Sturgeon then re-traversed some of the same experimental ground already covered by Faraday and Henry.

While both investigators interacted with instruments and their effects, Page's commitment to learn from the instrument was more productive than Sturgeon's reliance on explanation as a guide, and Page was no less thoughtful than Sturgeon. That thought was interactively and materially expressed, for example in solder joints and inventive ways to probe the circuit. Some recent scholarship identifies this kind of experience as 'exploratory experimentation', where no explicit hypothesis or theory is available to drive the activity, and yet productive work goes on.[55] Gooding characterizes Faraday's early electromagnetic study in this way: 'Though preverbal it was not inarticulate: new possibilities were articulated behaviourally and concretely . . .'[56] In generating and testing possibilities that had not even been apparent prior to Page's explorations, the paths of battery current and induced electric effect began to differentiate along the same long conductor.

5. Questioning the role of iron—and the mind—in experimenting

The material of iron was equivocal: did it promote the effect of heightened electricity, or not? An iron rod inserted in Faraday's hollow coil improved the sparks, but when put into the centre of Henry's spiral, it was irrelevant. Questions about iron emerged again as William Sturgeon tested more ideas about what was going on. Like Henry, but drawing on different experiences, he rejected what he took to be Faraday's reliance on iron for inducing electricity.

These historical controversies about iron confused me. To get beyond my certainty about iron's enhancing role, I assembled a circuit from a switch, battery, and hollow coil, and looked for changes in sparking at the switch when I put a rusty (but likely steel) rod inside. My expectations were unsettled when I often failed to see a spark or could not tell whether it brightened or dimmed. To assist comparison, I wired a double switch to flip between one case (11 yards of coiled wire) and another (11 yards of extended wire; Figure 9). My lab notes relate:

> don't see spark every time but when I do it's bigger on coil/rod side . . .

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[54] For example, 'contrary to expectation', Page experienced shocks from parts of his spiral that were entirely outside the direct current's path (note 41), 139.

[55] Neil Ribe and Friedrich Steinle, 'Exploratory Experimentation: Goethe, Land and Color Theory', *Physics Today*, July 2002, 43–49; Friedrich Steinle, 'Entering New Fields: Exploratory Uses of Experimentation', *Philosophy of Science* 64 (1996), S65–S74; Richard Burian, 'Exploratory Experimentation and the Role of Histochemical Techniques in the Work of Jean Brachet, 1938–1952', *History and Philosophy of the Life Sciences*, 19 (1997), 27–45.

[56] Gooding (note 24), 122–23.

Big difference in spark with coil as compared to spark with stretched-out wire . . . And [*it is not*] . . . brighter when 'iron' bar in there?[57]

My experiment's ambiguity helped me appreciate how historical observations might support seemingly differing views on iron. This ambiguity held up in my later study (see section 6) showing that a coil with a (steel-iron?) rod inside had a measured electrical response comparable with that of the same coil when empty.

Sturgeon's initial experience was similar. In the course of his single-coil experiments (described above), it occurred to him that iron placed within a coil might alter its shock. Having 'no idea' in advance regarding the likely outcome, he said his tests quickly 'convinced me' that iron was ineffectual.[58] Iron was not crucial, but Sturgeon asserted that something else was. He proposed a '*mediate* or intervening agent'—which is neither magnet nor conductor—that becomes 'polarized by the exciting *polar magnetic lines* of the magnet' and in turn gives rise to induced currents in conductors.[59] This mediate agent was there to convey the magnetism not only of permanent magnets, but also that associated with the currents in wires. Viewing the magnetic lines circling around a conducting wire as composed of little magnets, he argued that their effects reinforce each other more when wire is coiled, than when fully extended. This reinforced magnetism actually reduces the coiled wire's electrical resistance, affording an easier channel to the current by which its momentum increased. Under the idea (mentioned above) that the electric fluid's momentum in wires accomplishes its shocks, Sturgeon linked a wire's coiling to its greater shock. As he saw it, his prematurely claimed 'discovery' vindicated this model of magnetism.

Once Sturgeon had access to Faraday's precedent work, he objected vigorously both to the finding that iron seemed to matter, and to the analysis that sparks and shocks result from induction, 'the action of one current upon another'.[60] Disparaging Faraday's trials of soft iron as 'obviously too limited' and his allusions to induction as unhelpful and non-explanatory, [61] Sturgeon mounted an extensive experimental and theoretical enquiry of these behaviours in a single conductor. Summaries of each experiment in order trace how his experience developed. The first experimental sequence tested both for sparks and shocks from: a tube coil made from a medium-length wire (with and without iron), an electromagnet having the longest wire winding, and a compact multi-layered coil wound on wood from a 300-foot-long wire. Sturgeon repeated this sequence using each of three fluids to activate his battery: cold saltwater, boiling saltwater, nitrous acid. In all cases, the compact coil having no iron interior yielded strongest shocks, although the tube coil shocked better with an iron insert. Pausing at this point, he re-emphasized that iron 'is not the *sole* cause of the shocks', wondered why the compact coil did better than those containing iron, and reflected on his

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57 Excerpt from my lab notebook (14 May 1997) in my dissertation (note 28), Chapter 19.
58 Sturgeon (note 46), 72.
59 Sturgeon (note 46), 72.
60 Quote from Faraday (note 38), ¶1110, 340.
61 William Sturgeon, 'Remarks on the Preceding Paper, with Experiments', *Annals of Electricity*, 1 (1837), 186–91, quote 186.

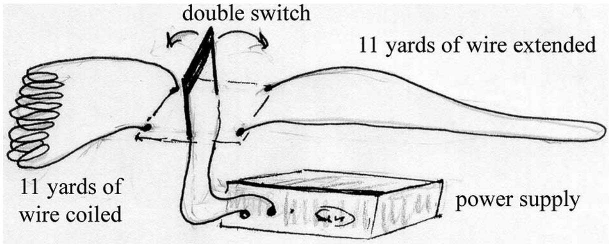

Figure 9. My comparison experiment between a circuit having 11 yards of coiled wire (left) and one with the same length of wire extended. A double knife switch joins either wire to the power supply. Brightest sparks were observed at the switch when it broke current flow through the coiled wire.

practical work with magneto-electric machines where long wires gave strongest shocks. [62]

On resuming experimenting, now he worked more systematically, attending to issues that surfaced in his preliminary phase. 'To prevent any misunderstanding', in each comparison involving iron he used the same length of wire—even to the point of unwinding all 300 feet of it off one bar and onto another.[63] Thus, for the first time he directly tested the good 300-foot compact coil, with and without an iron bar core. The iron-centred coil won out and in fact gave the strongest shocks of any arrangement of windings and iron that he constructed. Again he took up work with 'double conducting wires', found 'certain circumstances' where the additional wire added to the shock, but did not disclose either the instrumental design or those particular circumstances, except to note that the battery had to match the wiring.

Having accomplished these experimental studies, Sturgeon put forward his fuller theoretical views on the mystery of how 'secondary currents' are produced by 'primary ones':

> Electricity and magnetism are . . . playing their nimble powers on each other in the most profound retirement:—their motions concealed from corporeal vision permit of no other approach than by the perceptions of the mind: and by that mind only, already perfectly familiar with the proximate laws of magnetic-electricity. [64]

No sensually apparent mechanism governs electricity and magnetism. Sturgeon took that lack to portend a wide scope for working one out by 'mind', incorporating what sensual evidence and experience he had.

[62] William Sturgeon, 'An Experimental Investigation of the Laws Which Govern the Production of Electric Shocks &C, from a Single Voltaic Pair of Metals', *Annals of Electricity*, 1 (1837), 192–98, quote 195; reprinted in Sturgeon 1850 (note 46) 289–97. Instrument maker E. M. Clarke also remarked that with magneto-electric machines, long thin wire coils give higher-intensity electricity, 'Account of Experiments with . . . Magneto-Electric Machines', *Annals of Electricity*, 1 (1837), 73–76.

[63] Sturgeon (note 62), 197.

[64] Sturgeon, 'Theoretical Views of the Preceding Phenomena, Secondary Electric Currents, &c.', *Annals of Electricity*, 1 (1837), 198–200, quote p. 200; reprinted in Sturgeon 1850 (note 46), 310–311.

In framing his theory, Sturgeon relied on visible evidence provided by 'multitudes of exceedingly fine lines' that are taken up by tiny iron particles scattered around magnets or currents (Figure 10).[65] These iron filings lines were already well known among London's tightly knit electrical experimenters. Gooding traced examples of their use, including: Peter Barlow's illustrations of magnetic lines in the 1820s; Sturgeon's work with iron filings around the electromagnets he invented; and Faraday's 1831 analysis that currents are induced in conductors that move through a magnet's lines.[66] In these cases, the magnets are stationary, and their static lines are directly observable.

This situation no longer holds when magnetic lines are associated with changing electrical currents and said to have motion. That motion was inferred by Faraday (using a symmetry argument) and expressed by Sturgeon. When current starts going in a wire, Sturgeon described the lines as starting to move out away from the wire in '*distention*'; Faraday had regarded these curves as 'expanding . . . outward' from it. [67] When current stops, Sturgeon pictured them returning to the wire in sudden '*collapsion*' as 'the cause of their existence now ceases to exist'; Faraday had written they 'may be conceived as contracting upon and returning towards the failing electrical current'. [68] We now associate Faraday with understanding that motions of magnetic lines induce currents, but the contemporary perception in the 1830s was otherwise. Lecturer George Bachhoffner contrasted Faraday's view that the induction of currents is 'somewhat analogous to that produced by common Electricity' against Sturgeon's explanation that 'the exciting influence' of electro-magnetic lines causes the new currents.[69] At the time, Sturgeon was making the most public use of magnetic lines.

Unlike Faraday, whose analysis interlinked his questions about electrical conduction and induction across a range of evidence and experiment, Sturgeon framed his model (introduced above) to address the narrowly defined problem of how moving magnetic lines bring about what he called 'secondary currents' in wires. Not the lines alone, but an unseen magnetic medium activated by the lines, affects the electric fluid inside wires, thus promoting its momentum. For example, Sturgeon explained the shock experienced upon current cessation in coils in this way:

> . . . the electro-magnetic lines . . . suddenly collapse, and by advancing rapidly on the moving fluid on every side . . . of the current, give to it a new impulse . . . and the electro-momentum, thus increased, is now enabled to overcome those resistances which the battery energies alone were not capable of

[65] Sturgeon, 'On the theory of Magnetic Electricity', *Annals of Electricity*, 1 (1837), 251–58, quote p. 252.

