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The spiral conductor of Charles Grafton Page: Reconstructing experiences with the body, more options, and ambiguity

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Abstract. Following discoveries of self-induction made by Faraday (1834) and Henry (1832/1835), Harvard medical student Charles Grafton Page took bodily shocks in 1836 from his homemade spiralled conductor while interrupting its battery connection. Unlike his famous predecessors, Page inserted connectors intermediate along the conductor which increased experimental options: shocks could be taken across any interval. Surprisingly, Page felt shocks everywhere, even where no direct battery current passed. Acupuncture needles amplified his sensitivity. Bodily contact across greater spiral spans yielded greater shocks. Having no interpretation for these effects, Page researched productively, later developing the instrument and its interpretations in a community. I reconstructed Page’s experiment with a spiralled copper foil, an oscilloscope as detector, resistor substitute for the body, flashlight batteries and switch. Across intervals where Page reported increased shock, I encountered variable signals. My methods evolved to include activating the spiral with periodic signals or my spur wheel switch, and picturing data by alternative views. These techniques functioned like Page’s connectors to open up options for further testing. Page and I experienced ambiguity in the experimental effects and in interpreting what happened. In both the original experiment and its reconstruction, productive means of working with ambiguity – not dispelling it—emerged through exploratory generation of new options for experimenting and thought.

Introduction

People in the past noticed surprising and intriguing effects in nature, often helped by apparatus that they made or improvised. We can become extended observers in what they encountered by repeating some of their undertakings. Doing this has the potential for us to put ourselves, our bodies, materials, experience, and understandings into relation with those of others at another time and place. What those relations can be, and what we will learn, sense, come to wonder and consider, we cannot infer beforehand. For our research to engage with that potential depends on a widely observant and open curiosity from us. While we have experiences, analyses, tools and background that have arisen subsequent to the historical work, we enhance our overall openness by holding these extra-historical resources provisionally – as much available for us to question, try, doubt and reinterpret as the historical materials.

In this study of a nineteenth-century electrical experiment, exploratory qualities of the original investigation arose within the reconstruction, as present-day materials, improvisations and observations met up in analogue and response to past artefacts and accounts. The exploratory responses of my project also occurring in the historical case involved widening the options for configuring and testing the experimental apparatus while working in the midst of ambiguity about its behaviour. This resonance in exploratory qualities came about not by following the original protocol step-by-step, but in the course of many iterations of: my trying out of something in the lab; the experiment not happening as I expected; my revisiting of the historical work together with my own efforts, continued through further experimenting.

I first encountered Charles Grafton Page’s experiment with a spiral conductor (1837a) as part of my dissertation project (1999, Chapter 20) of constructing an induction coil along with reading nineteenth-century accounts and examining original artifacts. Page’s device intrigued me as transitional, through which electricity was detected in paths that were not identical with where direct battery current went. Whereas the eventual induction coils have two separate wires, one for direct battery current, the other for induced current, in Page’s spiral there is only one conductor (Figure 1). Battery current and induced

current occupy overlapping – and at the same time distinct – portions of the spiral’s one continuous path. In his brief four-page report about this experiment, Page described behaviors that surprised him. He probed these further, amplifying those effects while providing no explanation.

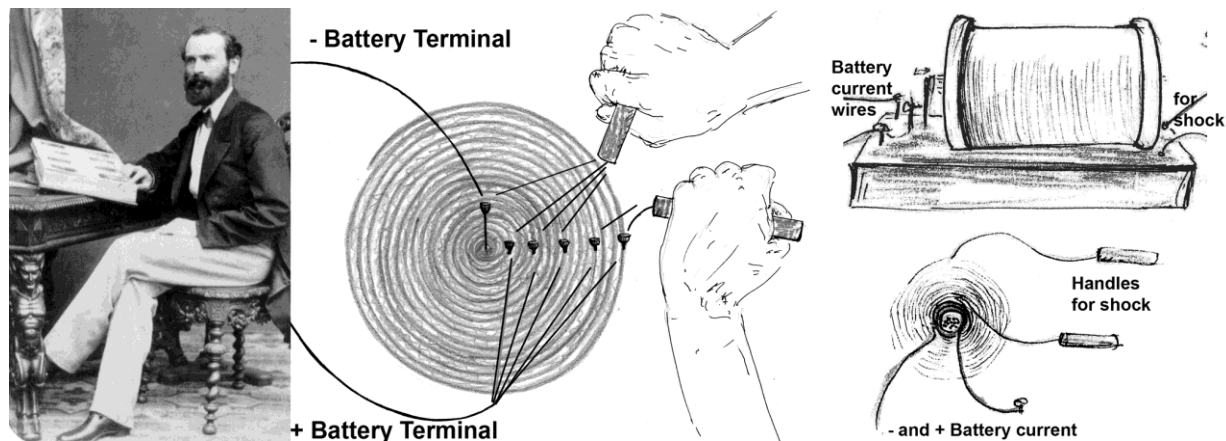


Figure 1. Left: Charles Grafton Page. Robert C. Post collection. Middle: Top-view diagram of Page’s spiral where one conductor serves for both battery current (which can be applied across any pair of connectors) and for human shock (which can be taken across any pair of connectors). Right: Side view and cross-section view of induction coil having two separate wire conductors; one for battery current, the other for shock.

When, after making my own induction coil, I began this project in response to what Page described doing with a single conductor spiral, I wondered how the spiral’s enigmatic electrical effects became a prelude to the seemingly different two-wire instrument. I started by trying to observe Page’s findings as voltages induced in a spiraled foil. With my hand-wound induction coils, I routinely used a storage oscilloscope to check for breakdowns and study the high voltage signals. Thus it was a natural extension of my lab practice and study to apply this test equipment in exploring signals induced in the spiraled foil. However, in contrast to the repeatable voltage spikes output by my wire coils, the signals of my foils are variable and inconsistent. Being caught up by that ambiguity, I improvised an experiment, responding both to my observations and Page’s report.

My experimental iterations always uncover more for me to notice, rethink, and go on to try. Confusion and ambiguity emerged so recurrently as to be repeatable across my extended efforts. I gradually realized that this *experience* offered matter to work with and research within wider contexts of experimenting, history and learning.

Exploring science and history through reconstructions and teaching

My own curiosity for our lived experience with experimenting, history and learning precedes my investigations of electromagnetic instruments. In college, I studied physics and made sculptures; in continuing further with science and visual art concurrently, I experienced alternations between active and reflective pursuits as a mutually supportive exchange. History, science, and our engagement with evidences, stories and materials became an ever-revising pattern of research and play while I was the researcher for the public science TV series *The Ring of Truth with Philip Morrison* and book (Morrison, 1987). Interweaving across the six films are historical figures, such as Galileo, Cassini, Andrew Ellicott and Cecilia Payne-Gaposchkin, with reconstructions of physics experiments such as the Franck-Hertz experiment, accompanied by science and educational demonstrations, such as a jelly doughnut bonfire in illustration of a Tour de France athlete’s daily caloric input.

While working at the insides and intersections among these stories and materials of both historical and everyday sources, one passage connected with my personal artistry: Galileo’s sepia watercolour sketches of the moon as newly observed through his telescope. Scholars then asserted that Galileo could not have produced these sketches while at his telescope; they regarded the act of producing graduated wash tones and bare white areas surrounded by colour as a studio technique incompatible

with observing (Gingerich 1975: 87-88; Whitaker 1978: 156). As my response, I looked at the moon through a small refractor with paint brush in hand, sketching it in ink and watercolours, night after night across several years. My watercolour renderings included: dark circles bordered in white rings within black washes; arcs and rays of darker tone overlaid on lighter tones; intense pigment bleeding into dilute regions; small white dots standing out against black (Figure 2). Painting with ink and colour fluidly extended my observing, both by the act of watching and recording changes of light and shadow and by sharing the excitement of Galileo's discoveries (1991). In subsequent reassessment, on looking more closely at how five of Galileo's seven lunar sketches are arranged on one side of a watercolour paper, the scholars reconstructed how the sheet was turned for each next sketch. Evidences from the page, of its composition sequence, enabled them to retrace how the "sheet makes sense as an original record" of direct telescopic observing (Gingerich & Van Helden 2003: 256).

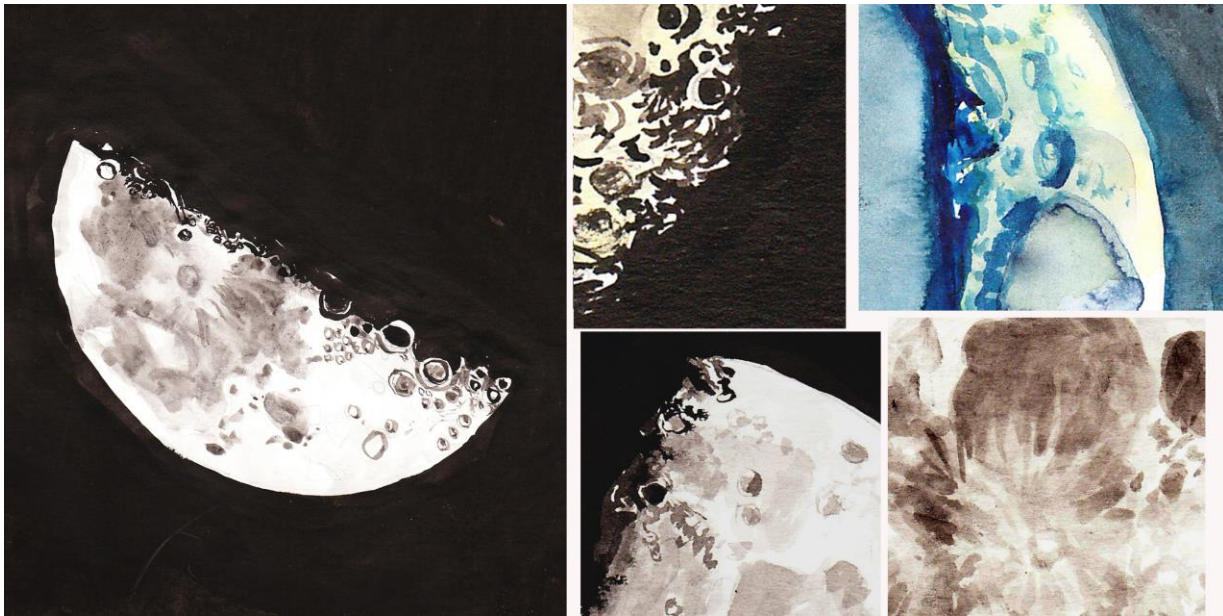


Figure 2. My sketches of the moon, as viewed through a small telescope, painted in watercolour and India ink. Left: 15 October 1988. Middle: Details showing ring craters and points of light in black; Top 9 September 1989; Bottom 20 August 1988. Right: Details showing bleeding of color and layers of tones in lunar rays; Top 25 October 1987; Bottom 27 September 1988.

Later, as a physics teacher, my sense that lecturing did not elicit physical understanding for my students moved me to seek more lively, interacting and inquisitive participation by students with phenomena. My initial attempts at teaching by having students experiment without being told what outcomes to find, evoked such creativity in their science that I went on to create explorative experiences and research the educational developments occurring within them. In sessions where I brought a few students together with evocative materials, I began learning to practice the pedagogy of 'critical exploration' that Eleanor Duckworth (1987, 1991, 2005) developed for the classroom from the historical work of Jean Piaget (1926) Inhelder (Inhelder, Sinclair & Bovet, 1974) and the Elementary Science Series (1970). In uncovering properties of magnets (1997), batteries and bulbs (1999), light and shadow (Cavicchi, Hughes-McDonnell and Lucht, 2001), or water (2005a), these learners became: invested in their own inquiries; observant and surprised by what happened; generative of new experiments; and reflective on what and how they learned (Figure 3, left). Not only were these developments unlike conventional instructional paths in the corresponding contents, but confusion and uncertainty – usually treated as something to overcome in a classroom – recurrently emerged as instigators of learners' new productive work. As the teacher following and seeking to extend exploration, I wondered if history might offer analogies and provocative insights for what we were doing. As with the explorative teaching and learning, that the students and I had to develop interactively, the history that I sought would not be written down somewhere already. To learn the evolving experiences of historical investigators responding to physical phenomena which were also unknown for them, I would have to investigate their work, in turn.



Figure 3. Left: My photos of my students participating in critical explorations with conductive wire (top left); batteries and bulbs (bottom left); a homemade fountain (top next); looking at water (top middle); looking underwater (bottom middle). Right: My hand-wound, two section induction coil (top); Detail of its contact breaker (bottom) (Coil photos by Joe Peidle).

The investigative method that I undertake with history is iterative, reconstructive, and reflective, as noted above. With my watercolours of the telescopically observed moon, personal artistry became a means to re-express and re-open historical experience. Similarly, with my studies of nineteenth-century electromagnetism (1997, 1999, 2003, 2005b, 2006a, 2008b) a personal experience – being a teacher of explorative science – brings about awarenesses, questions, and possibilities that open the reconstructive experience and its historical heritage (Figure 3, right). Reconstructing past experiments, like teaching, involves looking into another’s experience and our own, following the sense being formed on its own grounds, and partaking in the confusions or ambiguities along with their genuine productivity for continuing on.