[66] David Gooding, ''Magnetic Curves' and the Magnetic Field: Experimentation and Representation in the History of a Theory', in *The Uses of Experiment: Studies in the Natural Sciences*, eds., D. Gooding, T. Pinch, S. Schaffer (Cambridge, UK, 1989), 182–223; 'Experiment and concept formation in electromagnetic science and technology in England in the 1820s', *History and Tech*nology, 2 (1985), 151–76. An eighteenth-century discussion of 'magnetic curves', and an illustration of the iron filings lines around permanent magnets, appears in George Adams, *An Essay on Electricity, Explaining the Theory and Practice . . . with an Essay on Magnetism* (London, 1787), 433.

[67] Sturgeon, 'Application of the Preceding Theory . . . to the explication of Phenomena', *Annals of Electricity*, 1 (1837), 266–277, quote p. 269; reprinted in Sturgeon 1850 (note 46), 310–21. Faraday, Bakerian Lecture, Second Series, 1832, *ERE* 1839/2000 (note 1), ¶ 238, 68.

[68] Sturgeon (note 67) 273; Faraday (note 67), ¶ 238, 68.

[69] George Bachhoffner, *Popular Treatise on Voltaic Electricity and Electro-Magnetism* (London, 1838), 32.

> penetrating ... [thus] resistances presented by animal bodies are conquered ... [70]

Sturgeon had described a visualizable, but nonvisual, mechanism for electromagnetic interactions in general, and secondary currents in particular (Figure 10). It accounted for transitory currents, their relative strengths and directions, each detailed in separate cases, but offered no new predictions.

Satisfied with his model, Sturgeon did not understand how Faraday could discuss induction without providing any mechanism for it. Faraday's paper on currents induced within the same conductor, to which Sturgeon was responding, did not even mention magnetic curves and seemed, to Sturgeon, to ascribe to iron a crucial role in induction (it did not). Sturgeon's reading of Faraday lacked access to Faraday's still-incipient field thinking where the magnetic curves exhibit action in space.

Sturgeon disconnected from Faraday not just because he considered induction unclear and unexplained, but also because of the differing expectations he placed on experimental work. Sturgeon sought out mechanisms, whereas Faraday strove to characterize laws and patterns while keeping an open mind about what the underlying processes might be.[71] Sturgeon's mind worked inventively to provide a mechanism that was missing observationally; Faraday winnowed his creativity by a '*mental discipline*' to remain critical of his own ideas and resist self-deception.[72] As an experimental tool, the plasticity of mind was enticing for both Sturgeon and Faraday, but Faraday was more critical and persisted over a long time in seeking evidence for his ideas about the action of magnetic curves.

6. Great electromagnets with power, shock, and two-path wiring

The differentiation of separate paths for battery current and shock in the same coiled conductor, first expressed by Page, then dismissed through Sturgeon's disjointed reinterpretation, emerged independently in the experimenting of Irish priest Nicholas Callan. A report by Callan appeared in Sturgeon's journal immediately after Sturgeon's annotated reprinting of Page's work on the spiral (a year after its US debut).[73] Like Page's spiral, Callan's instrument had one path for battery current, while shock was taken across a longer extension of that same conductor—he did not specify what brought him to this configuration. His first test device was an iron bar overwound with two equal-length copper wire coils conjoined crosswise so the start of one coil affixed to the end of the other (Figure 11).[74] With current sent only through the first coil, already the shocks were intolerable.[75]

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[70] Sturgeon (note 67) 275.

[71] Morus (note 5) portrays the Sturgeon–Faraday split differently, along class and strategic lines. For him, Sturgeon concentrated on elucidating apparatus and communicating to electrical practicioners; Faraday crafted an elite image for himself by highlighting results and hiding his manual labour.

[72] Faraday, 'Observations on Mental Education', Lectures on Education (London 1859), 36–88, quote p. 58.

[73] Nicholas Callan, 'On the Best Method of Making an Electro-Magnet for Electrical Purposes, and on the Vast Superiority of the Electric Power of the Electro-Magnet, over the Electric Power of the Common Magneto-Electric Machine', *Annals of Electricity*, 1 (1837), 295–302, quote 295

[74] Although Callan did not explain why the coils' opposite (not same) ends are combined, this measure is necessary to preserve the same winding sense throughout and to prevent the cancelling of current effects. This issue is discussed in the context of other historical replications, Cavicchi (note 24, note 28).

[75] N. J. Callan, 'On a new Galvanic Battery', *Philosophical Magazine*, 9 (1836), 472–78. .

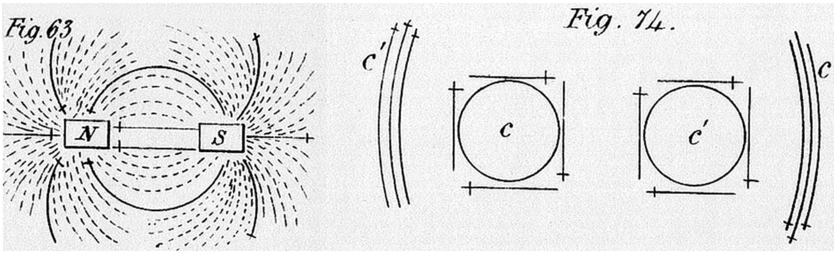

Figure 10. Left: Sturgeon's drawing of the iron filings pattern visible around a bar magnet. Right: Sturgeon's representation of magnetic lines (outer curves with arrowheads) distending or collapsing from a pair of conducting wires *c*, *c*'. From Sturgeon, *Annals*, 1837.

Callan's grounds for researching electromagnetic effects differed from the other investigators. For his large lecture demonstrations, Callan aimed to construct a battery-powered electromagnet having both the greatest attainable capacity for lifting weights and the most emphatic delivery of electric shocks. Students' bodies were the eventual recipients of both these achievements, for lessons long remembered, if not well understood! The students' view on their professor's undertakings comes out in one letter home: 'many are afraid he will blow up the College. Yesterday . . . we heard an explosion that was like the end of the world'. [76] Callan's own writing disclosed such large-scale ambitions as to supersede all batteries with a battery-electromagnet unit providing 'current of the highest intensity' as well as ordinary currents.[77]

Callan's focus narrowed and bounded his interest in ways uncharacteristic of other experimenters. He did not aspire to elucidate the operative electromagnetic processes. This indifference underlies the opening sentence of a paper presenting his search for a 'best method' of producing high-intensity electricity from an electromagnet. There he specified that upon the battery's stopping, an induced 'current is made to flow . . . in a direction opposite to that of the current from the battery'.[78] This incorrect, yet definitive, statement of current direction contrasts startlingly from Faraday's care in tracing current direction. Perhaps it suggests Callan's disengagement from fine details of experimenting that mattered as clues to Faraday and Sturgeon—clues suggesting to them (yet not to Callan) that the iron mass, in itself, was not indispensable to the effect. Similarly, Callan's assumption, that there is a single 'best method' of producing the effect, acted to simplify—and reduce—his relation to the complex phenomena.

Callan blocked out this 'best method' systematically, testing the delivery of shock under different conditions of the battery-electromagnet unit. The electromagnet was the prototype subject of research while the great Maynooth battery, having flexible

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[76] For student memories of Professor Callan, see McLaughlin (note 8), 35–54, quote 37.
[77] Callan (note 75) 476.
[78] Nicholas Callan, 'On the Best Method of Making an Electro-Magnet for Electrical Purposes, and on the Vast Superiority of the Electric Power of the Electro-Magnet, over the Electric Power of the Common Magneto-Electric Machine', *Annals of Electricity*, 1 (1837), 295–302, quote 295.

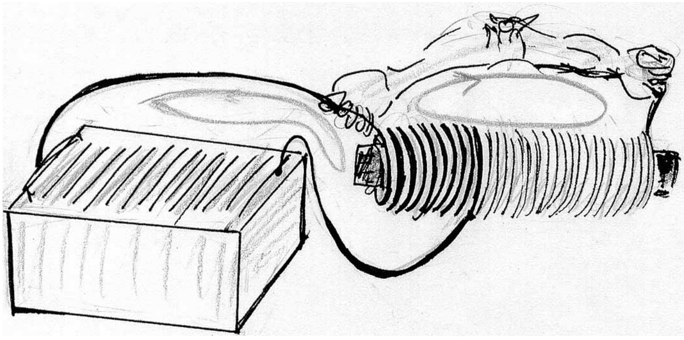

Figure 11. Callan's first electromagnet, where battery current went through just part of the coil, and the shock was taken across the entire coil.

ways for connecting its 20 pairs of plates, provided multiple means of stimulating trial electromagnets.[79] He separately varied electromagnet geometry or make-up, and battery action. In each trial, Callan applied current to the modified instrument and, upon its cessation, took the shock through copper handles grasped with each hand. In comparing cases, he described shocks as greater or lesser, not divulging how those judgements were made. Through doing this, he determined that the shock:

> ... increases with the magnetic power of the electro-magnet, with the length and thinness of the wire, with its inverse distance from the iron, and with the regularity of the coiling ...[80]

Unlike Sturgeon, who found that electromagnets with conventional windings spread out along the iron bar gave weaker shocks than compact coils with or without iron cores (see section 5 above), Callan only used electromagnet-style windings for battery current and concluded that an electromagnet's pull on iron (by an unspecified measure) correlated directly with its shocking capacity. Sturgeon, keeping identical paths for current and shock, had observed that shock did not always increase with wire length, but it was otherwise for Callan. As the shock path lengthened beyond the current path, shock stepped up (unless that wire was not wound tight against the iron).

Viewing shock as an outcome of an electromagnet's magnetic power, Callan sought to maximize magnetic pull. For this, great mass of iron in the electromagnet core was propitious. More iron mass gave better effect to the extent that Callan asserted that the quantity of iron was proportional to magnetic power. There was a payback, however; small iron bars quickly saturated in magnetization; to magnetize larger bars took greater current in the coils surrounding them.

Callan superimposed these findings about what enhanced magnetic power onto separately determined findings about what improved shock, in order to design an optimal instrument possessing both assets at once. Under this reasoning, the result

[79] Although Callan did not cite it, his battery with its 20 pairs of large plates that could be connected (in our terms) all series, all parallel, or in combinations, resembles that of Robert Hare, 'A New Theory of Galvanism ... by means of the Calorimotor, a new Galvanic Instrument', *American Journal of Science*, 1 (1818), 412–23.

[80] Nicholas Callan (note 78), 297.

would be a huge iron horseshoe wound with thick copper wire matched to the battery whose current it carried, with a long thin wire extended on to that. Callan speculated that an instrument with this design would have 'very great' magnetism, and its shocking intensity 'must be immense', thus demonstrating:

> . . . the best method of making an electro-magnet for the shock . . . first, to coil on a long and thick horse-shoe bar of iron . . . a very thick copper wire covered with silk or cotton . . . secondly, to coil over this wire . . . a very long thin wire soldered to the thick one . . . [81]

On construction, Callan's 13-foot-long iron horseshoe, weighing 210 pounds with 10,000 feet of long thin wire wound over it, was at a scale unprecedented for such instruments (Figure 12). And his recipe did not quite hold up: he wrote that the thick current-bearing copper wire had to be split into seven shorter segments which were separately connected to the battery. Callan's rationale for this (parallel) wiring expressed a perceptive observation about time. If the thick wire was left undivided, the quantity of current going through it would be insufficient 'in the time necessary for magnetization' of the mass of iron enclosed.[82] Callan's awareness of the crucial role played by time also showed in the repeating switch of great rapidity (3600 times a minute) that he installed in the battery circuit.[83]

This instrument was terrific: a powerful magnet when the current was running, and stunning in its shock at the moment when current stopped. The wily professor used this to trick students: he challenged them to pull a weight off the end of the horseshoe while it was magnetic. They pulled with all their might without budging it—and then he shut the current off and everyone fell back with the weight![84] And, the electricity heightened across its many coiled winds could shock unwary seminarians, decompose water, kill a turkey, and ignite the charcoal tip and mercury pool whenever their separation opened the battery circuit.[85]

That character of instruction accompanied by showmanship was integral to what interested Callan in doing his electrical work, and underlies the scale and style of his developments. For such demonstrations to work, they had to perform unambiguously in a large lecture hall. This pushed Callan to research dramatic effects, and not to study subtle ones. It is also reflected in his systematic structure for improving the instrument by separately testing each component and superimposing the results. By being oriented toward attaining a 'best method', the testing structure did not quite afford other sorts of questions and observations.

Communication of Callan's efforts stirred others to conduct experiments that extended the differentiating paths for current and shock which he and Page had innovated independently.[86] A description of Callan's electromagnet was published

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[81] Callan (note 78), 299.

[82] Callan (note 78), 300. Callan's original horseshoe is preserved at the Museum of St. Patrick's College, Maynooth, Ireland. See Charles Mollan and John Upton, *The Scientific Apparatus of Nicholas Callan and Other Historic Instruments* (Maynooth 1994), no. 068, 62–64.

[83] N. J. Callan, 'A Description of an Electromagnetic Repeater or of a Machine by Which the Connection Between the Voltaic Battery and the Helix of an Electromagnet May Be Broken and Renewed Several Thousand Times in the Space of One Minute', *Annals of Electricity*, 1 (1837), 229–30.

[84] McLaughlin (note 8), 70.

[85] N. J. Callan, 'A Description of the Most Powerful Electro-Magnet Yet Constructed', *Annals of Electricity*, 1 (1837), 376–78.

[86] In asserting his priority, Page (note 14), 15–18 tabulated the publication dates of his papers and Callan's.

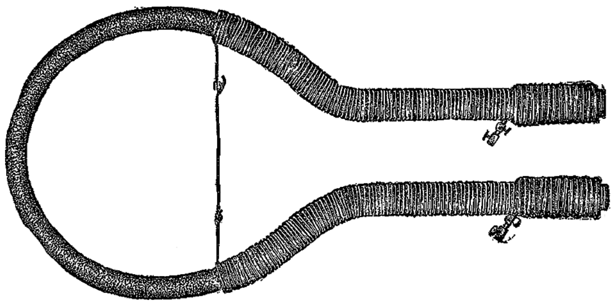

Figure 12. Callan's 13-foot horseshoe electromagnet; the battery connection is made at the posts midway along each leg. From Fleming (note 6).

both in Sturgeon's journal and in the Philadelphia *Journal of the Franklin Institute*, making it known in the US.[87] The circle closed between Callan and Page through the imitative response of another showman, the first electrician in the city of Boston, the venerable Dr William King.

During the 1830s, Dr King ran a shop for electrical instruments and lightning rod installation at 52 Cornhill St., an area where other instrument-makers were located. The *Boston Medical and Surgical Journal* advised medical electricians that King's electrical machines were 'not only exceedingly beautiful, mechanically considered, but quite superior in effect'.[88] A notice of his death in March 1839 described him as 'the distinguished Electrician, and the inventor of improved lightning conductors'[89]; while an inventory of his effects encompassed 'Electrical, Galvanic and Chemical Apparatus ... made in a thorough manner ... of the best quality'.[90] King's showmanship figured in a review of the great Mechanics Fair held in Boston in September 1837, where the 1500 inventions and handcrafts on display attracted 6000 guests per day. King often put his great electrical machines into action on the crowd, provoking the reviewer's quip that the crowd density was so great he might 'without the ceremony of taking hands, discharge his [Leyden jar] battery ... a shocking affair'.[91]

In the months following the Mechanics Fair, Dr King replicated Callan's great horseshoe electromagnet using similar overall dimensions but an even greater mass of iron (244 lbs) to make it count as 'the largest electro-magnet, probably, in the world'.[92] King overwound his horseshoe first with one (evidently undivided) copper wire longer and thinner than Callan's, and next with a wire equal in diameter and length (10,000 feet) to Callan's fine wire. This electromagnet also had a duo function, both as a 'mammoth magnet' and for shocking. In favourably noticing it as 'the most magnificent philosophical instrument ever constructed in America or, perhaps, in any

[87] N. J. Callan, 'A Description of the Most Powerful Electro-Magnet Yet Constructed', *Journal of the Franklin Institute*, 21 (1838), 57–59.

[88] 'Medical Miscellany', *Boston Medical and Surgical Journal* (26 April 1837), 195.

[89] Deaths, *Columbian Centinel*, 16 March 1839. His death was also noted 'In Boston, Dr. William King, electrician, 78' in the *Boston Medical and Surgical Journal* (3 April 1839), 132.

[90] Philosophical Apparatus, *Boston Atlas*, 16 April 1839.

[91] Fair of the Mechanic Association, *Boston Daily Evening Transcript*, 23 September 1837, 1.

[92] Mammoth Magnet, *Boston Daily Evening Transcript*, 20 December 1837.

other country . . . ', the *Boston Medical and Surgical Journal* encouraged some college to acquire it.[93]

Page went to watch it in operation, and noticed something that concerned him. When activated, the great electromagnet hefted a 1500 lb load, but once the current stopped, it still supported a 50 lb weight. The three-quarter-ton lift was impressive, but Page perceived inefficiency in its residual magnetism. 'Struck by this curious fact', he set out to reduce it.[94]

Page engaged with electromagnetic interactions differently than Callan's 'best method' approach. In contrast to testing components in isolation from each other, Page questioned how core material functioned in relation to windings. Like the tests conducted by Faraday, Henry, and Sturgeon to establish the role of iron, Page used a hollow spool, over which several current-bearing wires (used in parallel) coiled concentrically and within which different core materials were inserted. As with the spiral, Page's experiment was more nuanced than a single comparison. He tried not just a solid iron bar, but also a bundle of thick iron wire and one of narrower iron wire. The conventional solid bar remained magnetized when current stopped running in its coil, like King's great horseshoe. By contrast, the bundle of iron wires did not stay magnetized, and its wires would not even attract 'a very delicate needle' (Figure 13).[95] Page next committed to a core of barrel 'hoop iron' strips, and wrapped them within four concentric wire coils. With this new device, both the human response of wonder and the electrical spark were enhanced: 'Nothing can be imagined more intense and beautiful than the sparks produced by this little compound magnet'.[96]

Along with instrumentally linking these magnetic and electrical effects, Page evolved an interrelated outlook on these phenomena. He wrote that the heightened sparking was due to 'secondary current' resulting not only as ceasing battery current demagnetizes the iron strips but also as the like magnetic poles temporarily induced in the strips acted repulsively on each other. This use of 'secondary current' is perplexing under our terms, as there was no non-current-bearing (i.e. secondary) wire on Page's four-wire magnet coil. A later paper clarifies that Page defined secondary current as 'the natural electricity of the wire, set in motion by magnetic forces'.[97] With this analysis, he adapted Sturgeon's intermediary magnetic medium, but dropped or downplayed Sturgeon's electrical momentum. Even if it travelled the same path as the battery current, for Page any non-direct current was 'secondary' and brought about by magnetism either of current or moving magnets.

Page's finding that different core materials affect the electrical effect in surrounding coils connected with my suspicion that unresponsiveness from the metal core contributed to the failure of my 'iron' ring experiment (see section 3).

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93 Mammoth Magnet, *Boston Medical and Surgical Journal* (20 December 1837), 322.

94 Charles Grafton Page, 'New Magnetic Electrical Machine of Great Power . . . ', *American Journal of Science*, 34 (1838), 163–169.

95 Page (note 94), 168. Sturgeon and George Bachhoffner established that bundled iron wires amplify shock, independently of Page and each other (see section 8).

96 Page's compound electromagnet is first described in 'New Magnetic Electrical Machine of great power . . . ', *American Journal of Science*, 34 (1838), 163–69; quote 168. At the end of his reprinting of this paper, Sturgeon added a footnote referencing his prior research of different iron wire cores.

97 Charles G. Page, 'Researches in Magnetic Electricity and new Magnetic Electrical Instruments', *American Journal of Science*, 34 (1838), 364–73, quote p. 367. Here, Page also expanded his ideas about the neutralizing magnetism of iron or steel wires in the core bundle (p. 368).