The theme of ambiguity – a touchstone for me as a teacher – recurs in other historians’ studies of experimenting where science understandings were in flux. Friedrich Steinle (1997, 2002; Ribe & Steinle 2002) documented explorative creativity on the part of both Michael Faraday and André-Marie Ampère in their initial responses to Hans Christian Oersted’s 1820 announcement about conducting wires’ magnetism. David Gooding (1990, pp. 46-7, 118) discerned that subsequent to this initial exploratory phase, Ampère abandoned his openness and focused on bolstering his theoretical commitments. By contrast, Faraday persisted in puzzling over what he did *not* understand: the magnetism’s circularity.¹ By staying with that physical ambiguity – exploring it further – Faraday brought about experiences foundational to his invention of the first motor, a device that uses electromagnetism’s circular action to revolve a conductor around a fixed magnet. An example from early twentieth-century biology researched by Evelyn Fox Keller (2002, pp. 123-147) illustrates a mode of development inverse to Faraday’s, where ambiguity in the means of thought supported the investigators in recognizing and tolerating ambiguity in what they observed. The amorphous term ‘gene action’ gave biologists a way to talk about hereditary transmission and work with evidence of it before they had access to explanatory mechanisms, such as DNA. By sustaining generative relationships with ambiguity, Faraday and the biologists extended their experimental process without settling on a premature result having definite but artificially constrained design.

Reconstructing Page’s experiment gave me firsthand experience with this kind of physical ambiguity, and with working through my own resources and limitations in conceiving new options for tests and

¹See also Cavicchi, 1997; 2006b for related discussions of Faraday’s exploratory work.

pursuing these experimentally. I face variability, ambiguity, and confusion that holds my interest during more than 90 lab sessions over six years. The challenges of my reconstruction put me into a role, like Page, of dealing with confusion, although he and I might describe our confusion differently and approach it with differing tools and expertise. One such area, where he depended on an expertise and tradition which is now long out of practice, is that of taking bodily shocks and comparing their strength to evaluate an electrical device.

Background practices of putting the body into the circuit

Human bodies were integral components of the eighteenth-century circuits that first manifested many properties of electricity and its conduction. In April 1730, British pensioner Stephen Gray (1731-1732, pp. 39-42) suspended an eight-year old boy from the ceiling on clothesline, so the child rested either prone down or up. When Gray placed a glass rod, electrified by rubbing, near the boy's feet, a brass leaf indicator, set up near his head, deflected attractively toward the face. Subsequent technology amplified the electrical effect. Hand-cranked friction machines rubbed glass against leather at high rotation rates; the Leyden jar stored this electricity for later uses (Figure 4, left). The body's responsiveness to the electrification and shocks delivered by these devices provided entertainment in public science lectures, and cheap medical therapy accessible to the poor (Rowbottom and C. Susskind 1984; Bertucci 2001, 2006; Hochadel 2001).

Body parts were components in the trial assemblies of dissimilar metals and moist substances by which late eighteenth-century Italian investigators produced electricity by non-frictional means. While everything touched in a circle of contact, these body parts reacted unmistakably, exhibiting a newfound electricity. To Luigi Galvani, the frog leg's twitch indicated an electricity originating in life processes. Convinced otherwise, Alessandro Volta substituted a sensitive instrument for the frog and still detected electricity. But Volta soon realized that this instrument's internal materials produced some of the electricity it detected. By stacking metals and liquids in analogy to the electric fish's anatomy, Volta eventually constructed a chemical battery whose enhanced potency he demonstrated by using only himself to close its circle (Pancaldi 2003, p. 183; Figure 4, right). The body was back in Volta's circuit, but he viewed its function as only to manifest shock, not to generate it.

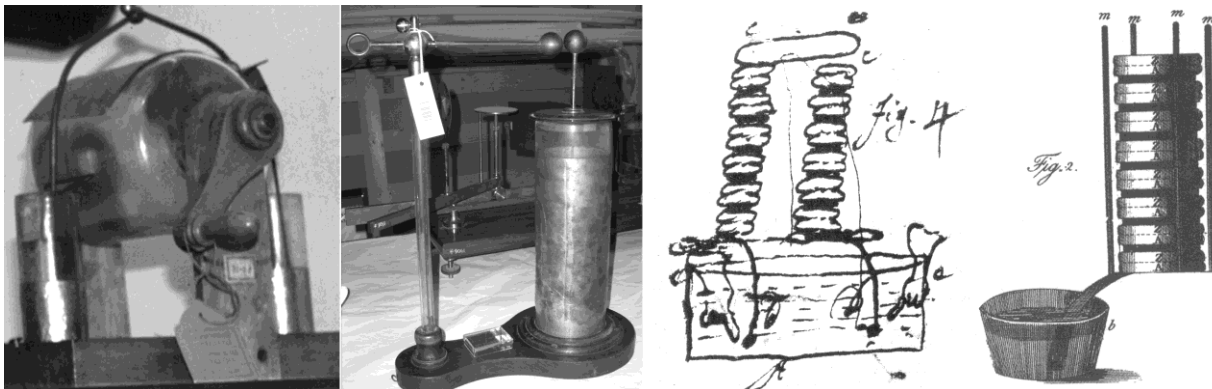


Figure 4. Left: Hand-cranked friction machine made from a glass bottle; Next: Leyden jar and discharger at the Norsk Teknisk Museum. Middle: Volta's sketch showing how his hands made contact with his alternating pile of silver (a), zinc (Z) and moist cardboard (Volta, 1918, vol. 1, pl. XXII). Left: Volta's published diagram where the pile links to a saltwater basin where he placed one hand, while putting the other on the top of the pile (Volta, 1800).

As voltaic sources of electricity became available around 1800, some physicians substituted these for friction electrical machines in electrical therapies (Rowbottom and C. Susskind 1984; Bresadola 2001). In doing so, they had to adapt to the distinction between the high tension (voltage) and low quantity (current) of the friction machines, and the higher quantity at low tension of voltaic sources. The body's resistance to voltaic electricity introduced a barrier that was not present before. Just to get electricity past the skin's high resistance, practitioners imposed wounds into their patients' bodies to receive electrodes. Avoiding this need to wound, British surgeon Charles Wilkinson (1804, v. 2, p. 444) introduced the technique of placing broad metal discs (attached to electrodes) in close contact with

moist skin. At the same time, care had to be taken to regulate and limit the voltaic battery's currents within a safe range.

The electric circuit intruded further into patients' bodies through the "electropuncture" technique innovated by French physicians who reintroduced the Chinese method of acupuncture to Western medical practice around 1820.² Demonstrating that the needles affect an electrometer, these physicians inferred that acupuncture's effect involves electricity. To augment it, they attached a voltaic battery's electrodes to a pair of needles inserted in a patient's body, bringing on 'more pungent pain' (Morand 1825, p. 36). Members of the American medical community took interest in 'the growing importance of the remedy' (Morand, 1825, p. 3) as it was introduced by Benjamin Franklin's great-grandson, physician Franklin Bache in his translation of a French volume on acupuncture. Not long after Page's experiment, a Kentucky physician delivered a presentation acquainting his colleagues with French techniques for applying galvanism through acupuncture needles (Peters, 1836 (ASP, 2010. p. 18)). Entering this community as a Harvard medical student who was authoring the dissertation 'On the Ear' (Anon., 1836), Page attended to these new therapies and extended them.

The body's reaction to voltaic electricity interested experimenters as well as physicians. Their own bodies, not a patient's, provided a convenient detector of electricity. Sometimes this detection was inadvertent – and a harbinger of new electrical behaviour. In 1834, British amateur Mr. William Jenkins got shocked upon disconnecting a battery from a coiled helix whose ends he grasped in either hand. He had not expected this; experimenters working with direct current from one or two cells ordinarily felt no shock. Jenkins told Michael Faraday.³ Faraday's ensuing investigation set off the network of experimenting which Page furthered with his spiral. Faraday elaborated that the body's reception of Jenkins' shock depended on good contact between the body and the electrical conductors:

On holding the two copper handles tightly in the hands, previously moistened with brine, and then alternately making and breaking the contact of the ends of the helix with the electro-motor [battery], there was a considerable electric shock felt... (1834, p. 351)

When Page put his body into the circuit of a spiralled conductor, he applied these experimental and medical practices in new ways. Like Faraday and Jenkins, Page took the shock hand-to-hand directly through his body's core. In some configurations of his test circuit, Page scarcely felt the shocks, so he amplified his sensitivity by piercing his fingertips with acupuncture needles available from a Boston medical supply shop (White, 1828).⁴ Without either the therapeutic intent or the direct battery current which characterized medical 'electropuncture' techniques, Page's use of these needles as assists in detecting electricity was innovative. No other detector than his body would as compellingly report the marginally observable electricity induced in parts of the spiral remote from the battery current's direct path.

While Page used his body as a detector in research, he regarded the shocks he took as having potential in electrical therapy. Active in the local medical community as a teacher, student,⁵ he sent a one-paragraph notice about his research on 'Medical Application of Galvanism' to the *Boston Medical and Surgical Journal* (1836a). While disclosing no details about his apparatus, Page promoted its suitability for a French electropuncture technique where needles burned flesh between them, or transmitted medicines.⁶ In doing so, he demonstrated conversancy in novel treatments that were outside

²The introduction of "electropuncture" is attributed to Jules Cloquet, Jean Baptist Sarlandière and Fabré-Palapat in 1825 by Gwei-Djen and Needham (2002, pp., 295-302) and by Rowbottom and Susskind (1984). Boston physician William Channing(1849) credited it to M Berlioz.

³A recent physics textbook adapts the story of Jenkins and Faraday in its introduction to self-induction and associated exercises (Saslow, 2002, p. 533-544).

⁴*Boston Medical and Surgical Journal* is the predecessor of *New England Journal of Medicine*. All historical articles cited from *Boston Medical and Surgical Journal* and *American Journal of Science* are now available in the Proquest digital resource American Periodical Series (2010).

⁵Praise of Page's electromagnetic inventions and teaching of a chemistry course in chemistry appeared in the *Boston Medical and Surgical Journal* (April 26, 1837), 195 and (November 22, 1837), 256. Page published notices in that journal (1836a, 1836b).

⁶Page referred to 'M Palabrat's discovery ...transmission of remedial substances...' (1836a). Fabré Palapat described his electropuncture technique in La Beaume, 1828, pp. 36-61. Channing summarized it, 1849, 38-9.

conventional medical instruction (Eve, 1836). Page's experience with shocks applied in treatments is evidenced by his remark that shocks from his device were 'quite unlike and less disagreeable than' those of a conventional galvanic source (Page, 1836a). A medical journal based in Atlanta, Georgia published a frustrated inquiry about Page's device, offering a fifty-dollar premium. Although the Boston journal republished the southern medical society's query (Page 1836c), Page never responded in print.

Bodies and circuits combined in fluid relation throughout the investigations by which voltaic electricity was originally observed and explored. The participants' understanding of that relation shifted: from Galvani's assumption that the frogs' bodies produced the electricity, to Volta's exploitation of bodily shock to demonstrate his inanimate pile, to the French physicians' inference that acupuncture needles tapped into bodily electricity. With voltaic electricity's expanding use, experimenters like Faraday routinely took shocks to check their circuit and healers applied it in therapies. As Page drew on both these experimental and therapeutic practices, he participated in a larger trend toward directly involving the body in its medical treatment that Michel Foucault has identified (1963). While eighteenth-century doctors diagnosed without touching patients, anatomist Xavier Bichat broke from this tradition by establishing diagnosis criteria that related pathologies inside patients' bodies to a disease's usual progression, as charted through autopsies. Devices like Page's spiral intervened further by sending electricity into the body (Page, 1836c, p. 183).

Page's experiment

Page's parents' home in Salem, Massachusetts housed his spiral conductor experiment, as it had his many electrical adventures from childhood on (Figure 5, left). At nine, he climbed onto its roof, three stories up, to catch lightning with a shovel during a storm. The next year, he converted his mother's lamp glass into an electrical friction machine (like that in Figure 4, left). Page augmented these electrostatic pursuits by applying his chemistry studies at Harvard (class of 1832) in constructing voltaic batteries, organizing a college chemistry club, and giving public science lectures in Salem. Page's parents' home hosted his brief medical practice where in 1836-7 his longtime mentor witnessed Page's 'miniature magnetic engine' speeding laps on a scaled-down railway track! (Lane, 1869, p. 2-3) This miniature train was a forerunner of the electromagnetic locomotive which Page constructed in 1851, being predated only by the Scottish inventor Robert Davidson. Running off huge zinc-platinum cells and funded by a Senate allocation, Page's full-sized train limped back to Washington DC from its truncated test run (Figure 5, right). It won him great notoriety then, but little notice by historians (Post 1972, 1976a).

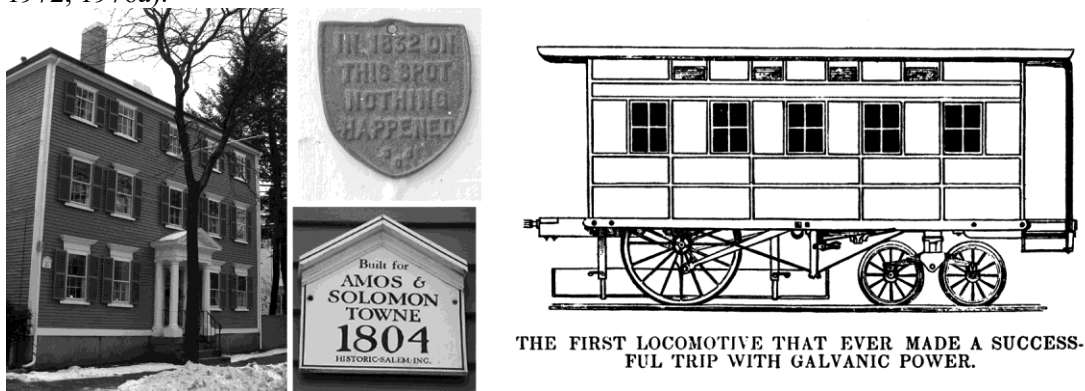


Figure 5. Left: The Page home in Salem MA today, with its historical plaques. Right: Page's electromagnetic locomotive (Greenough, 1854, p. 257).

Just as my spiral reconstruction was a response to Page's terse report, Page's original experiment was in itself an effort to replicate one that he read about in a short notice by Princeton professor Joseph Henry (Bache, 1835; Henry, 1835).⁷ In turn, Henry's experiment was done in a haste incited by Michael

⁷Henry presented his work with the spiral on February 6, 1835, but his full paper was not published until 1837. To secure credit for Henry (Faraday was publishing related work at the time), Alexander Bache composed an

Faraday's latest work (1834, 1835) that opened into an area where Henry had a prior observation (1832). Adding yet further to the chain, Faraday was researching the strong shock that, as described above, he first learned about from Jenkins.

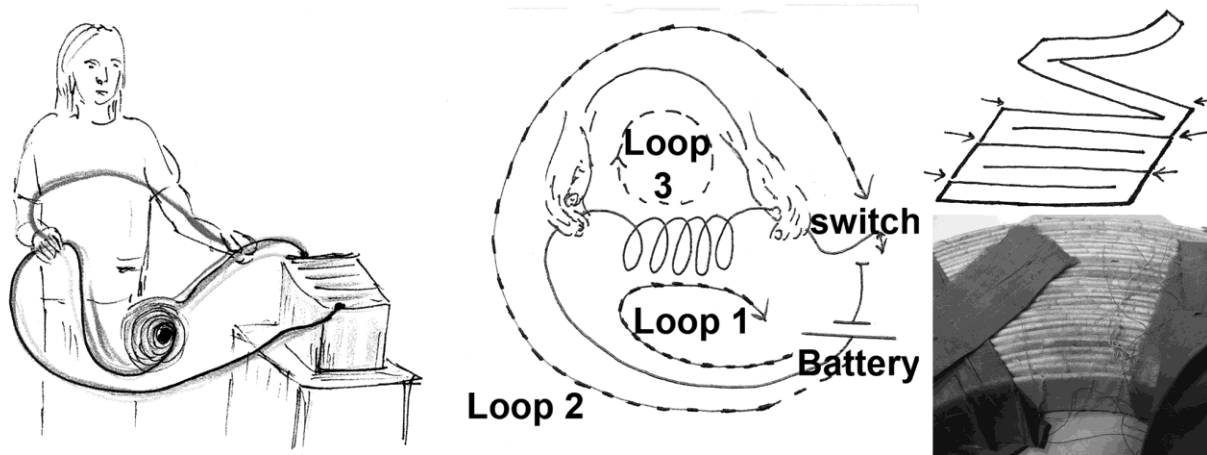


Figure 6. Left: A person holding both ends of a coil feels shock when the coil breaks its connection to the battery. Middle: current traverses Loop 1, from the trough battery, through the spiral or coil, and back. The person adds a second Loop 2, running from battery and then through their body. When the switch opens, the shock takes Loop 3, running between the person and the coil. Right Top: My diagram of the Page's method of slitting a copper sheet from opposite sides (arrows) so that it would open as a zig-zag strip. Right Bottom: Fabric wrapping around the copper ribbon of a spiral used by Joseph Henry. Catalogue number 181,540, National Museum of American History.

The circuits constructed by Faraday and Henry were composed of loops. In Faraday's circuits, one loop consisted of a wire helix connected across the plates of a voltaic cell; a second loop circled from that cell, through his body by way of his hands (Figure 6, left, middle). When a break in battery connection stopped current in these loops, electricity arose in a third loop whose circle joined the helix with the body (Faraday, 1834). Henry's circuits were similar. In place of Faraday's helix he substituted conductors having other configurations, obtaining the most intense electrical effects with a spiralled copper ribbon (Bache, 1835; Henry, 1835, 1837).

Both Faraday and Henry gauged the effect's intensity by two means. One was the brightness of a spark that appeared where the battery was disconnecting from the circuit. The other was the severity of shock felt only during battery disconnection, and while both hands spanned the long conductor. Whenever battery current was maintained steadily, no perceptible current passed through the body's high resistance and the experimenters felt nothing. Thus Faraday distinguished the felt electricity when the battery stopped from that of the unfelt direct battery output.

In Faraday's view, the shocks were due to an electricity brought about, or *induced*, by the stopping of battery current. This induced electricity had an intensity (voltage) heightened above that of the battery current. Faraday realized it related to his seminal 1831 finding that a changing current induces currents in nearby separate conductors. Yet something new and different was going on: the changing current acts on *itself* and induces another current in that *same* wire which exhibits *differing* electrical properties. Page had read only Henry's notice and not Faraday's. Tantalized by Henry's claim that the maximum shock of a spiral was "not yet determined" (Henry, 1835, p. 328), Page constructed a spiral more than twice the length of Henry's. Having no continuous copper ribbon, he cut flat copper sheets in zig-zag strips, soldered these lengthwise together, and wound up the length with fabric (Figure 6, right). He assembled this apparatus by hand and covered it in a box.

abstract by Henry, which was immediately published in *Journal of the Franklin Institute* (March 1835), and in *American Journal of Science* (July 1835) with the addition of a brief appendix by Henry (1835).

The homemade construction of Page's spiral belied an experimental flexibility more sophisticated than Professor Henry's. Instead of sensing shock only while battery current went through the entire conductor as Henry and Faraday had, Page set up connector cups at six positions along the length of the spiral (Figure 7). Each cup contained mercury; on dipping a bare wire into a cup, a good electrical connection was quickly formed that could be easily undone just by its removal. With these cups, spaced at different distances apart, Page could direct current through part of the conductor, and take shocks across that same part -- or any other part. But there was more. The cups made the spiral into a research tool whose options he recognized and explored over time.

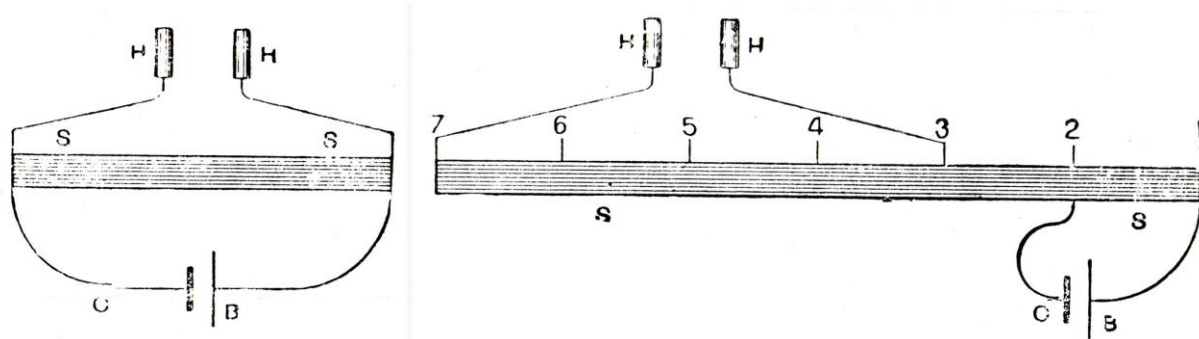


Figure 7. Left: Henry's spiral unwound; the shock is taken across the handles *HH*, while the battery is applied across the same span. Right: Page's spiral unwound; the shock may be taken across parts of the spiral that may differ from the segment carrying the battery current. (Fleming, 1892, vol. 2, p. 6, Figs. 1 and 2.)

Extending Henry's finding that a longer conductor gave greater effect, Page lengthened the conductive path successively within his one spiral, instead of making separate, longer ones. He did this by putting one battery wire into the central cup 1, and the other wire into cup 2, and then observing the spark when either wire was removed from its cup (Figure 8, right)). Leaving the first wire in cup 1, he then placed the other in cups 3, 4, and so on, observing the spark produced upon each wire's removal (Cavicchi, 2008b; Figure 1, middle). These sparks were brightest and loudest when the break was made from cup 3, and declined as the battery current was sent through more of the spiral. Page suggested that if mercury cups were soldered to every spire, the exact location of the turnaround in spark brightness could be determined.

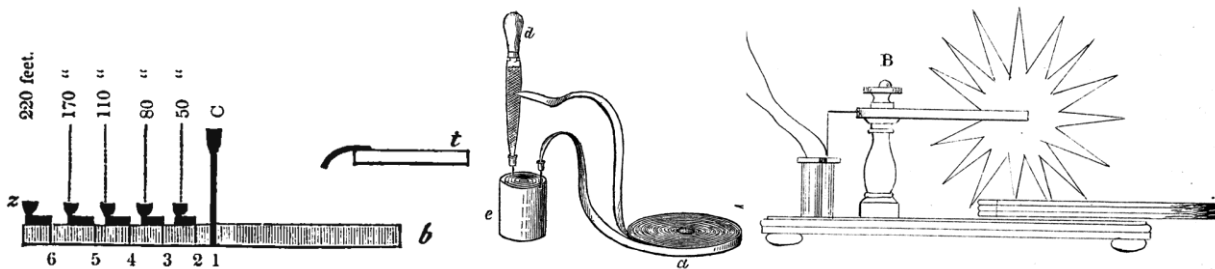


Figure 8. Left: Side view of Page's spiral showing numbered connector cups spaced across its length (Page, 1837a, p. 137). The handgrip is below letter *t*. Middle: The rasp interrupter, invented by Page, in an illustration from Henry (1839, fig. 1, p. 304). Right: The spur wheel interrupter, introduced by Page; illustration (Clarke, 1837).

Shock intensity worked different from sparks. While an assistant operated the battery connections across the same successively widening span, Page took the shock by way of handgrips running to the same pairs of mercury cups. The longer the span traversed by both battery current and bodily connection -- up to the whole length -- the greater the shock. Layering water over mercury in the cup amplified these shocks, puzzling Page: 'the rationale I am unable to give' (Page, 1837, p. 139).

Page then perceived other options for configuring the experiment. The battery and the body could be inserted across *different* intervals of the spiral. Page's tests of these options yielded results that he found 'curious...difficult to explain' (Page, 1837, p. 139).

First, he kept the battery's connectors placed across the spiral's inner turns (cups 1 and 2). One hand grip remained always at the inner cup (cup 1); the other was placed at each of the other cups in turn. The loop defined by the battery connections remained fixed; the loop passing through his body traversed more of the spiral. When his assistant broke that battery connection, Page reported a greater shock than if his hands spanned just the cups that took the battery current. This shock increased in severity as his hands encompassed more of the spiral. The instrument delivered its greatest shock of all when the battery current traversed about half the winds (1 and 4), and his hands spanned the entire spiral (1 and 6; Cavicchi 2008b). That the shock was not as strong, when the current went through the entire spiral, suggested that turns extending beyond the current's path were electrically operative, by some means which Page termed 'lateral cooperation' (Page, 1837, p. 139).

Page expanded the experimental options to put battery and body across non-coincident spiral intervals, and met with astonishment. "Contrary to expectation", on disrupting battery current from traversing the inner turns (cups 1 and 3), he felt a weak shock while his hands spanned *only* the outer ones (5 and 6). Page amplified his sensitivity by piercing acupuncture needles into his thumb and finger. Now the shock felt "extremely painful" (Page, 1837, p. 139). The needles also enabled Page to greatly reduce the scale of the battery activating the spiral, from a large 'calorimotor' such as Henry had used – a cell with large plates that put out high currents at low tension -- to a 'single pair of plates of only four inches' (on a side) (Page, 1837, p. 141).

Something was happening even where direct current had not passed, which could be sensed throughout the spiral. Page realized that this sensual detection distinguished whatever it was that he felt, from the battery's direct – and insensible – current. Page checked that this was so, by putting his body *in series* with the battery's direct path. In this case, nothing could be felt, even when he again heightened his sensitivity by inserting 'fine needles deep into the thumb and fore finger' (Page, 1837, p. 140). By contrast, the sudden stopping of battery current within the spiral gave rise to a momentary electricity of high enough intensity in that same conductor, to overcome skin resistance and shock a human body in parallel with it. Spiralling the copper magnified this, and the body functioned as an acute detector.

Spark and shock occurred only on breaking battery connections. Realizing the technical import of this finding, Page innovated switches that operated repetitively. The first contact breakers were Page's steel rasp that when scraped by another conductor emitted sparks accompanied by intolerable shocks (Figure 8, middle) – and a spurred wheel that rotated its conducting tines in and out of mercury (Figure 8, right).⁸ Sparks shone where each tine exited mercury, making beautiful stroboscopic effects in the dark (page 1837b).⁹ Page made this wheeled switch self-actuated by positioning a magnet so its gap was crosswise to the conducting tine, thereby rotating the wheel as a motor.

The spiral, as accessorized by its spaced cups, acupuncture needles, single-cell source and switches, provided electricity across a graduated range of outputs. More forthrightly than in his preliminary notice to the medical journal, in presenting the spiral to the scientific community Page ascribed its suitability for "medical galvanism" to this instrumentally manipulatable feature: 'shocks of all grades can be obtained' (Page, 1837, p. 141).¹⁰ Yet while Page identified a therapeutic value for the electricity newly accessed by the spiral, he did not go on to pioneer therapies in this new area of medical galvanism. It was the interaction between electricity and his instruments that held his curiosity for further research.

Starting with a circuit which was the forefront research of Faraday and Henry, Page took it further. His tools -- cups, needles, rasp and wheel breakers – opened up possibilities. His body functioned as

⁸Page's spur wheel was an adaptation of Barlow's wheel (Barlow, 1822).

⁹ Also in 1836, Charles Tomlinson (1837) produced similar effect with a sparking motor. In 1831, Faraday used a slotted spinning wheel to explore optical deceptions associated with the persistence of vision which rendered Page's wheel apparently stationary (Tweney, 1992).

¹⁰Page did not specify the dimensions of his initial 'calorimotor'. Page followed Henry's preliminary notice, which was vaguely worded in recommending 'one of Dr. Hare's Calorimotors' (Henry, 1835, p. 329). Henry later stated that he employed one pair of large plates having 1.5 square feet of zinc surface area (Henry, 1837, p. 224).

conductor, detector, and potential beneficiary, yet throughout, *he* was the agent of change. What Page learned and felt kept the experiment going. As his means of detection made evident electricity where no one expected it to be, he flexibly reconfigured and extended his instrumentation. In observing behaviours that violated ‘received theories of electromotion’, Page put forward no explanation, yet followed those behaviours productively, amplifying the effects and widening contexts of detection (Page, 1837, p. 139).