After hand-winding coils loosely over a metal bar or flexible-walled tube with the intention of interchanging cores, I found the coils' layering tightened so that the cores could not be removed.[98] Thus, I appreciated Page's need for a stiff-walled tube as the base for winding a hollow wire coil. In redoing his core test, I wound a thick current-bearing primary wire (gauge 18) over a stiff tube and wound a long, thin, enamelled secondary wire (gauge 28) directly over it. Into the tube, I separately inserted different cores: air; a solid (steel?) bar; a bundle of thin florist's wire. I broke the thick wire's contact with two D cell batteries by rotating the tips of a copper star in and out of a drop of liquid metal (in analogy to the nineteenth-century mercury interrupters).

Unlike Page and his contemporaries who took electrical shocks routinely, I was advised against taking the shock to detect voltages induced in my test coils when current stopped flowing in them. Where the historical experimenter's body went in the circuit, instead I substituted a high voltage probe connected to a digital storage oscilloscope.[99] By superimposing onto a single plot, signals that were digitally saved while the coil operated with various core materials and wiring arrangements, I prepared a direct comparison among the electrical effects in those cases (Figure 14). Plotted voltages show characteristic shapes and peak magnitudes. When the coil's hollow contains only air, the voltage signals are damped and resonating, a wavy line of declining amplitude. The initial voltage spike is accentuated, and the trailing resonance diminished when metal cores are inserted in the hollow. Peak values produced with the bundled wire core may be several times greater than those induced with the solid bar. Perhaps these characteristic electrical signals bear on the qualitatively distinct sensations that Page reported from different cores.

Page and the historic investigators found that shocks improved when taken across the entire length of a current-bearing coil plus a thin wire winding added to it, and my voltage observations bore this out—particularly with a bundled wire core (Figure 14, middle). To conduct this test, I joined the outer end of my primary to the inner end of the secondary. The voltage probe spanned this combined length to record the signals induced when the circuit broke. The peaks were greater than when the primary was used alone (Figure 14, left). And these voltage patterns were further enhanced when I disconnected the secondary from the primary, and connected the probe only across the secondary (Figure 14, right). In my test, this advantage of the separate secondary was conspicuous only when the iron wire core was used, corroborating the interdependence of core and wiring that was crucial to the instrument's historical development.

Across these studies, from Callan to King to Page (and then to me), the instrument was transforming along with means for testing and observing. The two paths along a single conductor, one for battery current, the other for shock, differentiated further from Page's spiral where each path was distinguished only by its points of connection. Callan's first two-coil electromagnet where each wire was of equal length and thickness gave way to the grand horseshoes where the battery current's conductor was thick, short, and sometimes divided for parallel connection, and the shock path extended beyond it on an increasingly long thin wire. The two paths remained connected at a

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[98] Cavicchi (note 28), Chapter 20. I was familiar with the double-helix coil of Page's associate Boston instrument maker Daniel Davis Jr in the Collection of Historical Scientific Instruments at Harvard (# 0118). Davis worked skilfully enough that the winding itself preserves a hollow, whereas mine did not.

[99] The HP Infinitum oscilloscope was used with a Textronics P6015 high-voltage probe. For more discussion on using electronic test equipment in substituting for historical shocks, and for the star wheel interrupter, see the references in note 43.

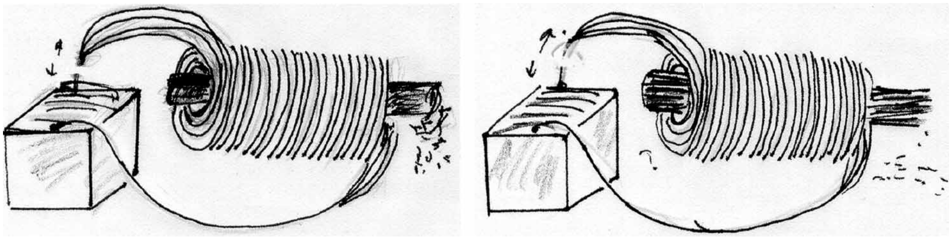

Figure 13. Page's hollow electromagnet, carrying current through four wire coils in parallel. Left: when the hollow contains a solid iron bar, and the battery connection is broken, bits of metal remain attracted to the iron bar. Right: when the hollow contains a bundle of iron wires instead, the bits of metal drop when the battery connection is broken.

point, yet their specialized function is identifiable in the materials: thick short wire for carrying current; long fine wire for the shock. These two features, standard on all future induction coils, were absent from Faraday's two-wire inducing coils of 1831. The intervening experimenting figured in discerning not just the two paths, but also their differing electrical roles and material make-up.

Although seeming superfluously grandiose as a transition between Faraday's modest iron ring and the later induction coils of Ruhmkorff and others, the horseshoe electromagnets of Callan and King were crucial in physically differentiating the two paths. Despite all his experimenting with coils and iron while theorizing about electricity and magnetism, Sturgeon educed no relation between battery current and shocking electricity that showed in an instrumental form. By Callan's targeted goals—to lift great weights and give severe shocks—the wiring branched unmistakably: thick for strong currents to magnetize the iron; long and coiled for elevating the shock. And the grand scale of King's horseshoe was fortuitous in magnifying the otherwise small residual magnetism to the point where Page noticed it and instigated research to diminish it—which concurrently elevated the inductive spark. Iron remained core to the effect, contrary to Sturgeon's claims, yet its change in form from bar to divided wires bespoke a material understanding attainable only through experiment.

All these changes in the instrument are also telling of the transformative and diverse ways of development. Change happens along multiple routes, by multiple strategies. Its transformative qualities—those that convey development—come about interactively, through venturing to try out another instrumental configuration, through doing something that affects the observations. To form and reform understandings of what is going on takes an active effort of coordinating evidences from all the trials, all the views. Callan and Page did this differently; Callan by superimposing the most promising results derived from disparate components, Page by questioning the relationships holding among parts where unresolved issues lingered.

7. Two conjoined wires separate into two wires, two coils

The two paths, one for current, one for shock, were physically distinct but had not yet separated. The solder joint remained, residue of the belief that high-tension electricity would be induced in winds outside the battery current's path only if the total wire was continuous. These two wires eventually separated, yet their transitional

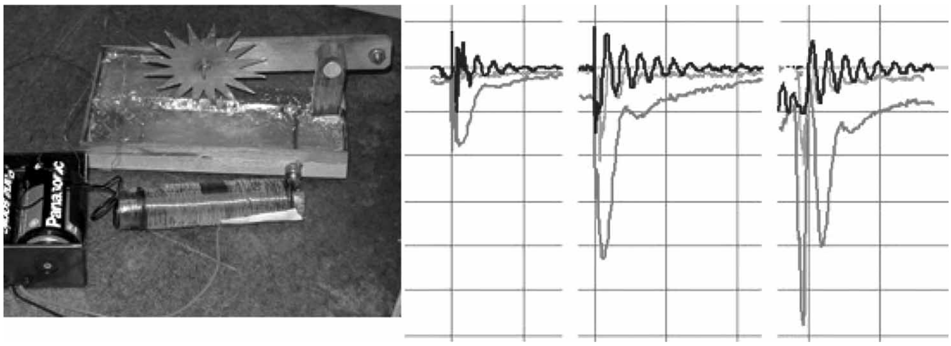

Figure 14. Left: my double coil, star wheel interrupter and battery. Graph: left: superimposed traces of voltage taken across the primary wire when different cores were used (air core in black(blue); solid bar in light grey (lavender); iron wire bundle in grey (orange)). Middle: same superstition plot, where the voltage is taken across a primary joined to a secondary wire. Left: superposition plot where voltage is taken across a detached secondary. Vertical scale: 50 V/division; horizontal scale: 10 s/ division.

connection suggests that material continuity was essential in people's understanding of the induced effects.

Callan reactivated Sturgeon's involvement with two-path conductors by enclosing the gift of a 'powerful horseshoe electromagnet' along with his paper. Not only did Sturgeon print the paper in his journal, but he also demonstrated Callan's (small-scale) horseshoe by treating attendants of the nascent London Electrical Society to its 'forcible shocks'.[100] The presentation magnet exemplifies Baird's contention 'things bear knowledge' that can be communicated through the gift of a thing, even when there is no verbal explanation of its workings to transmit.[101] Callan's electromagnet worked, it shocked people, and bound in its coiled wiring was an experimentally derived know-how that Sturgeon and his associates lacked. Even so, the knowledge expressed in Callan's instrument did not transfer to Sturgeon as a whole; instead, Sturgeon had to rework and rethink it using his own skills and understanding.[102]

Sturgeon soon built an instrument uniquely his own. From Callan, he borrowed the practice of carrying current through a thick 'bell' wire and joining a long thin wire to that for the shock. Taking account of his own prior findings that coils wound along an entire iron rod's length gave weaker shocks than those covering a shorter portion of the bar and having more layers, he rejected Callan's treatment of the

[100] Sturgeon's talk and demonstration occurring on June 24, 1837 was noticed in *Annals of Electricity*, 1 (1837), quote 417, and 'First Annual Report', *Transactions and Proceedings of the London Electrical Society*, 1837–1840. Bachhoffner also credited Callan's gift coil with being an instigator of his own, 'On the Electro-magnetic Machine', *Annals of Electricity,* 2 (1838), 207–13, footnote p. 207.

[101] Baird (note 20) 3–4, quote p. 213.

[102] That Sturgeon could not accept Callan's device without reworking it echoes Keith Pavitt's 1999 observation that 'there are very few technological free lunches. Even borrowers of technology must have their own skills and make their own expenditures', quoted p. 1255 in 'What do we know about innovation', editorial, *Research Policy*, 33 (2004), 1253–58. A related discussion of scientists' differing individual views and shared understandings is found in Kenneth Caneva, *The Form and Function of Scientific Discoveries*. (Washington, DC, 2001).

instrument as an electromagnet. Instead, he constructed a short compact coil, similar to those made to revolve on magneto-electric machines, but with a hollow wood bobbin for comparative testing of core materials. He also adapted from the magneto-electric machine its hand-cranked wheel but applied this rotary action to open and close the circuit rapidly, either by spinning a disc-interrupter (540 times a second), or by a cam action to lift a wire in and out of mercury (36 times a second; Figure 15).