In the lab with spiraled tape and its confusing signals

Where a science experiment or technology is redone as part of a historical study, there are many possible expressions for the relationship between the historical work and materials, and those of the researcher. While some studies emphasize close following, reproduction or reuse of original artifacts and accounts (Withuhn 1981; Heering 1994; Weber and Frercks 2005), others incorporate practices and instruments of disparate contexts, historical and otherwise (Finn 1966; Settle 1996; Tweney 2006; Chang 2007, 2008). Similarly, the role of the researcher ranges from studies which highlight experimental results while sidelining human involvement (Mills 2002, Usselman et al. 2005), to others where the historians’ actions, interactions, and personal reflections are a source for the interpretations brought to light by the experimental project (Gooding 1989; Tarver 1995; Tweney 2005; Heering 2008). Because my study’s concern was to understand the experience and process of an exploratory experiment, my starting point was my personal involvement in observing phenomena, including responding by a variety of means, including with instruments that were not available for the original investigation. Rather than replicating an instrument or a particular experimental path from (necessarily) incomplete historical resources, I look to understand the range of possibilities that can emerge within the experiment. For example, using modern test equipment to observe similar phenomena is a way of uncovering complexities that were not mentioned historically, yet invisibly influenced what was historically observed. By freshly entering the historical inquiry along any path, experiences and improvisations undertaken along the way become means for expressing and opening understandings, where actions and phenomena of experimenting in the past interrelate with our current experimenting (Settle 1996; Heering 2008; Cavicchi 2008a).

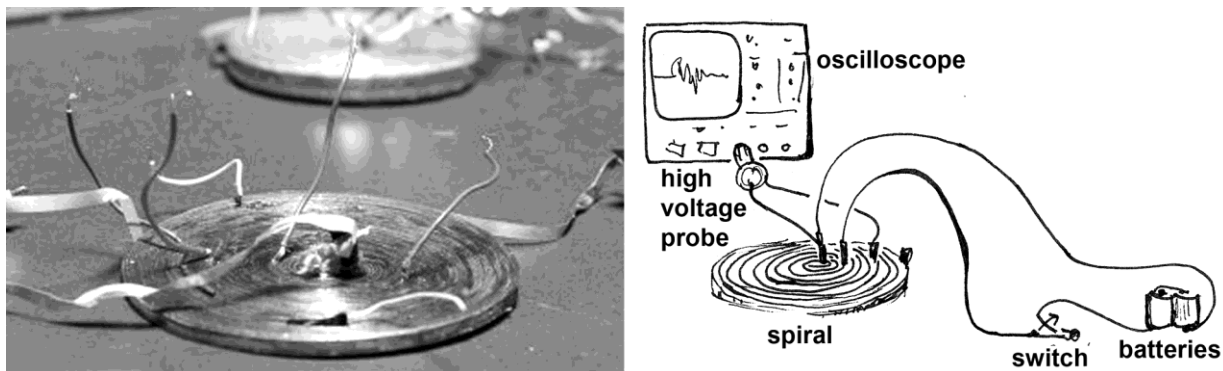


Figure 9. Left: my copper tape spiral; Photograph by Omari Stephens. Right: Diagram of my circuit with battery applied across part of the spiral, and oscilloscope probes connected across a wider span.

The path by which I entered a relation with Page’s spiral passed through materials readily at hand in the electronics student lab where I developed this project and in crafts that I pursue as an artist. For the spiralled conductor, I repurposed copper foil tape from stained glass art (Figure 9, left). The conductive foil spirals outward in an unbroken path, while its paper backing insulates successive turns from direct contact. At first, I used this foil just as it came on a spool; later I rewound foil off spools, into tight spirals winding out from a center (2005). At intervals along these spirals, I inserted copper strips to function like Page’s cup supports; on revising the spiral, I soldered these strips onto the spiral foil. I joined batteries and other apparatus to these strips using alligator clip leads, in place of wire dipped in mercury cups. Having discerned from my previous reconstruction projects that *D* cell batteries suffice for demonstrating many nineteenth-century electromagnetic effects (1999, 2003), I used two of these, or a 3 V power supply, as a source. Initially, I broke the circuit with a mechanical leaf switch that I had found to act consistently during my prior experimenting; eventually I tested and constructed a range of switching mechanisms.

Being smaller in scale and less robust than Page's copper sheet spiralled in fabric, the foil spirals of my improvisations would not stand up to the amperes of direct current that Page's 'calorimotor' may have delivered – nor would such high currents be necessary to induce electricity in my foil's tight windings. Those high currents were among many features of Page's practice that are now understood to pose health and safety risks. Others include: battery acids and unvented fumes; contact with mercury and its vapours; taking unknown electric shocks bodily; piercing the skin without sterile needles and medical cause (Butterfield 1975). For each of these hazards, I substituted safer means through modern technology. Where Page relied on liquid mercury for making and breaking electrical contacts, I employed a range of techniques including alligator clipleads, mechanical switches, a frequency generator, and my own analogue to Page's spur wheel where the liquid metal alloy galinstan substituted for mercury. In place of taking bodily shocks, I viewed voltage traces on a storage oscilloscope, having a high voltage probe to protect the instrument from the high voltages (Figure 9, left).¹¹ While the shocks afforded by my instrument would be much reduced in scale from those Page took, they were present nonetheless, as I experienced when handling it carelessly with wet hands.

While the spiral's behaviours surprised Page, initially I did not expect to be surprised. I had the outcome of his experiment before me, along with the subsequent interpretation of its phenomena of 'self-induction', where a disruption of current in a coil brings about a transitory voltage in that same coil. I supposed that by following Page's practice of testing different parts of the spiral, I would recognize distinctive features in the corresponding oscilloscope signals. Where Page had applied battery current across a pair of cups, such as 1 and 3, I hooked battery leads across the first and third tabs of my spiral and put oscilloscope probes across parts corresponding to where Page put his hands (Figure 9, left). Then I switched the circuit on and off. Typically, whenever current *stopped*, the probe picked up a brief pulse of high voltage, which showed on the oscilloscope screen. A typical trace displays a voltage spike of several hundred volts, followed by lesser peaks declining within a damped envelope whose periodicity lies in the microsecond range (Figure 10, right).

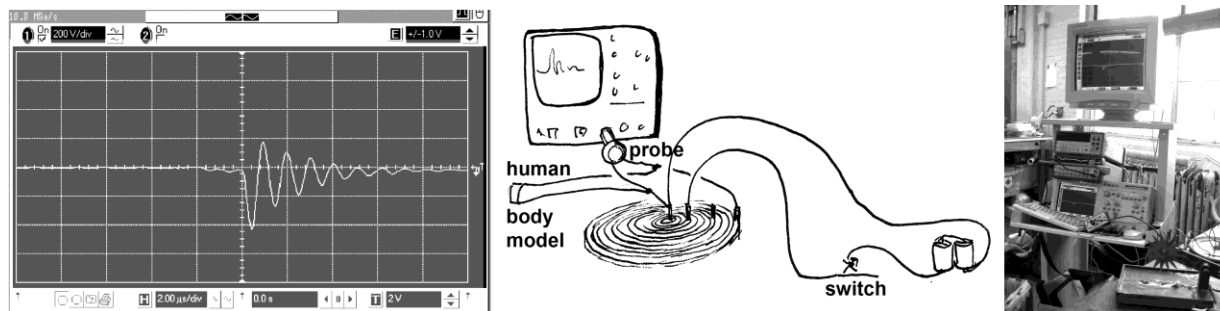


Figure 10. Left: A typical oscilloscope screen image showing voltage (vertical 200V/div.; horizontal 2µs/div.) induced in the spiral when the switch opens. Middle: The human body model (such as a resistor) is connected in parallel with the oscilloscope probe. Left: Photo of the test equipment, including digital oscilloscope and monitor (top) with spur wheel and spiral in the foreground.

I started by using an analogue storage oscilloscope having no means of recording such a trace. Finding that I could not remember the traces produced by each switched event, I paused after each to write down the peak value or sketch its appearance. Then I switched the circuit again. I was constantly redoing how I worked with the circuit and instruments. For example, noticing the oscilloscope's two channels gave me the idea of observing two intervals of the circuit at once. I put one probe across the part of the circuit where battery current went, and the second across a different, longer segment, like that of Page's body. Over and over, I repeated the cycle of switching the current, observing a trace, and repositioning the connectors. Sometimes the signal taken across more of the spiral was more pronounced than that taken across a lesser interval; often it was hard to tell. Every event seemed so different. The probe from the second channel seemed to perturb the overall signal. I took it out.

¹¹I worked with the following storage oscilloscopes in successive phases of my study: HP 54600B; Lecroy 9450A; HP Infinium 54810A. Hewlett Packard's product Infinium is now serviced under Agilent, 2010-2011.

The circuit resonated after each switching. The peaks of those resonances varied so that I could not tell what was going on. In discussing this with others in the lab, drawing on interpretations of electricity from our training, we noted that a source of electrical resistance absent in my circuit, but present in Page's, was his body. Maybe Page's *body* contributed to the electrical behaviors he described!

Having this idea was an intriguing moment in my study. It expanded my awareness of roles in the historical circuit beyond my initial interpretation. I realized that I had regarded Page's body only as a detector, not as a circuit component. Perhaps Page also had this view. Using an oscilloscope as a detector was a different case; presenting a very high resistance ($M\Omega$) to the circuit, under most conditions an oscilloscope can be regarded as a passive detector. The experiments where Page detected the spiral's electricity by observing only a visual spark without taking shocks would be more analogous to the configurations I had tried with an oscilloscope probe, than those where bodily shock provided Page a means of detection. Like me, Page may have considered these two modes of detection interchangeable.

Acting on this idea, I sought to add into my circuit something that would function as an analogue to the human body. Through discussion with other experimenters and readings, I considered many methods for providing an electrical substitute for the body. Most interpretations represent the body as a pure resistance whose value decreases with moister skin, or as a resistance combined with inductance and capacitance. I constructed several alternative models consisting of a resistor, or of resistors combined with other elements (2005, 2008b).

This question about the electrical role of the body increased the options of what to include in the circuit. It was a lengthy process to test these further options across many spiral configurations by placing each in parallel with the oscilloscope (Figure 10, middle). Would an overall pattern emerge in the voltage traces? It did not. In response to this impasse, I let off doing more with the spiral. Its fleeting signals did not register my interventions and each sequence of trials appeared undifferentiated. My experimental work stalled where my expectations for identifying particular trends met with ambiguous outcomes.

When I later resumed the experiment, I overhauled the apparatus, doubling the spiral's length, improving connections, and substituting a digital oscilloscope for the analogue one (Figure 10, right).¹² This switch to a digital oscilloscope again added many more options for experimental tests and their analysis. Through visual observing and sketching voltage traces, I was not taking in enough of what the oscilloscope detected to make out any pattern in the electrical behaviours. With the digital oscilloscope, the values in voltage and time making up a trace could be saved as a file containing paired numerical values. I subsequently plotted these values in Excel or Matlab (1994-2010). By superposing plots of traces taken under different arrangements of the circuit, I look for trends that in turn raise questions, setting off further trials. Providing feedback to my interventions, these means of recording and analysis moved me out of the impasse, opening a window on the electrical behaviours and experimental options that was not available before.

¹²HP Infinium 54810A.

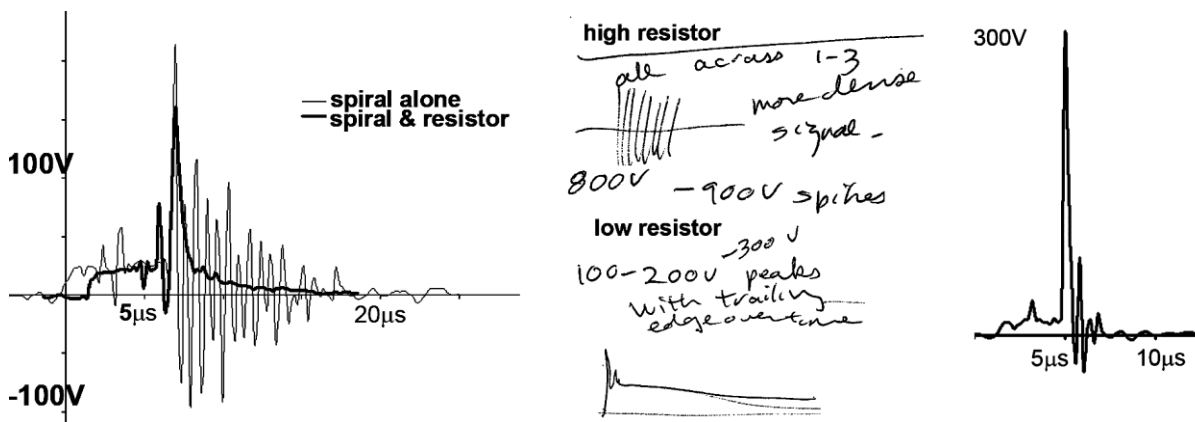


Figure 11. Left: The light gray line is a voltage trace induced across a part of the spiral when the switch opens. The dark line shows a trace induced across the same portion of the spiral when a resistor (1kΩ) is put in parallel with the probe. Middle: My handwritten notes showing my first observation of a difference in the trace resulting from using a high resistor (vertical lines representing ringing, top sketch) and a low resistor (single peak, bottom) as models for the body. Right: The voltage trace produced with a human volunteer connected across my spiral, in place of the resistor. The peak voltage is 300 V.

An example from my early use with these analytic means involves the effect of inserting a resistor in parallel with the oscilloscope probe, as a stand-in for the body. When the resistor's value was high, the traces resembled those produced with no resistor: an initial high-voltage peak followed by a resonant 'ringing' of many peaks whose value declined successively. When the resistor's value was low, there was a difference in the traces' overall appearance; the voltage of that initial peak was lower voltage, after which the signal declined without ringing (Figure 11, left).¹³ My hand-written sketches and notes made while using the analogue oscilloscope contain these same features (Figure 11, middle). At the time I did not appreciate this finding and was expecting instead a distinct trend in peak voltage values that was not manifested. The data analysis plots assisted me in seeing what I had observed but failed to appreciate. A confirmation that the placement of a body (substitute) in the circuit alters the induced signal, yielding a single prominent voltage peak without ringing, came when Professor Pancaldi of Bologna voluntarily put himself in parallel with the probe – feeling no shock (Figure 11, right). This characteristic shape held for traces produced with other substitutes for the body that I tested.¹⁴

However, while I had characterized the effect on the spiral's circuit of adding a body or substitute, this effect applied to all circuit configurations. It did not seem to correlate with the differing severities of shock that Page described, exhibiting greater intensity when more of the spiral was included in a test.

Whenever I switched the circuit, the peak values of the voltage traces varied. Sometimes the peaks were indeed highest when I probed my spiral in the ways that Page had when reporting strongest shocks. Then my experiment seemed to cohere with Page's findings. In analogy to Page's heightening sense of shock when battery current and his body were put together across successively longer spans of the spiral, my comparable tests demonstrated an increase in voltage. Similarly, with the configuration that had most astonished Page, that of feeling weak (acupuncture-amplified) shock from turns outside the battery current's direct path, I too detected small voltage peaks from a probe placed across intervals entirely outside my battery current's direct path.

¹³In the trial illustrated, I varied the resistor's value from a low of 330Ω to a high 560kΩ. These values correspond to those tabulated for the human body's resistance to current: dry skin ~500kΩ; wet skin ~1kΩ; internal body length ~400Ω (Jefferson Lab, n.d.).

¹⁴In addition to the resistors, these substitutes included neon bulbs; a metal-oxide varistor; a resistor in series with a capacitor, and several variations on the Siconolfi model (Siconolfi et al., 1996). This human body model consists of a resistance in series with a capacitance, in parallel with another resistance in series with an inductance. Steven Siconolfi provided data enabling me to construct models. A 1.87kΩ resistor is in series with a 2.2nF capacitor; this is then in parallel with a 510Ω resistor and an inductance (of 27μH in parallel with 56μH). For more extensive empirical and modeling studies of the human body's impedance (Reiley, 1998). Observed impedances range from over a kΩ at low frequency, to below 500Ω at high frequency.

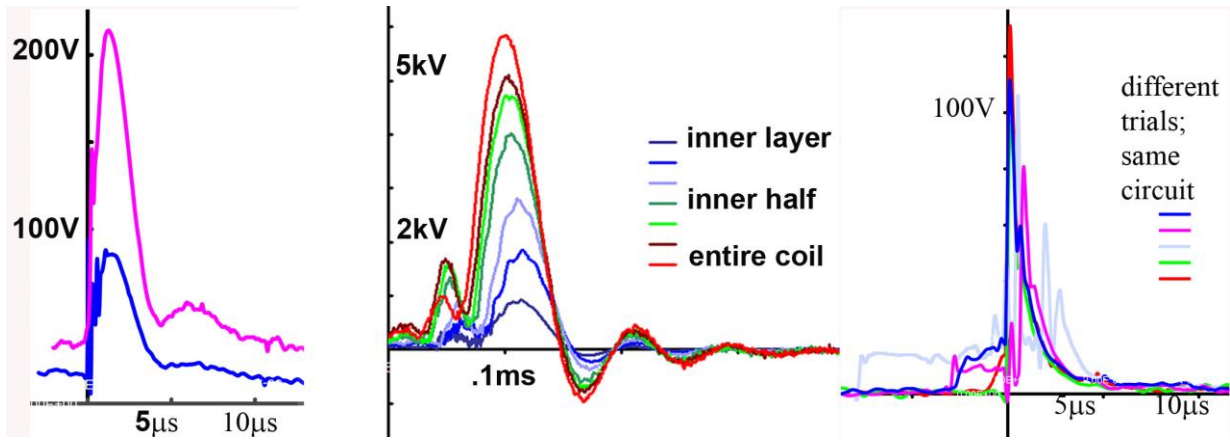


Figure 12. Left: A superposition plot showing two cases of voltage induced in parts of a coil that I wound from one continuous wire, over a core of thin iron wires. Battery current was applied across only an inner portion of this coil. For the trace indicated by the black line, the probe was placed across the portion of the coil that carried battery current. For the trace indicated by the gray line, the probe was placed across the entire coil (including the current-bearing segment); the voltage peak was higher in this case, analogous to Page’s findings with the spiral conductor. Voltage peaks induced in my wire coils having iron cores were more stable from event to event, than with my spiral. Middle: In one of my induction coils, peak voltage increases for traces are taken across successively longer segments of the outer (secondary) wire, when battery current stopped flowing in the inner (primary) wire. Right: An overlay plot illustrates the variation in voltage traces exhibited by my spiral. Each of the five traces, designated by different colors of gray, was taken across the same interval of spiral, when my wheel interrupter switched off the current.

However, when my probe spanned the battery current’s path plus an additional length, I could not always tell whether the peak voltage had increased along with that addition. The peak voltages were so variable as to render ambiguous any attempt at interpretation. Gradually I noticed that this underlying ambiguity occurred with my spiral, but not when I performed the comparable test on wire coils that I wound onto iron cores. With my iron core coils, putting a probe across more length resulted in consistently greater induced voltage (Figure 12, left and middle; Cavicchi, 1999, 2006a).

Although I did not realize it for some time, the variability attending my spiral observations tended to overwhelm whatever characteristics might be due to the different spiral configurations that I tested. I demonstrated this variability by overplotting successive traces taken from the same circuit configuration after I switched the battery off successively, without changing anything else (Figure 12, right; 2005, 2008a).

Did this variability have to do with the switch? As with my inquiry about the role of the body, this question about the switch brought me to reconsider the circuit, both through its historical components and by means of stimulating and observing it that electronic test equipment now makes accessible. I went on to explore effects of switching in the spiral circuit in two ways: with mechanical switches; and by substituting periodic electronic pulses for switched battery current.

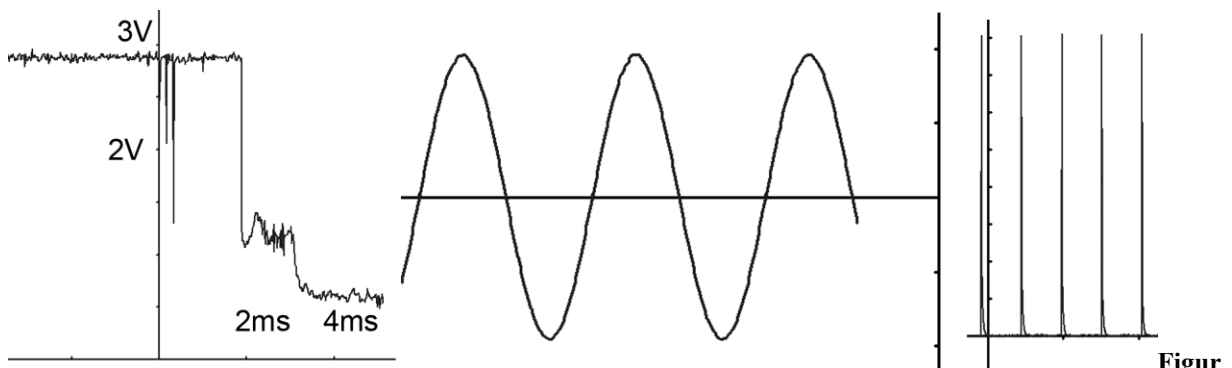


Figure 13. Left: A voltage trace taken when a knife switch opens a circuit consisting of just the switch and two flashlight batteries (3V). The trace shows a complex structure as the switch contacts break away and reconnect erratically. Middle: A voltage trace showing a periodic waveform produced by a function

generator; the frequency of the wave can be adjusted within the instrument's range (Hz to MHz). Left: A voltage trace showing a periodic pulse, exhibiting a very sharp rise and fall in voltage, produced by a pulse generator. The frequency and shape of the pulse can be adjusted.

My testing of the effects of mechanical and periodic switching brings into play many further options for consideration in each experiment. Mechanical switching is an inherently irregular process; the two surfaces of a switch are jagged at a microscopic scale. When separating, these surfaces disconnect and reconnect, making for erratic momentary voltages in the circuit (Figure 13, left). When applied to a circuit containing the spiral, these switches induce complex signals that are composed of high and low frequencies. As I sought ways of examining the circuit's behaviour across the diverse frequency ranges of its mechanical switching, the number of experimental and interpretive options increased. By contrast, pulse and frequency generators output just one well-defined waveform at a time (Figure 13, middle, right).¹⁵ From the complex range of frequencies manifested in a switching event, a wave generator provides only one frequency to the circuit for any given test. To view the circuit's response to different frequencies, I select and test frequencies of differing logarithmic domains, from Hertz to Megahertz. This practice, of sampling across representative frequencies, results in numerous test options for each circuit configuration.

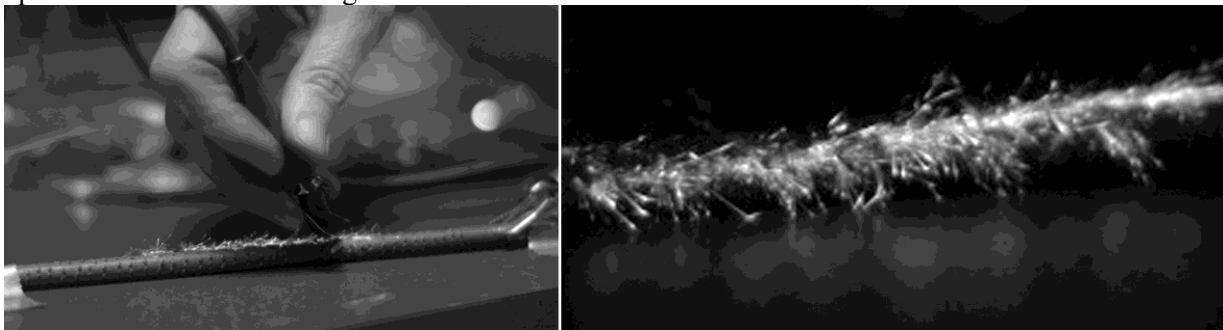


Figure 24. Left: A metal rasp is used as an interrupter for my spiral circuit (see Figure 8, middle) by connecting one end to the battery and the spiral. A cliplead coming from the spiral is scraped across the rasp teeth. Sparks arise in the dark. Photographs Omari Stephens.

I expanded my experience with mechanical switches by constructing analogues to Page's metal rasp (Figure 14) and rotating spur wheel (Figure 15). Through my novice efforts in a machine shop, I made a succession of spur wheel switches. When I first operated a wheel as a switch for the spiral, what I saw amazed me. Manually turning it through a glob of the liquid metal galinstan¹⁶ in the dark, for the first time, I saw purple sparks and heard snaps (Figure 14, left)! Caught up by the beauty, I followed a practice of Page's by affixing bits of metal leaf to the star's tips. When current combusted through them, the sparks were colored corresponding to the metal (2005, pp. 131-2, Figs. 10-11).

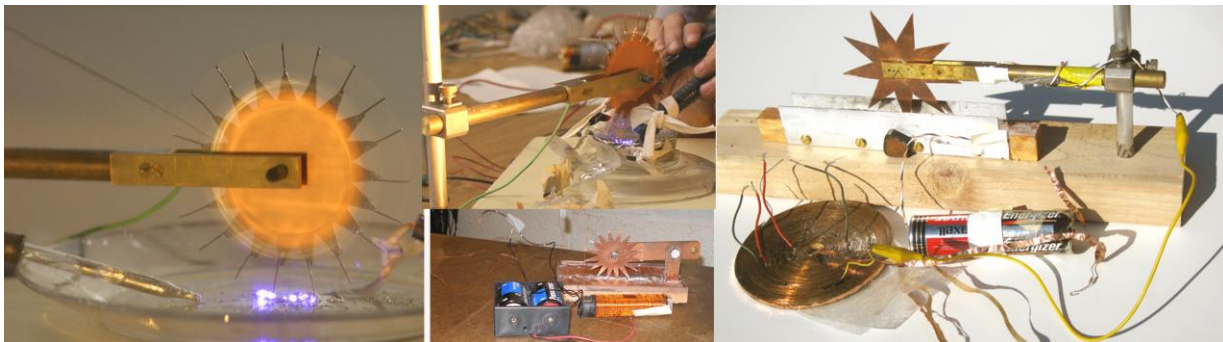


Figure 15. Three versions of my spur wheel interrupter. Left: Sparks show where the spur's points leave

¹⁵I use the HP33120A function/arbitrary wave generator for sine and square waves up to 15 MHz. For higher voltage square pulses (up to 150 V at periods down to .01ms), I used a Grass S44 Stimulator of Grass Medical Instruments, Quincy MA.

¹⁶I used the liquid metal galinstan, a product of Geratherm Medical Diagnostic Systems (n.d.), a safe substitute for mercury. It will, however, be mistaken for mercury by security detectors (eg. airports). For more description of the reconstructed spiral and wheeled switch, see (Cavicchi, 2005, 2008b).

the galinstan pool in this time exposure of my first interrupter, pulled by a string (left) wound around its hub. Photo Jeff Tinsley. Middle: Top: The spur wheel spins and sparks in the gap between two magnets that I hold. Photo Jeff Tinsley. Bottom: My second wheel interrupter, connected to batteries and the wire coil for the experiment discussed in Figure 12, left. This second interrupter with the spiral were used in producing the traces of the video 1 at https://www.youtube.com/watch?v=mVvX_SQMGRM Left: My third interrupter, photographed with a spiral, spins like a motor in video 2 www.youtube.com/watch?v=99Ar-mzNLV8.