Sturgeon borrowed Callan's practice of using a thick wire for current and a thin extended wire for shock. It took care to solder thick to thin wire and prepare to test the coil, as Sturgeon described:

> One end of the thin wire is now soldered to the last convolution of the thick one, and a strip of silk laid over the last coil. This done, the coiling of the thin wire is performed in precisely the same manner as the thick one . . . The process is exceedingly tedious. When the shock is taken . . . one hand is connected with the outer end of the thin wire, and the other hand with either of the ends of the thick one . . . When the hands are connected with the two ends of the thin wire, the secondary producing the shock runs through that wire only; and the effect is greater than by the other connexions.[103]

Perhaps this finding, that the shock felt greater when taken only across the thin wire, raised the question of whether the two wires need be united, for shock to occur (see Figure 14). Sturgeon's electrical momentum theory had depended on such a physical channel between battery current and shock. When Sturgeon subsequently began experimenting with a coil having truly separate primary and secondary wires, he modified his analysis and dropped the momentum argument: secondary currents were produced by motion of the 'electromagnetic lines' alone.[104]

Sturgeon took this instrument on the road, presenting it to the London Electrical Society and science gatherings in Manchester, Preston, and Liverpool. Medical practitioners grasped its relevance in therapy and requested their own. The shock, first taken by experimenters to detect electricity, became the instrument's designated output. Sturgeon produced medical coils for subscribers ('Letters must be post paid') by outsourcing their construction to local workmen.[105] In an 1849 postscript to a reprint of his 1837 paper on the coil, Sturgeon made the unwarranted claim that his (by context, the soldered wire version?) device had 'attained greater celebrity than any other electro-medical apparatus whatever'.[106]

When I examined one of these medical coils attributed to Sturgeon in the London Science Museum (no. 1860-72; Figure 16), it provoked me to wonder whether the hired workmen understood his plan for its electrical operation. The artefact reflects Sturgeon's design (Figure 15) in: its hand-cranked wheel and cam for raising and

[103] William Sturgeon, 'An experimental investigation of the influence of Electric Currents on Soft Iron . . .', *Annals of Electricity*, 1 (1837), 470–84, quote 478; reprinted in Sturgeon 1850 (note 46) 298–309.

[104] William Sturgeon, 'On the production of secondary electric currents in a metallic spiral, independently of opening and shutting the Battery circuit; or, of giving motion to either the primitive or secondary conducting wires, *Annals of Electricity*, 2 (1838), 109–12; reprinted in Sturgeon 1850 (note 46), 322–24.

[105] Sturgeon (note 103), p. 484.

[106] Sturgeon 1850 (note 46), quote p. 309. His footnote (p. 289) states that he demonstrated this coil to the London Electrical Society on 5 August 1837. See also his retrospective synopsis of this paper, pp. 46–47.

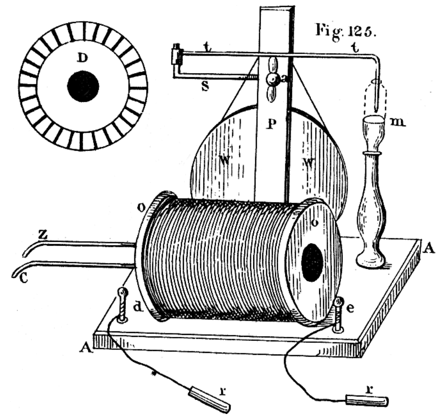

Figure 15. Sturgeon's shocking coil, with a wheel-driven interrupter at mercury cup *m*, and handles for taking the shock at *rr*. From Sturgeon, *Annals*, 1837.

lowering the wire switch into its mercury cup; the hollow wood bobbin housing a compact coil (concealed however under cloth): and the layout of two posts for battery connection and two for shock. However, the underside wiring is unlike Sturgeon's example (Figure 16). The wire from each post for shock is soldered directly to a wire attached to one of the two battery posts. According to this wiring, the shock was taken across the primary's current-bearing winds. While the museum coil may have a concealed secondary wire added to one end of its primary (and contributing to its shock), I found no exposed access to it. The wiring clues of the instrument itself tell a story differing from its reputed origin. Perhaps this artefact shows how more readily appearance and mechanical function could be conveyed to others (such as the artisan-makers) and replicated than electrical behaviour.

Further experimenting with electromagnet coils split the thick wire from the thin wire at its junction. For Callan, this came about in the course of dividing the iron core.[107] Unlike Page and Sturgeon, who divided the iron core longitudinally—exchanging thin bundled wires for the solid bar—Callan divided the bar lengthwise in half. Each half's current-bearing windings were connected in parallel with the battery, while the two thin coils were joined in one long series. Perhaps the practicality of making these different connections pushed Callan toward finally disjoining thick from thin wire.

In direct response to Callan, Sturgeon took this disjunction a step further. He next wound each wire coil on a hollow spool; the thick wire's spool was nested within the wider opening of the thin wire's spool. This construction helped illustrate the phenomena for his lectures: 'By this means it is obvious to every auditor, that the battery current has no communication with the outer coil'.[108]

[107] N. J. Callan, 'On a method of connecting electromagnets so as to combined their electric powers, &c.... ', *Annals of Electricity*, 1 (1837), 491–94.

[108] The quote from Sturgeon is his editorially signed footnote to Callan's paper (note 103), 493. J. A. Fleming misattributed the footnote to Callan (note 6), p. 12. On this misinformed basis, Fleming credited Callan with the invention of the induction coil: 'it is to Callan that we owe this simple piece of apparatus, now found in every physical laboratory ... having two separate wires, one thick and the other thin'.

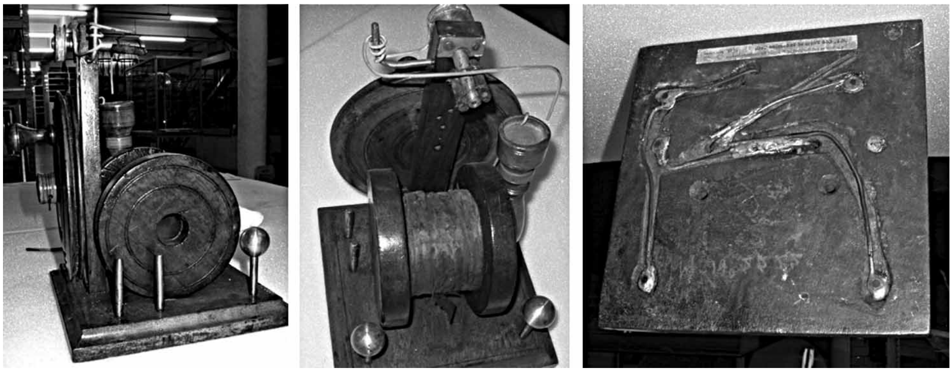

Figure 16. 'Sturgeon' coil in London Science Museum (no. 1860-72). Left: Side view showing crank wheel and the coil's hollow opening. Middle: Top view showing mercury cup, brass knobs for shock (front of base) and battery posts (left). Right: Underside view of wiring (inverted to match middle view). Shock handles connect to two solder blobs at bottom of photo; battery posts connect to two blobs at left of view.

Through evaluating the great Callan/King horseshoes, Page developed a concern about how electromagnetic effects scale with changes in materials and instruments. To research this systematically, he set up sixteen electromagnets, varying in overall size, and in the dimensions and configurations of core wires and conductive windings. On cross-comparing the sixteen, dimensions and scale emerged as critically interlinked. For example, the largest electromagnet failed to give the strongest shocks because it needed thicker current-bearing wires. Balances in scale partook in the wire's electrical function:

> The larger the wire, the more freely it conducts, but large wire cannot be used with advantage on small magnets, as the coils or turns will not be sufficient in number, and the axis of the wire will lie more oblique to the axis of the magnet, than that of a smaller wire, or than upon a larger magnet. [109]

Callan previously observed conductive advantage in thick wire, and disadvantage with oblique windings, but did not interrelate these two features as a trade-off. Only on completing this analysis did Page go on to add a long thin wire over his best four-coil electromagnet, and take shocks across the summed coil:

> Combining the secondary currents of the large and small wire, the shock was so great as to render it difficult to keep even the tips of the fingers upon the wires.[110]

Through having a question that Sturgeon, due to his theory, was prevented from conceiving, Page wondered if the physical joining of thick and thin wires was operative in the high tension effect:

> It appears irrational to suppose for a moment, that the shock obtained by breaking the circuit with coiled conductors, can receive any augmentation from

[109] Page (note 97), 365.
[110] Page (note 97), 365.

> the conjunction of the primitive [direct] and secondary currents, for the presumption is, and the fact itself seems sufficiently obvious, that the sparks and shocks indicating a new and secondary current are directly consequences of the dissolution of the primitive current.[111]

Thin wire separated from thick as Page took his integrative questioning further by constructing the horseshoe electromagnet with rotary keeper of his novel 'Magneto-Electric Multiplier' (Figure 17). Aware that the act of dislodging the keeper from a horseshoe electromagnet gives rise to momentary current in its windings, he devised a hand-cranked cyclic mechanism to do this at the very same moment that the battery broke its connection to the electromagnet's thick wire. These two actions—rotating the keeper off and stopping the battery current—coincided in time and reinforced their electrical effects as exhibited in the separate fine wire:

> The sparks are exceedingly brilliant, and the shocks so powerful that they are sometimes felt by bystanders through the floor.[112]

Since the fine wire's ends were now freed up from the thick wire, Page united them to produce one continuous coiled loop. Then, when battery current stopped and secondary current arose in the loop, its flow was unimpeded. That persisting flow was apparent by affecting the rotating iron keeper, either stopping or propelling it (depending on the initial state): 'Here then the secondary becomes a new source of magnetic power'.[113]

This experimental test illustrates Page's deepening sense that what he called 'secondary currents' are not promoted merely by linearly summing optimal components as Callan had done in producing his great electromagnet. Something about induction is inherently interactive, not merely reducible to the sum of its instrumental parts. Page probed this by connecting two of these Magneto-Electric Multipliers in sequence with the same battery. On applying the keeper to one but not the second, the second dropped its weights. The interlinked systems affected each other by the 'power of this reacting current'. Page's curiosity kept his thinking open to such unexpected complexities that Callan, bent toward amplifying effects, never imagined.