Page discerned brightest sparks where battery connection broke from half of the spiral's length. When I tried to compare spark brightness, I experienced ambiguity again. I could not tell whether sparks were brighter when the whole spiral was interrupted, or just the half. Only when I reduced the battery source from two cells to one, did overall sparking diminish to where the midpoint brightness stood out from dimmer glows at other points.

Page had his wheel spinning on its own as a self-actuated switch by placing the gap between a magnet's poles crosswise to where the wheel spur contacts the mercury pool. My attempts to produce this motion have met with setbacks and given rise to my reconstructing several versions of the wheel switch (2005). The motor effect is minutely sensitive to the relative positions of magnet and wheel (Figure 15, middle, right). That motion is astonishing!!! (VIDEO 2 www.youtube.com/watch?v=99Ar-mzNLV8)

Whether my wheel turned by hand, or as a motor, the repetitions of its breaking contact revealed more than the individual switching I had done before, where only one event at a time showed on the oscilloscope screen. In contrast, my star wheel interrupter made it possible to quickly spin through many events. Successive voltage traces appear on the oscilloscope screen while I turn the wheel, switching the circuit and observing by the oscilloscope probe connected across it. Voltage peaks dance like an animated movie of fluctuations; nothing is steady (VIDEO 1 https://www.youtube.com/watch?v=mVvX_SQMGRM).

With this method of observing, the variability underlying the mechanical switching became more apparent to me. As I noticed distinctive patterns, I stopped the spinning to select those events to save on disc for plotting. However, high peaks flitted past too quickly for me to capture their traces by this manual selection method.

I experienced an opening of another kind of window on the trace's behaviour when I began to use oscilloscope functions that save data from successive events in real time (instead of single selection) and compute averages of the voltage values taken in these events. Keeping the circuit at one configuration, I employed various of these oscilloscope functions to collect and average many hundred switching events produced by spinning my spur wheel; I then repeated this procedure at another circuit configuration, and so on. Stabilized curves resulted for each circuit configuration. By contrast, there was erratic variability among the traces of the individual events making up each set of averages.

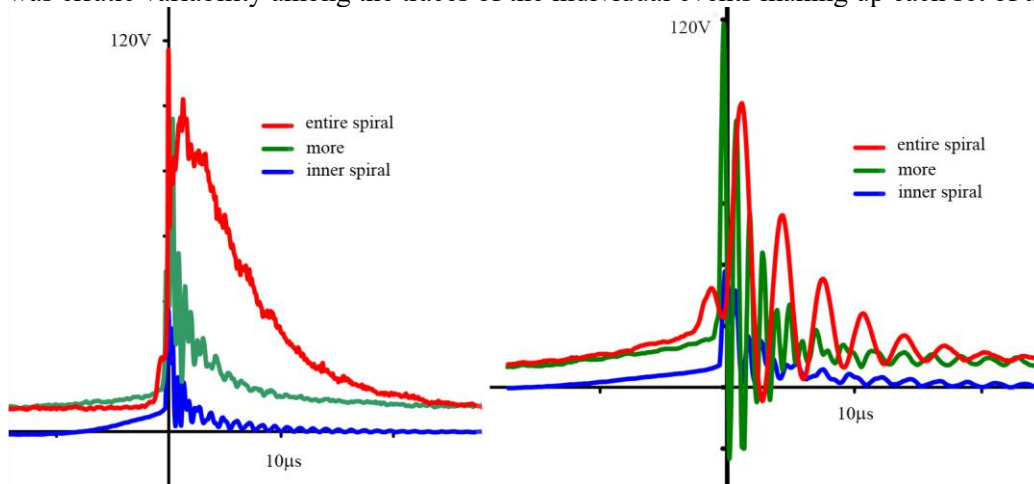


Figure 16. An oscilloscope function records the average value of voltage from all those that occurred at each time slot for 1024 events switched by the spur wheel. The spiral's voltage was observed across its inner segment (black), mid region (gray), and entire length (light gray). Left: Battery current is applied

across each of the three regions along with the probe; the average curves show an increase in voltage and extension in duration as more of the spiral is stimulated. **Right:** Battery current is applied only across the inner region; the average curves show a periodicity of greater duration and lesser value in the initial peak as more of the spiral is observed.

For example, one oscilloscope function computes the average -- at each discrete point in time -- of all the voltage values (from one-thousand collected traces) that occurred at that discrete time in the history of the triggered event trace. I applied this function when taking traces across three regions of the spiral: the first, taken across the inner portion of the spiral; the second taken across a longer segment of the spiral, and the third, taken across the entire spiral. I conducted this three-region study for two cases, in analogy to Page's experiment. For the first case, I applied both the battery current and the probe across each region together (Figure 16, left). As more of the spiral is stimulated with battery current, the averaged signal has an increase in both the peak value of voltage, and its duration. For the second case, I applied the battery current only across the inner region of the spiral, and placed the probe across that same region, then the mid-region, then the entire spiral (Figure 16, right). The average taken across the spiral's current-bearing region is high in voltage and brief in time; where the entire spiral is observed, the average exhibits a peak value somewhat lower in voltage, while the signal persists longer overall.

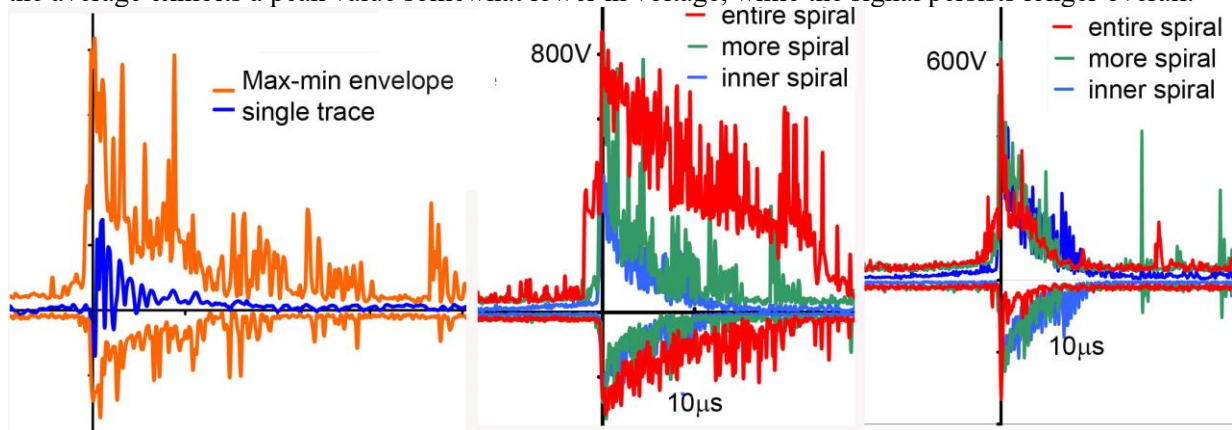


Figure 17. Left: An oscilloscope function records extremal values of voltages taken at each time, cumulatively across many (1024) events where the spiral was switched by the spur wheel with no body substitute in the circuit. **Left:** An individual trace (black) appears within the spiky extremal boundaries (gray). **Middle:** Overlay of extremal boundaries that resulted across inner spiral (black), mid-spiral (gray), entire spiral (light gray). Both battery current and probe were applied together across each region; the boundaries separate and increase in voltage. **Right:** Envelope curves resulting where the battery current is applied across the inner spiral, and the probe is placed across longer spans show more overlap and ambiguity among the boundaries.

Another oscilloscope function automatically records the extremal voltages (high and low) occurring at each time position in the time history of successive triggered events. This function outputs an upper and lower boundary envelope for each set of sampled traces; any individual trace falls between those two boundary limits (Figure 17, right). The complexity of voltage spikes in these upper and lower boundary envelopes depicts the varied, ambiguous behavior that I had encountered before through individual events. I applied this function for the same two cases identified above, and across the same three regions of the spiral. For the first case, where battery current and probe are applied together, the extremal boundaries indicate an increase in overall maximal voltages when the entire spiral is involved (Figure 17, middle). For the second case, the extremal boundaries are approximately overlapping, with perhaps lesser high voltage spikes when more of the spiral is observed (Figure 17, left).

These two functions of average and extremal boundaries, viewed by superposition constructed from averages or compilations made over many successive switching events, depict an overall voltage effect across the spiral, an analogy of what Page reported. I wonder if these methods of averaging and accumulating sequences of hundreds of traces relate more to a blurring within Page's sensation of shock over many spins of the wheel, than do the separate transient voltage traces.

In addition to, and alongside, these experiments with mechanical switching by my wheel devices, I stimulated the spiral by periodic means. Periodic stimulation removes the variability which figures so prominently in my mechanically switched events; however each test's finding holds only for one

specific frequency. To survey over many frequency domains, I conducted extensive tests of the spiral and its intervals, applying periodic waves and pulses.

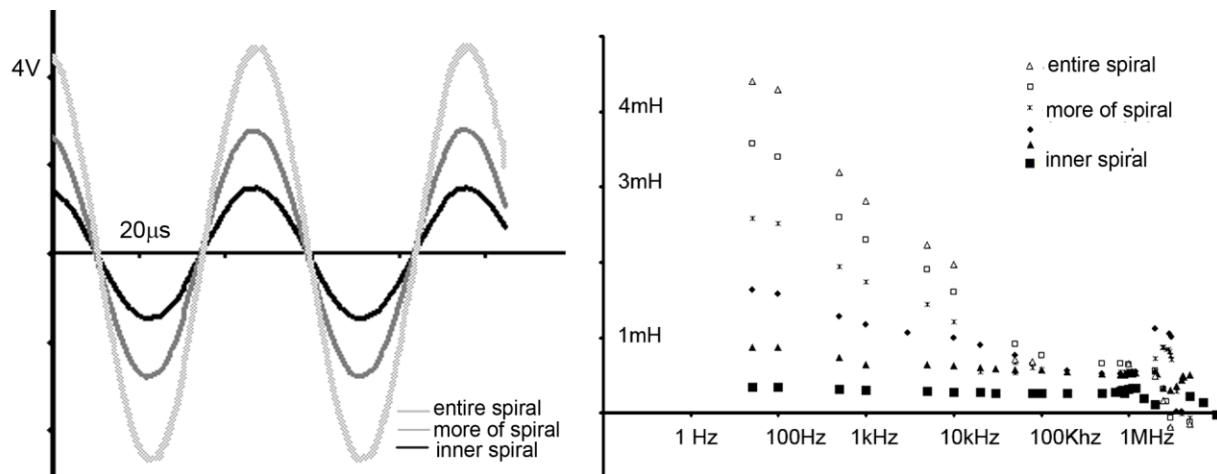


Figure 3. Left: A constant frequency of 20kHz was applied to three intervals of the spiral in succession (inner, middle, outer). The observed voltage is superimposed, showing an increase in peak voltage across the spiral. Right: Plot of inductance measured at several frequency decades, for different spiral intervals, its value increases as more of the spiral is covered. Overall, these values decline as frequency rises, and an anomaly appears above 1 MHz.

With a pure 20 kHz sine wave, I first recorded a case where voltage distinctly increases as the probe is put across more of the spiral than the current-bearing segment (Figure 18, left; 2005). This result correlates with Page’s report that his sense of shocks increased when he put himself across more of the spiral than where battery current passed. It also is consistent with my spiral having a greater value of electrical inductance – as this property is interpreted today—the more of its length is included in an observation. I checked this implication further by using an inductance meter to directly measure the spiral’s inductance across each of the successive intervals where I have positioned connector tabs in analogy to Page’s cups. As with the pulse generators, the inductance meter operates at one frequency at a time. At low frequencies, the inductance increased across the spiral (Figure 18, right).¹⁷ At high frequencies, its value declined overall, displaying an anomaly above 1 megahertz.

This megahertz anomaly intrigued me; I was curious about the spiral’s differing electrical response when stimulated by frequencies of different magnitudes (eg. Hz, kHz, 10kHz, 100kHz, MHz). During any mechanical switching event, the spiral is exposed to a range of frequencies, including high values. Might the spiral’s apparent anomaly at very high frequencies contribute to the variability that I observed with mechanical switching?

I realized that a method of further investigating this possibility lay in applying Fourier transform analysis to my data; this analysis takes as input a function having values in time, and outputs a breakdown of the component frequencies of which that function is constituted. For example, it converts a pure sine wave, where voltage varies with the same period for all time, into a function having one value: the value of the frequency corresponding to that period. An input function consisting of two superimposed sine waves converts to the two frequency values associated with those waves. A more complicated function, such as my voltage traces, will convert to a multivalued function of frequency, where the value at each frequency represents the relative weighting of a wave of that periodicity in the overall make-up of the original signal. The digital oscilloscope that I used had a rudimentary software for computing this analysis; eventually finding it inadequate, I submitted my voltage trace values to the Fast Fourier Transform (FFT) program in Matlab (1994-2010). Applying these programs to my data, I produced log-log plots of the log of impedance against the log of frequency; in these plots, frequencies that are particularly resonant with the spiral appear as dips, not peaks.

¹⁷A HP 4192A impedance analyzer was used. The spiral’s overall inductance was on the order of 4mH at low frequency; its resistance went from 5.6Ω at low frequency, into the kΩ range at 50 kHz.