A two-wire double coil, wound over iron wires and activated by a battery and interrupter, was emerging as a distinct instrument. Page's next paper presented it entire as the self-actuated 'Compound Electromagnet and Electrotome for Shocks, Sparks &c.' (Figure 18).[114] Unlike Sturgeon, whose 'workmen' assistants were inexperienced with electromagnetism, Page's technical associate Daniel Davis Jr. was a highly skilled Boston instrument maker and electromagnetic researcher in his own right. Davis offered Page's coils in his trade catalogues, for $8.00 to $12.00, as did other instrument makers who carried Davis apparatus. Soon Davis came out with his own advancement, a $25.00 version, the 'Double Helix and Electrotome' with more extensive windings

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[111] Page (note 97), 366.
[112] Page (note 97), 372.
[113] Page (note 97), 372.
[114] Page's 'Compound Electromagnet and Electrotome' is described in 'Magneto-Electric and Electro-Magnetic Apparatus and Experiments', *American Journal of Science*, 35 (1839), 252–68. One of Davis' productions of it is on display in the National Museum of American History (cat. 309,254) in Washington, DC.

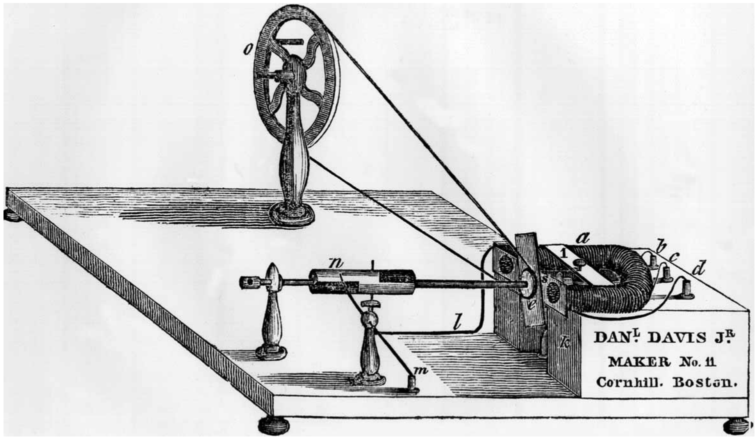

Figure 17. Page's Magneto-Electric Multiplier, made by Daniel Davis Jr. Turning the wheel *o* (by hand) rotates the keeper *e* across the (iron wire) horseshoe's ends and also closes the circuit. From Page (note 97).

and a rapid spring-wound (not self-actuated) clockwork action.[115] As these instruments became commercially accessible for schools and medical uses, they underwent changes in portability, the vibrator, finish, and means of regulating and applying shocks.[116] While the coils succeeding Page and Davis were used in new applications, their role in electrical research diminished, as Page himself later remarked. [117]

An instrumental witness to the transitional period when thick wire conjoined to thin survives in the Allen King Collection of Scientific Instruments at Dartmouth College.[118] This coil resembles that illustrated in Figure 18, yet appears improvisational: its windings are uneven; its core cross-section is irregular; one screw, not two, affixes supports to base; and it lacks the turned posts, connection cups, and feet (Figure 19). The difference in wiring is more substantive than these construction discrepancies. Davis concealed each wire's ends under the wood base; these

[115] Davis' 'Double Helix and Electrotome' was reported by Joseph Hale Abbot in 'A Description of Several New Electromagnetic and Magneto-Electric Instruments and Experiments', *American Journal of Science*, 40 (1841), 104–11. Both instruments are listed in Davis' *Catalogue* for 1842; only the one with a faster clockwork interrupter is discussed in his *Manual of Magnetism* (Boston, 1842), 251–53 and included in the *Catalogue of Apparatus* (Boston, 1848). The patent model, submitted decades later on 14 April 1868 as part of patent no. 76 654, is displayed at the Smithsonian's National Museum of American History, catalogue no. 309 254; accession no. 89 797. For patent history, see Post (note 10).

[116] Double coils based on the Page–David instruments were listed in catalogues by Joseph Wightman, *Catalogue* (Boston, 1842), and Benjamin Pike, *Illustrated Descriptive Catalogue* (New York, 1856). Physician William Channing described and illustrated use of Page-Davis double coils in *Notes on the Medical Application of Electricity* (Boston, 1849). Many Page–Davis instruments are in the Smithsonian National Museum of American History, the Collection of Historical Scientific Instruments at Harvard, and other college museums. A compilation is available at http://www2.kenyon.edu/depts/physics/EarlyApparatus/

[117] Page stated 'very little transpired on the subject of induction coils from 1842 until 1850' in (note 14), 41.

[118] The Dartmouth instrument, accession number 2002.1.35088, was listed in an 1870s Dartmouth inventory as 'Page's apparatus for shocks with mercury break'. This coil, with its possible links to Page and Davis, is described in David Pantalony, Richard L. Kremer and Francis J. Manasek, *Study, Measure, Experiment: Dartmouth's Allen King Collection of Scientific Instruments* (Norwich, VT, 2005), 157–159.

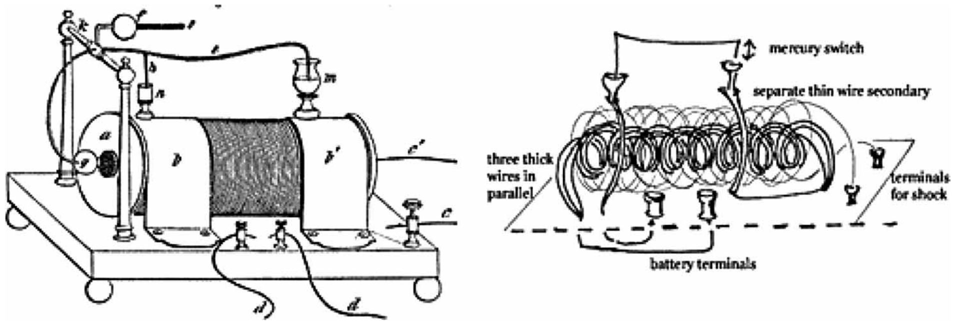

Figure 18. Left: the Compound Electromagnet and Electrotome of Page and Davis, from Page (note 114). Right: diagram showing connections for the separate thick wire primary and thin wire secondary.

were capped by the four topside ornamental binding posts: two for battery connection (*dd*) and two for taking the shock (*cc′*). The Dartmouth coil has just three connection cups: one at each end of the thick wiring (linked to the battery terminals) and the third terminates the thin secondary wire. The shock is to be taken between the third cup and either of the others—thus allowing comparison between including and omitting the thick current-bearing wire.

Even more intriguing is the solder blob on the support to a mercury cup in the coil's rocking contact breaker. This blob unites the ends of five wires. Four of these are thick wires, each coiled in one layer over those previous, and having their similar ends connected so that battery current runs through all four in parallel, analogous to the four wire layers of Page's early 'compound magnet' (see section 6).[119] The fifth wire exiting the junction is thin and commences the two or three layers of secondary winding (Figure 20). The solder blob materially expresses the understanding that the elevated electrical effect required the primary to connect with the secondary. This understanding, grounded in the single long conductor of Page's first spiral, came to be questioned and changed. Is the Dartmouth coil an original prototype from a transitional phase in the experimenting of Page and Davis? Many design features of the artefact support this provocative inference.

The two-part wire's deliberate connection and its eventual disjunction makes an instrumental record of understandings that were in the course of developing. The solder joint stands for the single-wire origins of the two-wire device, and for continuity in how the instrument evolved under diversely conceived experimenting. This junction would never occur if the two-wire solution was projected forward from the start, or if it completely replaced the earlier prototype. It attests to authenticity in the developing process.

The continuity expressed in these developments encompassed many experimental paths, instrumental constructions, and interpretations such as Sturgeon's adoption of Callan's differentiated wiring without the elongated electromagnet shape or Page's acceptance of Sturgeon's magnetic medium without the electrical momentum. The electromagnetic phenomena were complex enough for investigative work of such

[119] Page (note 94), p. 168.

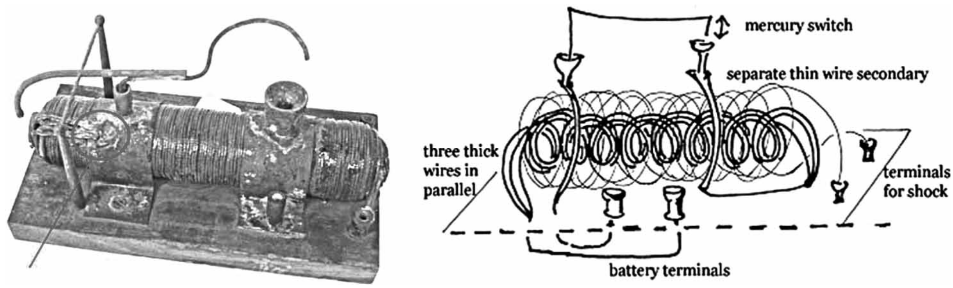

Figure 19. Left: photo of shocking coil number 2002.1.35088 in the Allen King Collection of Scientific Instruments, Dartmouth College. The circle identifies a solder joint on the Dartmouth shocking coil which unites the thick current bearing wiring to one terminus of the thin 'secondary' wiring. Right: diagram showing the coil's solder joint and wiring.

diversity to be productive. At the same time, their interactive nature could not be overlooked; all the productive paths addressed the core and its magnetization, as well as the shock and its long coiled windings. The phenomena being accommodating and distinctive, and the experimental paths being varied yet continuous, brought about developments in instruments and people's understandings that were coherent while always opening to new observations.

8. Experimenting with electro-magnetic coils

In Britain, the two-wire coil evolved under the hands of instrument makers and others who put it to use—people more rooted in popular working culture than in the new practices of electrical research. The sparks, shocks, and motions of electro-magnetism so intrigued people that they flocked to demonstrations in London and other locales. Addressing Sturgeon through his journal, Nesbit, a mechanic in Manchester, depicted this upswell of interest:

> Your lectures in our Institution have induced many of our members to engage in the study of Electro-magnetism; and they have stirred up a spirit of enquiry and a desire for philosophical knowledge, which cannot fail to be attended with beneficial effects.[120]

This loose and growing community of shared electromagnetic curiosity instigated the next period in the instrument's history. Within 'little more than a twelvemonth', numerous participants had personal experience with the double coil's properties and problems.[121]

The pages of Sturgeon's journal document some experiences of this novice experimenting. Reacting to Callan's one-wire electromagnet by coiling wire on a small horseshoe (Figure 21), a mechanic in Gosport (near Portsmouth) observed something

[120] J. C. Nesbit, 'On Electro-magnetic Coil Machines', *Annals of Electricity,* 2 (1838), 203–205, quote 203.

[121] George Bachhoffner, 'On the Electro-magnetic Machine', *Annals of Electricity*, 1 (1837), 207–213, quote p. 207

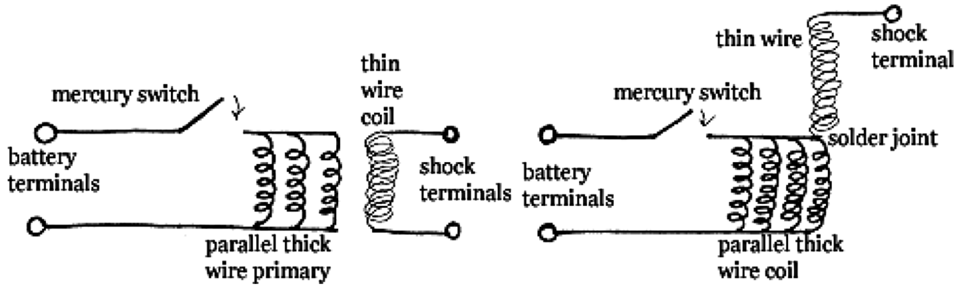

Figure 20. Left: wiring diagram of the Page coil illustrated in Figure 18. Right: wiring diagram of the Dartmouth coil illustrated in Figure 19. With the Dartmouth coil, the shock is taken across the entire length of the thin wire added to four parallel coils of thick wire at the solder joint.

anomalous: 'I do not find the shock so strong when the communication is made and broken too quickly'.[122] Months later, Sturgeon happened upon this defect while running his coil with joined thick and thin wires.[123] Contrasting that with magneto-electric machines that work even when cranked rapidly, a member of Sturgeon's lecture audience (Nesbit) suspected that a switch without liquid mercury would do better. Nesbit's metal-on-metal breaker operated so terrifically that six people joining hands with its thin wire to take the shock, could not let go, 'despite their utmost endeavours to do so' (Figure 21).[124] A Leicester mechanic had similar results on adapting Nesbit's breaker to his modest coil.[125] In an editorial, Sturgeon pushed Nesbit back to the original question: was shock severity lessened when his breaker turned fastest? Responding for the next issue, Nesbit admitted this problem remained. Sturgeon revived his electric fluid theory in accounting for the loss:

> ... the magnetic exciter of the iron has to be *called into existence* every time the primitive circuit is completed. This process requires time ... probably when the opening and closing of the battery circuit is performed with great rapidity, the electric fluid ... has not sufficient time to operate on the magnetism of the iron ...[126]

Although this discussion about the breaker's maximally effective rate lapsed unresolved, the contact breaker remained under active investigation (see below).

George Bachhoffner, chemistry lecturer at the newly established Polytechnic Institution,[127] was proactive in experimenting with the coil and outreach to others.[128] Curious about the coil and its potential, he left its scientific explanation to others, 'I

[122] Charles Barker, 'To the Editor of the Annals of Electricity, Magnetism & Chemistry, *Annals of Electricity,* 1 (1837), 157–159.
[123] Sturgeon (note 103), 480.
[124] Nesbit (note 120), 204.
[125] Uriah Clarke, 'On the Electro-magnetic Coil Machines. In a Letter to the Editor', *Annals of Electricity*, 3 (1838), 12–13.
[126] W. Sturgeon, 'Answer to Mr. Nesbit's Letter', *Annals of Electricity,* 2 (1838), 205–206.
[127] Morus (note 5), 81–82.
[128] An unsigned footnote to Bachhoffner's paper claimed the presentation of a coil at the London Electrical Society meeting 'on August 5, 1837 ... was, I believe, the first of the kind exhibited in public ... '; Bachhoffner, (note 121), footnote p. 207. Was this footnote written by Sturgeon? See note 106.

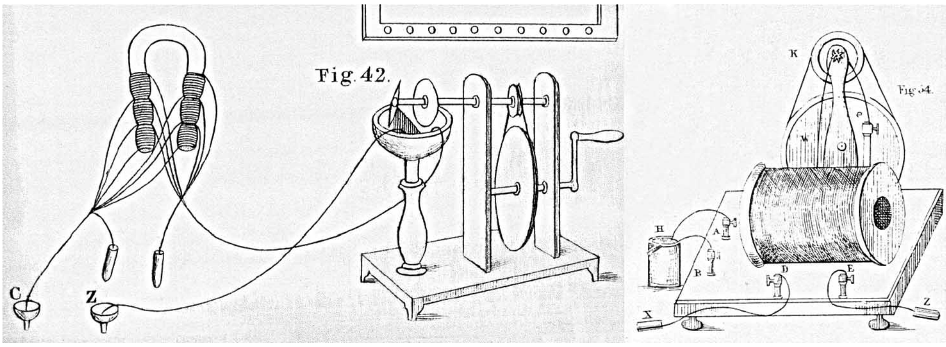

Figure 21. Left: Barker's horseshoe coil where the shock is taken across a primary wound over a horseshoe core and a cranked wheel breaks the circuit. Right: Nesbit's coil with its cranked metal-on metal breaker, and shock handles. From Sturgeon, *Annals*, 1837.

am quite content to rest in the situation of a silent spectator . . . '[129], and advocated wide public involvement:

> At the present time, these machines are in the hands of but few experimentalists: when, however, they become better known, there is every reason to hope for very important results.[130]

Acting on this idea, he brought out a pamphlet 'designed chiefly for the use of amateurs', describing how to make and use electromagnetic apparatus and experiments.[131]

Bachhoffner started by acquiring an early Sturgeon coil, whose thick and thin wires were joined, and refitting its accessories (Figure 22, left). His replacement of the iron rod core by a bundle of insulated iron wires constituted the first British use of a divided core and led to a twenty-fold increase in shock. Bachhoffner warned grasping the handles 'with hands moistened is out of the question . . . from the excruciating agony which they communicate'. [132] Then, going on to build his own coils with separate thick and thin wires (up to 2000 feet long), Bachhoffner was the first in print to emphasize that these wires be kept apart from each other 'by appropriate insulation . . . in no case do I permit the primary and secondary to be in metallic contact with each other'.[133]

The value of insulation in the core was unmistakable yet perplexing. The instrument worked best as an electromagnet—lifting greater weights—with a solid core, yet delivered greatest shock when insulated iron wires served as its

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129 Bachhoffner (note 121), 207–208.
130 Bachhoffner (note 121), 213.
131 Bachhoffner (note 69).
132 George Bachhoffner, 'A Letter to W. Sturgeon, Esq.', *Annals of Electricity*, 1 (1837), 496–97; quote 497. Bachhoffner's estimate of a twenty-fold increase in power due to the insulated iron wire core is noted in *Annals of Electricity*, 2 (1838), 73 and Bachhoffner, 'A Description of the Different Arrangements of the Electro-magnetic Coil, and the Influence of a Spiral Conductor in Increasing the Power of a Voltaic Current', presented 28 October 1837', *Proceedings of the London Electrical Society* (1840), 132–33.
133 Bachhoffner (note 121), 212.

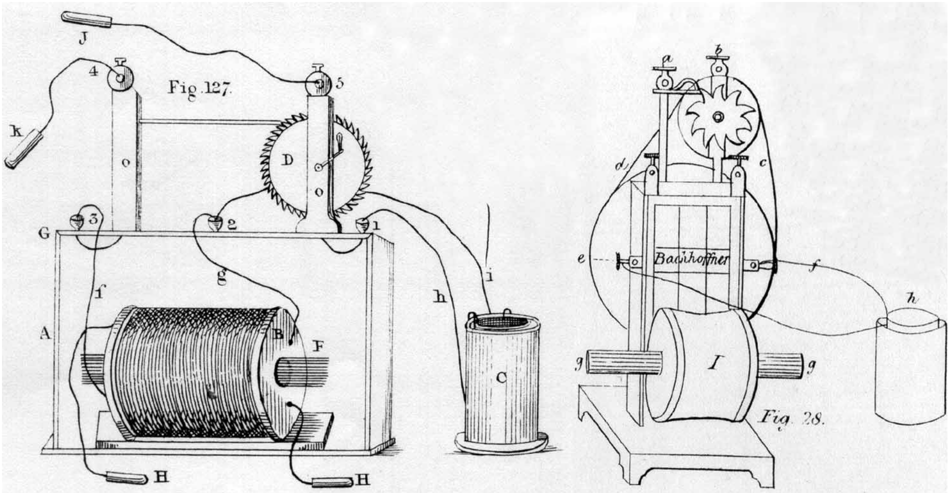

Figure 22. Left: Bachhoffner's revision of Sturgeon's coil, using bundled wire core and rachet wheel breaker. From Bachhoffner (note 121). Right: Bachhoffner's own design with divided iron core *gg*, secondary separate from primary, and metal wheel breaker. From Bachhoffner (note 69).

core: 'a fact not easily understood'.[134] The electromagnet and the new 'electromagnetic machine' were diverging as instruments. It took something different to promote the effect of one, than that of the other. This emerging realization of distinction between the two instruments had not been apparent to Callan—and yet it depended on Callan's contributions of seriously evaluating electromagnet behaviours.

While improvements to the instrument's wiring and core still met with confounding vagaries of electromagnetism, improvements to the contact breaker, being mechanical, were more readily accomplished and demonstrated. The most appealing breakers used the electrical surge, evoked on breaking contact in the thick wire circuit, to combust metals and display their characteristic spectral colours in the spark. Vivid emerald sparks attended the break-away of a conductive star-wheel tipped with silver leaf as Page turned it through a mercury pool to stop and start the current in his spiral (Figure 23).[135] Several colours sparking in succession under the turning of Sturgeon's contact breaker disc studded with different metals gave an indescribable light:

> No language can convey a proper idea of the beauty of an experiment with this apparatus, when attached to a good coil and battery. It must be seen to be understood.[136]

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[134] Bachhoffner (note 121), 213.
[135] Page (note 41), 140. For a replication, see Cavicchi, 'Sparks, Shocks and Voltage Traces . . . ' (note 43).
[136] William Sturgeon, 'Description of Three Different Instruments for Opening and Shutting the Battery Circuit of an Electro-magnetic Coil Machine', *Annals of Electricity*, 3 (1838), 31–35, quote 35.