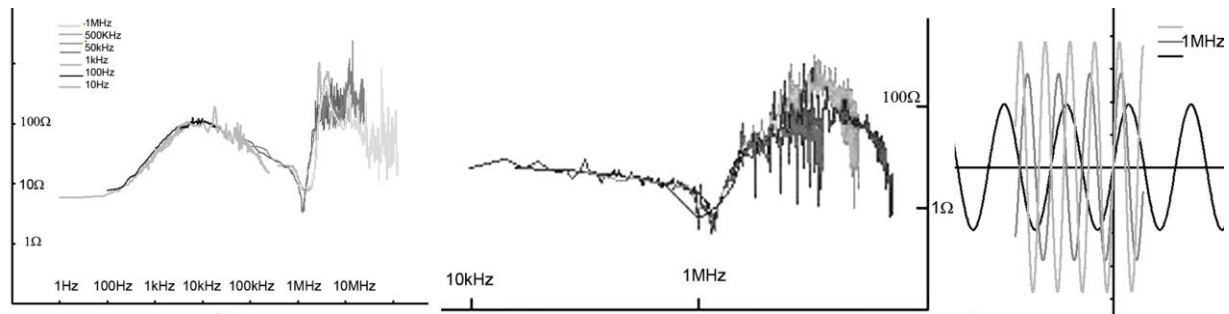


Figure 19. Left and Middle: A distinctive dip in impedance occurs at about 4MHz in these log-log plots of observations taken across the same spiral interval. The spiral was stimulated by waves of different frequencies in each frequency range. **Right:** A plot showing the spiral's response to three different sine waves (black: 500kHz; gray: 1MHz; light gray: 1.7MHz). The amplitude (height) of the sine wave is greater for the MHz waves that are near the spiral's resonant frequency.

To study the spiral's responsiveness across different frequencies as computed by the FFT software, I stimulated the spiral with either my mechanical wheel switch, or a square pulse of different durations (frequencies) that was an output option of the signal generator. The experimental options widened yet again, as I alternated among these multiple modes of stimulation, and, as before, among all the intervals of the spiral's length across which these stimuli and the oscilloscope probes could be placed. My initial studies showed a distinctive dip above 1MHz in the spiral's response both to the wheel's mechanical switching of battery current, and to periodic stimuli. This dip shifted slightly in its frequency when the spiral was observed across different intervals and by other varied conditions (Figure 19 left, middle).¹⁸ In some later tests, this Megahertz dip did not recur. As an alternative means of checking the spiral's resonance frequencies, I stimulated it with a pure sine wave whose frequency I varied by successively dialling the generator through all values from Hertz to Megahertz. Resonances showed as an increased amplitude in that wave as detected by a probe placed across the spiral (Figure 19, right).

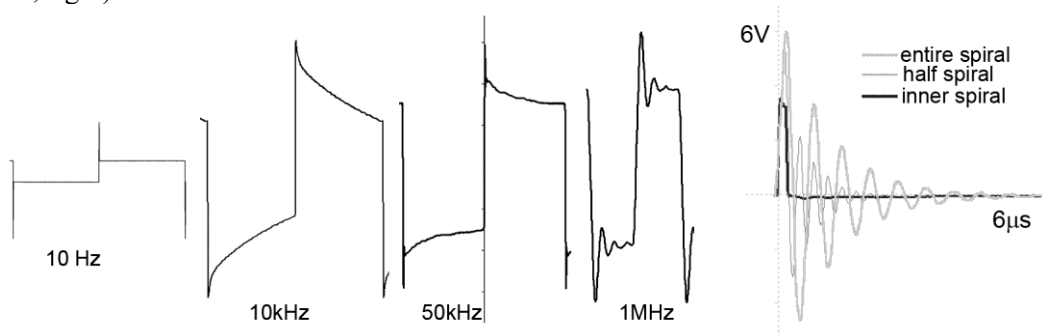


Figure 20. Left: A periodic square wave of different frequencies (10Hz, 10kHz, 50kHz, 1MHz) is applied across half the spiral, and the probe is placed across the entire spiral. The transmission of the wave in the spiral distorts it; this distortion is greatest for the high frequency MHz wave. **Right:** The spiral's inner interval is stimulated by a narrow voltage spike (.3μs duration); when viewed across more of the spiral, the observed signal stretches out in time, and may increase in voltage.

I came across other frequency-related effects. For example, I applied square waves from different frequency domains (10 Hz to 1MHz) to part of the spiral, and applied the probe across the entire spiral. The detected waveform was not so square (Figure 20, left)! In the spatial extent of the spiral beyond where the square wave is applied, the signal becomes distorted, especially at high frequency. As another illustration of how a distinctive input signal is affected when it is observed across the entire

¹⁸The electrical property of admittance is the reciprocal of impedance. Impedance (measured in Ω) is the ratio of the complex voltage, V , to the complex current, I ; where both these are real, that ratio is the familiar electrical resistance. Impedance depends on frequency. I compute spectrums of spiral impedance from the ratio of the Fast Fourier Transform (FFT) of a voltage trace to that of a simultaneously observed current trace. As inputs for stimulating these traces, I use square waves generated at selected frequencies, as well as excitations made by dipping the spur wheel into liquid metal. Present results suggest that the megahertz regime where the spiral impedance drops may represent a transition from capacitive to inductive behavior. See Lehar, n.d. for a pictorial depiction of Fourier Transforms, and Brigham, 1988 for a more complete discussion of the FFT.

spiral, I applied a narrow voltage spike to the spiral's inner section, and placed the probe across more of it. Further out, the pulse spreads in time and rings with peaks of decreasing height. ((Figure 20, right)).

In looking into the spiral by means not available to Page, I – like him – find electrical behaviours to wonder about. Always, the overall effect is amazing: on putting a spiral into the circuit, the voltages induced exceed my flashlight batteries' 3V input by over two orders of magnitude. This heightened voltage, its variations in degree, and its presence in winds outside the battery current's direct path, had intrigued Page and was also unmistakable for me. Having no stable sense of what to expect while exploring apparatus and effects that were new to him, Page improvised the intermediate cups and circuit breakers – that opened original experimental options – that revealed otherwise unseen behaviours. In writing about an experimental development by Michael Faraday that is commensurate with Page's, historian David Gooding characterized it as 'experimenting to *realize* possibilities, not to *decide between* two distinct or incompatible interpretations' (Gooding, 1990, p. 124). Page and Faraday functioned productively in an environment of ambiguity through generating experimental options or 'possibilities'. Analogous to how the extra cups in Page's spiral expanded the experimental options, so amid the ambiguity that arose in my study, the oscilloscope, test equipment and analysis techniques offered new opportunities. Realizing possibilities meant coming up with more to try, widening the world of options beyond what prior explanations might prepare me to consider.

While Page and I both experienced ambiguity in our work with the spiral conductor, this ambiguity was expressed in differing forms. In part, Page developed his experiment by qualitatively comparing the shock or spark exhibited by one circuit configuration with that of another. Usually there was sufficient difference between effects being compared, for him to report which seemed stronger. However, on discharging a Leyden jar through different regions of the spiral, he could not distinguish one case from another. Characterizing these results as 'somewhat equivocal', he suspected that the fabric separating the spiral's turns provided inadequate insulation (1837, p. 140). Page's sense of something 'equivocal' going on in his Leyden jar tests correlates with the ambiguity that is so prevalent for me in comparing voltage traces from the same, or differing, circuit configurations. Leyden jar discharges involve high voltages and frequencies: the same regimes that showed anomalous and resonant effects in the spirals of my studies.¹⁹

Along with the ambiguity of electrical effects that makes it 'equivocal' to compare and describe them, ambiguity of a second form was involved in construing and interpreting the underlying behaviours. While Page's experiment accessed the inductive phenomena in ways that often made the effects more distinctive than in mine (leaving him perhaps with less awareness of ambiguity regarding those effects than I encountered), he was immersed in the second form of ambiguity, as characterized here. The means available to him for interpreting the new electrical effects were insufficient, plunging him in uncertainty about what was going on. His paper reveals this uncertainty in such remarks as: 'the rationale I am unable to give'; 'still more curious...difficult to explain'; 'contrary to expectation' (1837, p. 139). Under Page's hands – and through them!—the experiment changed and complex electrical relationships became apparent even while he lacked an explanatory description. By contrast, I had access to electronic tools and analyses by which the self-inductive properties of a conductor can be identified and described. I did not pretend not to have this access, yet I soon found that my expectations for particular experimental outcomes could be both unfulfilled, and limiting. I traversed no direct path to demonstrating Page's findings. Even with modern tools at hand, the spiral conductor experiment retained ambiguity and complexity for me, as it had for Page. Instead of dispelling ambiguity with definitive outcomes and answers, the instrumental resources and analyses allowed me to observe effects that I had not expected and to move beyond the limits of my expectations in flexibly developing experimental options for exploring that ambiguity. Experiencing confusion in this way, I became as much an explorer of the spiral conductor as Page.

Revisiting the spiral

¹⁹I am curious to apply Leyden jar discharges to conductive spirals or coils. Working with the high voltages might entail further modifications to the spiral experiment and methods of detection.

Page's electrical investigations soon took over to the extent that his medical practice fell by the wayside. The most productive period (1837-1839) in Page's scientific contributions to electromagnetism spanned either side of his relocation from Salem, Massachusetts to a town outside Washington DC with his parents in 1838. His unique electrical expertise came to public prominence through Page's roles as US patent examiner, key witness in the 1848 Morse vs. O'Reilly lawsuit, and independent inventor (Post, 1976a). A US Senate allocation of \$20,000 launched his electromagnetically powered locomotive whose fortunes collapsed even before its beleaguered test run. The foundational yet rudimentary spiral of 1836 was core to Page's deathbed appeal to the US Congress for a retrospective patent on it and his subsequent double coils. The resulting 'Page Patent' sweepingly interpreted to cover circuit breakers and other essential telegraphic apparatus, garnered a fortune for Page's heirs and ill will from the telegraphic community (Editor, 1872; Post, 1972, 1976a, 1976b).

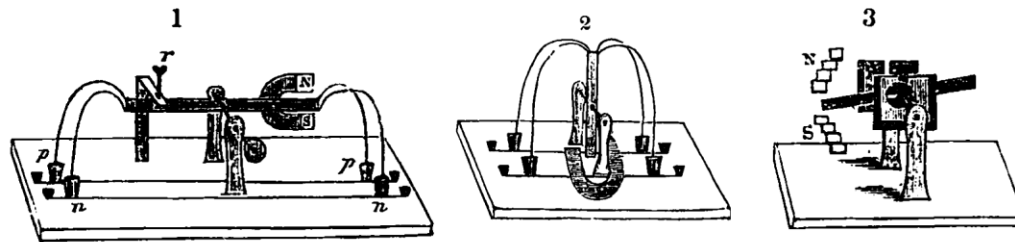


Figure 21. Page's homemade circuit-breakers, invented for use with his lengthened spiral (Page, 1837b, p. 356.). Left and Middle: small cups (labelled *p* or *n* on left) contain mercury and connect to the battery's + or - terminal. A current-bearing wire bobs up or down between the poles of a magnet; its downward curving wire ends rock into or out of these cups, breaking or making the circuit at a rate which Page described as 'inconceivably rapid' (p. 365). Right: Page's revolving interrupter scattered drops of mercury as it turned in the presence of a horseshoe magnet (not included in the diagram).

After his first publication on the spiral, Page continued finding more to try and in the process deepened his understandings of electricity. A year later, the spiral was 100 feet longer, with four more mercury cups for making connections (Page, 1837b). Page acknowledged Ampère in naming it the 'Dynamic Multiplier' and in describing its function as 'Electro-dynamic'. Page's exhaustive inquiries into its inductive sparking under series and parallel battery configurations led to original research on the battery, resulting in a more compact, stable cell. Going beyond the acid battery, Page also activated the spiral with a thermo-electric source. To replace the human operator's action in opening the circuit and overcome problems he encountered with his spur wheel switch, Page pioneered rocking and spring-loaded forms of the self-actuated switch (Figure 21): 'I have tried a variety of means and succeeded in the contrivance of several beautiful pieces of apparatus' (Page, 1837b, p. 355; Sherman, 1988).

These innovations heightened the spiral's effects so that it was no longer essential to put the body in the circuit. Page applied the spiral's heightened electricity to standard demonstration tests of the time, including sparking across separated charcoal points and decomposition of water. He alluded to the body only in indirectly mentioning 'acupuncture' shocks showing the thermo-electric source's influence on the outer spiral (Page, 1837a, p. 358).

But even if the body was superseded, it remained essential to experimental development that something fill its role as detector. For example, Page found the faster the contact breaker went, the more ferociously foamed bubbles of water decomposed by the spiral's induced electricity. Just as differing shock intensities had enabled Page to evaluate successive placements of his hands across the spiral, now he used this bubbling as feedback while improving the interrupter. He achieved greatest rapidity when his rotary wheel operated electromagnetically as a motor powered by a miniature battery separate from that which ran the larger circuit.

In the widening range of experimenting brought about by the spiralled conductor, Page observed yet another new phenomenon, one which contributed to the future of telephony. Instead of resting the spiral horizontally, this new set-up involved vertically mounting a lighter-weight spiral of cotton-covered wire so that it resided edgewise within the horizontally oriented gap between a horseshoe magnet's poles. On each interruption of electrical current through the spiral, the magnet rang with a

characteristic musical tone; different sized magnets gave different tones (Page, 1837c, 1838a).²⁰ Alexander Graham Bell opened his ground-breaking lecture at the American Academy of Arts and Sciences on May 10, 1876 by crediting Page's 1837 discovery of 'galvanic music' with kindling world-wide inquiry on sounds associated with magnetization and demagnetization, including his own research (Bell, 1876-1877, p. 1).

But the magnet's singing merited only passing notice in Page's 1869 obituary. Page was long out of the top ranks of American science when he died penniless of sufferings that chemical exposures perhaps had exacerbated ((Lane), 1869). Public laurels in telegraphy and telephony came to rest on others, both during Page's abbreviated life and subsequently. In contesting this injustice, Page's biographer Robert Post sheds light on culturally imposed expectations about the conduct befitting a scientist, whose violation by Page resulted in marginalization during his own day, and in succeeding historical assessments (Post, 1976a).