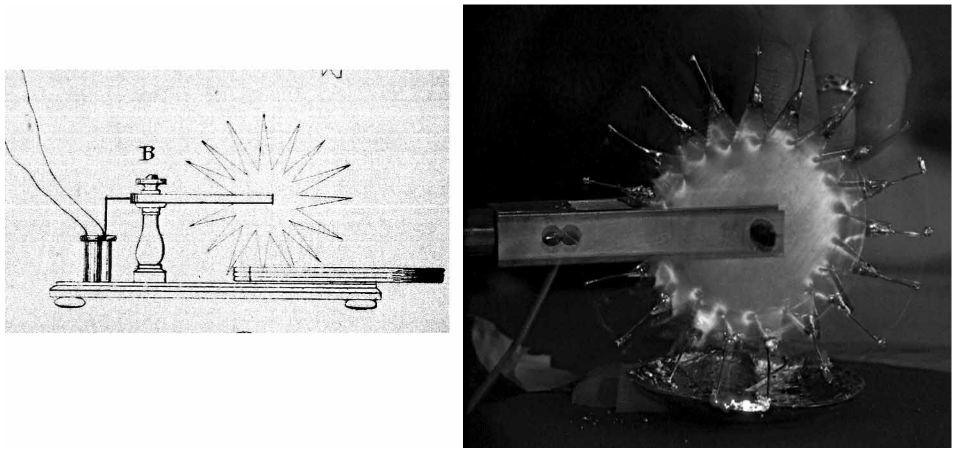

Figure 23. Left: star wheel contact breaker developed by Page, here illustrated by E. M. Clarke in *Annals*, 1837. Right: my replication of Page's star wheel sparks with the colour of the combusting metals. Photo by Jeff Tinsley.

Chemistry teacher to London artists,[137] Bachhoffner expressed glinting colour by abrading metals at the contact break: green for silver, blue-green for copper, purple for lead, and blue for zinc (Figure 22, right).[138] The eight-pointed interchangeable stars of various metals sparked on striking a spring in the hand-cranked operation of Bachhoffner's production coil, originally made by Edward Palmer for 4£ 4s.[139] Six of these stars remain with a Palmer coil of Bachhoffner's design in London's Science Museum (1900-124; Figure 24). The multiplying wheel easily turns a star's points one by one against a conductive spring, and although no battery is attached, the wiring is functional with primary and secondary coils intact and distinct as registered by my ohmmeter readings. In a variant of this breaker, built by London instrument maker E. M. Clarke, spinning metal blades contacted a serrated (interchangeable) outer metal ring to give the impression of circling sparks.[140]

As beautifully as they shone, these coloured sparks also signify that the electromagnetic coil was still short of its potential. These sparks generated on the double coil's primary circuit were not yet successors to the tiny spark Faraday glimpsed at the *B* coil of his iron ring in 1831. The sparks that crackled across sizeable air gaps terminating the ends of great secondary coils and rivalled the discharges of friction electrical machines lay in the future. More remained to learn and experience with wires, iron, other materials, and the electromagnetic phenomena.

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137 Bachhoffner called himself 'a chemist and not an artist' *Chemistry as Applied to the Fine Arts* (London, 1837), 167.

138 Bachhoffner (note 121), 210–11.

139 Edward Palmer, 'Catalogue of Electro-magnetic and Voltaic Apparatus' (London 1838), bound with Bachhoffner (note 69). Palmer, an ironmonger's guild member, had a shop from 1838–1845 at 103 Newgate St. London; Clifton (note 7), 207.

140 An example of E. M. Clarke's 'Lockey coil' with interchangeable blades and discs, is in the Moosnick Medical and Science Museum at Transylvania University, Lexington, Kentucky.

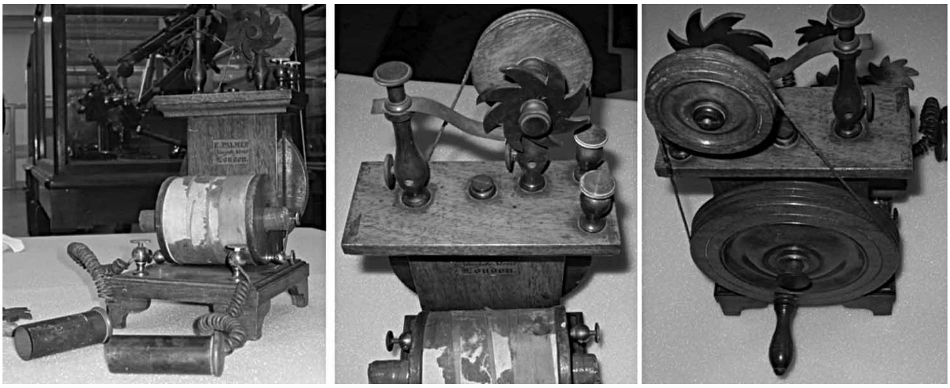

Figure 24. Side, top, and rear view of a Bachhoffner induction coil made in 1837 by E. Palmer, London, number 1900-124 in the London Science Museum.

In the experimental process under way, the coiled conductor was already becoming increasingly a distinct instrument, although still going by various names: 'compound electromagnet' or 'double helix' in Boston; 'electromagnetic coil' in Britain. Both Page's spiral and Callan's great electromagnet carried, in their structure, a record of each one's unique path of enquiry—even to the soldered junction between thick and thin wire. As the instrument became more accessible to others, those unique records were omitted, and the instrument converged around a shared form: the compact double coil with its wire core. Through building and reworking it for themselves, people made the instrument, along with its bodily and visual effects, into something held in common.

That more common access, putting the instrument within reach of anyone who could work metal in their hands, opened a florescence in its development just as Bachhoffner had imagined. Across the succeeding decades, hundreds of amateurs made, tested, and used their own double coils; some became adept at rendering the electrical effects by unique instrumental means, while others struggled to coax out feeble shocks or sparks from their homemade devices. This later widening in participation suggests that by being actively engaged with complex electromagnetic effects, development of electromagnetic apparatus and understandings did not stop, even if some seemed to have finalized their efforts.

9. Seeing developments in instrumental work

Seeing developments in instruments and the experiences brought about with them involves letting byways, confusions and seeming backtracks emerge in what was made, tried, and thought. No easy metaphor maps out the coil's experimental course; linear progression, 'trial and error', and even such thread-like images as network, weaving, and tangle are inadequate and can be misleading.[141] Rather

[141] F. Lawrence Holmes considered the pathway, its limitations, and alternative metaphors for representing an individual scientist's experimental work in *Investigative Pathways: Patterns and Stages in the Careers of Experimental Scientists* (New Haven 2004).

than paths or maps, perhaps a complex landscape renders a more descriptive analogy, where at each place it is helpful to look closely into one's surroundings; give credence to the limits, entry ways, and resources there; and correlate this distinctive and partly obscured panorama with those of other places. By this depiction, we see more in what occurred experimentally by taking each instrumental innovation seriously—with its material constraints, preceding observations, concurrent aspirations, and ideas—and by coordinating that partial story with the evidences from other innovations.

These differing and related terrains are illustrated in experimenters' responses to actual coils or descriptions given to them by others. In these responses, they adapted some of these materials, yet did not accept features that were not coherent or did not serve the recipient's purpose, interest, or understanding. No literal transmissions occurred; there was always a transformation. In remaking Henry's spiral, Page not only expanded its length but also added access to its interior, so that new kinds of observation became possible. Both Peabody's report about a spiral in the US and Callan's gift electromagnet stirred Sturgeon into constructing coils that reflected his ongoing thinking. However, in the process of examining and demonstrating Callan's actual coil, Sturgeon was challenged to notice details and try things out in ways that resulted in a new and distinctly different instrument. Perhaps for Bachhoffner (who overhauled Sturgeon's and was not committed to any explanation), the move to split the soldered wire came most readily, with least ambivalence. For Page, this split was observantly considered, as was his reaction to the King/Callan horseshoe by extensively testing small electromagnets coiled with thick wires before going on to append a thin wire. For me, taking up my own experimenting and realizing where my materials and ideas limited or assisted it, helped me recognize the differing responses of historical investigators along with their underlying experimental concerns. To see the responsive and creative developments of others, I had to engage with coils deeply enough to become confused and let uncertainties arise.

Developments sustained both continuity and diversity. The lengthening conductor kept that continuity materially intact—as expressed in the solder joint between wires whose union was no longer efficacious for the electrical effect. Similarly, the iron core remained a consistent feature of the changing instrument. Those continuities were ongoing, accompanied by a diversity sprouting from exploring or questioning that was neither broadening randomly, nor funnelling into constriction. The wire became both thick and thin in response to understanding that both high currents and numerous coiled winds elevated the shock. The iron changed, too, becoming gigantic under reasoning that mass mattered, and then dividing into fine wires as a means of more quickly extinguishing its temporary magnetization. Each of these instrumental wirings embodied a built—and always partial—understanding of how the new electromagnetic effects were being experienced investigatively.

Development was both episodic and integrative across the span and depth of people's experiences.[142] For example, during spurts of configuring coils of various

[142] See Holmes (note 141) for related observations on episodic and ongoing features of investigation in scientific careers.

dimensions with and without iron, Sturgeon inferred unseen relations among magnetic lines, their motions and currents, which guided and illuminated his subsequent work in both productive and limiting ways. Page coordinated observations from test electromagnets and brought them into direct relation with each other through such composite instruments as the 'Magneto-Electric Multiplier'. Understandings evolved through noticing specific outcomes as well as ways in which multiple outcomes can be coordinated.

The interactive nature of electromagnetic phenomena—that figured in instrumentally exhibited actions of heightened electricity and magnetization—also deepened the human reactions by which people stayed involved with their work. Sparks, shocks, magnetic pull, or other physical behaviours gave the feedback on trial circuits that was crucial for developing 'working knowledge' and experimental innovation. People's sense of beauty, delight, and the evocation of amazing, awesome, and unexpected effects sustained their curiosity and kept them wanting to try something more, even if this meant tedious wire winding or experimenting until 'eleven o'clock at night', as Sturgeon did.[143] Personal awareness of wonder had as much to do with the meandering of paths or panoramas in the landscape of development, as did differing instrumental and interpretive experiences.

Instrumental developments, only superficially shown by setting Bachhoffner's coil beside Faraday's ring, happen through experiences that are not so readily charted and, while partly confusing, inarticulate, or doubling back, characteristically leave open something to wonder or to try. Learning to see where those openings are, and nurture the trust and persistence needed to explore them, is the task set not only to these historical experimenters, but also to each of us in learning from things of the world and extending those experiences to others through teaching.

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[143] Sturgeon (note 46), 75.

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