Extending and interpreting the spiral's effects

The spiral was the first of Page's electrical contributions, and through communicating about it he engaged a broader community of electrical experimenters. Two figures, one foreign, one local, are conspicuous in supporting young Page's development. London-based William Sturgeon reprinted Page's papers in his journal with his own commentary (Post, 1976a, p. 207-213; Morus, 1998); Boston instrument-maker Daniel Davis, Jr. collaborated with Page in making new and production apparatus (Post, 1976a; Sherman, 1988; Cavicchi, 2006a). From both, Page's interest in following inductive phenomena deepened, and his instrumental work shifted from the spiral and toward electromagnetic coils. However the spiral remained to offer yet new inductive behaviours to later researchers.

Sturgeon first heard about Page's shocking device from a traveller from Salem who visited the Adelaide Gallery of Practical Science in London, then a locus for science experimenters and the curious public. Crucial details about the instrument – including that its inventor was allegedly Henry! – were garbled in the informal transmission (Sturgeon, 1837a; (Page), 1867, footnote p. 11). Sturgeon sought to replicate its effect of heightened tension, but in his version there was no spiral at all! Just as Page responded to Henry's spiral by improvising with copper sheet, and I to his with artist's foil that I had on hand, Sturgeon appropriated two helical coils of wire from a magneto for his reconstruction. Joining these two coils in sequence, he sent battery current through one and took shocks from it alone, and both together (Figure 22, left). The second coil failed to enhance shocks so he dispensed with it and configured a single coil variously for shocks. In the process, Sturgeon rediscovered the shocking effect reported first by Jenkins and reinvented many of the tests by which Faraday extended it, while being unaware of their prior work. Initially ecstatic over 'bringing to light a novel principle' (1837a, p. 75), Sturgeon subsequently conceded Faraday's precedence in doing some experiments (Sturgeon, 1837b) and reprinted Faraday's paper in his journal (Faraday, 1835).

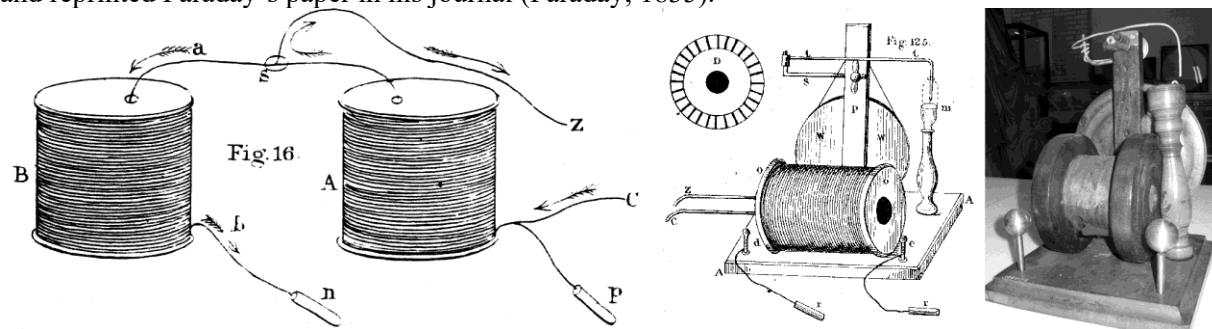


Figure 22. Left: Sturgeon's two linked coils A and B; he found the shock was not increased by adding coil B (1837a, plate ii, Fig. 16). Middle: Sturgeon's shocking coil where current flows through an inner coil and shock is taken from the handles *rr* of a second coil that is wound over the inner one (1837d, plate xv, Fig. 125). Right: Sturgeon's shocking coil in the London Science Museum (no. 1860-72).

²⁰In my unsuccessful attempt to reproduce 'galvanic music', the spiral mounting was so insecure that the current-bearing spiral moved into contact with the horseshoe magnet's pole.

Later when Sturgeon received Page's actual text, he grasped what he had misunderstood before. In republishing Page's paper, Sturgeon remedied Page's lack of interpretation by appending his own to it:

In every instance the phenomena may be traced to the *collapsion* of the electro-magnetic lines.

In some instances the phenomena proceeded from a *primitive* current; in others, from a *secondary* current; and in others from both *primitive* and *secondary* (Sturgeon, 1837c, p. 294).

'Primitive' current came direct from the battery; 'secondary' had another path. To illustrate each of the three cases, Sturgeon cited an example circuit from Page's paper. Sturgeon admitted that he too had not formerly understood that wires bearing these two currents needed to be located 'within the influence of each other'. With his new understanding from reading Page's paper, Sturgeon redid his experimental reconstruction – with wire coils, not with a spiral. Only after Sturgeon over-wound the secondary on his primary coil, was the combined coil's shock greater than that of the primary alone (Figure 22, middle, right). He marketed this instrument with a revolving contact breaker whose sparks combusted in differing colors (depending on its interchangeable metal discs) like the effect Page produced with his spur wheel tipped with metal leaf (Sturgeon, 1837d; Cavicchi, 2006a).

Sturgeon's published commentaries moved Page's thinking. Previously Page had not speculated about the spiral's electricity. As a result, Page wrote about it as an example of electromagnetic induction and made sense of such aspects as the interrupter's role. Subsequent experimenting developed his ideas so far as to reject an earlier, now 'irrational', view that conjoining 'primitive and secondary' currents (as in the spiral) was what produced shocks:

...the sparks and shocks indicating a new and secondary current are directly consequences of the dissolution of the primitive current...due solely to magnetic excitation, and have no connexion with that primitive, except that of cause and effect (Page, 1838b, p. 366).

Secondary currents did not offshoot directly from battery current, but instead arose from changes in a magnetic medium surrounding them, as envisioned in what Page called Sturgeon's 'beautiful theory of electro-magnetic lines' (Page, 1838b, p. 367). Page's acknowledgment of Sturgeon's contribution meant much to the recipient; Sturgeon excerpted it in the last publication of his life, adding 'I know of no philosopher more capable of close reasoning on electro-magnetics and magnetic-electrical physics than Prof. Page, M.D.' (Sturgeon, 1850, p. vii)

As spatial relations among coils and magnets became increasingly critical in Page's experimenting, he consulted the 'ingenious' Daniel Davis, Jr., first American manufacturer of electromagnetic demonstration instruments. Their collaboration was reciprocal. Davis refined Page's prototype devices and marketed them through his shop, trade catalogues, and textbook. Page illustrated his scientific papers with Davis' distinctive apparatus and acknowledged Davis' contributions to his work. The instruments and understandings that Page and Davis developed together elucidated electromagnetic phenomena elegantly and went into wide instructional use (Davis, 1838, 1842; Sherman, 1988; Greenslade, n.d.).

But before new instruments attained commercial viability, Page improvised them experimentally. Page reacted to Sturgeon's reports about iron core coils by constructing coils of varied dimensions, wiring, cores, and batteries and by testing their magnetic pull, sparks, and shocks. In revising his instruments, Page applied what he learned from these tests about the differing characteristics of primitive and secondary currents. For example, he employed thick wire to carry primitive currents, and thin for secondary.

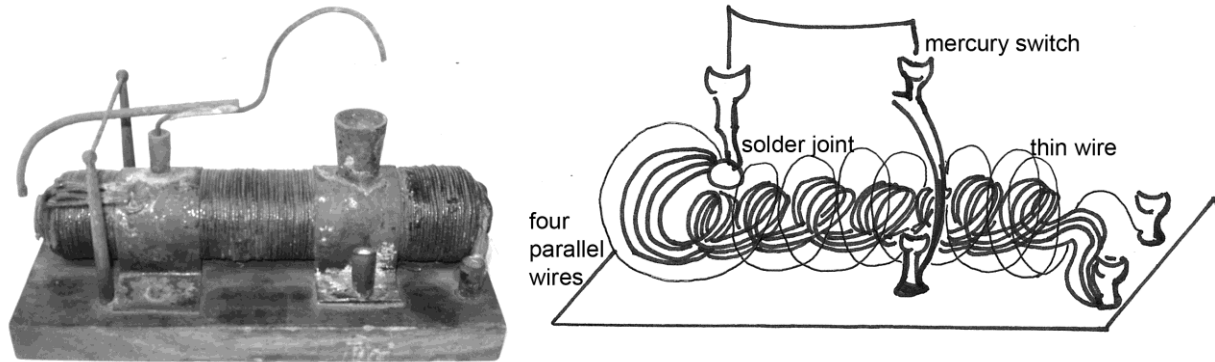


Figure 23. Left: Shocking coil number 2002.1.35088 in the Allen King Collection of Scientific Instruments, Dartmouth College. A solder joint on the Dartmouth shocking coil unites the four thick wires that bear current to the thin ‘secondary’ wiring from which shock is taken. Right: My diagram shows the coil’s solder joint and wiring.

A shocking coil that may represent the early Page-Davis association is now in Dartmouth College’s Allen King Collection of Scientific Instruments (Figure 23).²¹ Appearing to be a prototype, without Davis’s usual high craft, design features link this instrument to Page while its materials correlate with Davis. A similar, presumably subsequent, coil was first offered for \$8.00 in Davis’ 1838 catalogue and illustrated in Page’s 1839 paper and Davis’ 1842 textbook (Figure 24) (Davis, 1838, 1842, 1846; Page, 1839; Channing, 1849, p. 20; Garrett, 1876, pp. 49-50, 53).²² These publications describe an instrument having two separate, concentric coils: one for battery current; the other for shock. The Dartmouth instrument is wired differently (Pantalony et al, 2005). A solder joint affixes the secondary coil directly to the current-bearing coil. Shock may be taken either across the secondary alone, or across the combination of both coils.

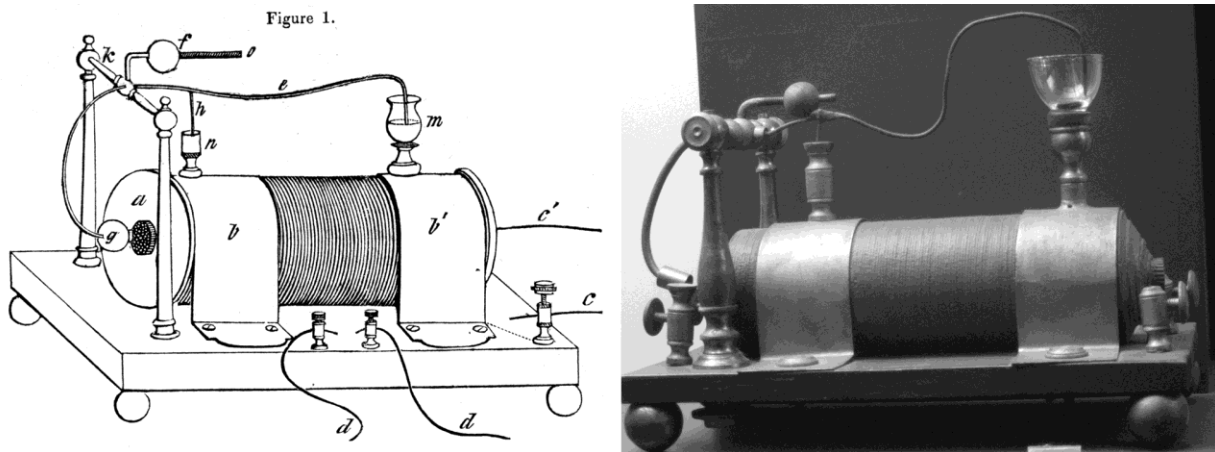


Figure 24. Left: Page’s double helix coil, where cc' are battery terminals and dd' are connectors for taking shock. The rocking wire e interrupts the primary circuit when the coil’s magnetism attracts iron ball g , lifting e from mercury cup m , giving rise to sparks in cup m and shocks at dd' (Page, 1839, Fig. 1, p. 258). Right: Page’s patent model for his double helix coil, displayed in the National Museum of American History, catalogue number 309,254.

This solder joint preserves the continuity between secondary and primitive paths that Page’s spiral first exhibited. It embodies the transitional moment before Page rejected as ‘irrational’ the notion that the elevated, shocking electricity depends on continuity between these two paths (Cavicchi, 2006). While the solder joint reflects ambiguity in understanding electromagnetic behaviours, it also accommodates multiple options regarding which parts of the coil can be used for taking shocks. Those multiple options, originating in the intermediate tabs of Page’s spiral, are eliminated in Davis’ commercial version of Page’s coil and in Page’s patent model of it (Figure 24, right), where shock was taken only

²¹The Dartmouth instrument, accession number 2002.1.35088, was listed in an 1870s inventory as ‘Page’s apparatus for shocks with mercury break’ (Pantalony et al, 2005, pp. 157-159; Cavicchi, 2006a, pp. 351-353).

²²Page’s 1868 patent model of this instrument is on display in the National Museum of American History in Washington DC, catalogue no. 309 254, accession no. 89 797.

across the secondary. The spiral's intermediate cups, and the coil's solder joint, were gone. Where these connectors opened up multiple options for electrical paths, the commercial instruments limited current to one fixed path instead. Being constructed to reproduce pre-existing effects, not create new ones, the commercial apparatus closed off experimental space and access to ambiguity.

The spiral had a further experimental history, but not in medicine where electromagnetic coils like Page's soon gained wide currency for electrical therapies.²³ Instead, it figured in landmark experiments with wireless transmission of electricity from place to place. Joseph Henry pulled pranks with his wireless apparatus by mounting a battery-interrupted spiral on one side of a wall and putting a spiral with handles on the other side so that someone grasping its handles received mysterious shocks (Henry, 1839, 1843). A half-century after Page's spiral experiment, Heinrich Hertz experienced a 'surprise' analogous to those Henry and Page encountered. Whenever Hertz electrically stimulated one spiral, sparks appeared in the air gap between ends of a distant spiral. The sparks' high frequencies (hundred megahertz) represented wavelengths long enough to make lab experimenting practical. This pivotal observation launched Hertz's research of the electric waves that Maxwell predicted.²⁴ Thus the spiral contributed to wireless communication, where the high frequencies amplified through spiral resonances transport electrical imprints of speech without any mediating body.

Conclusions

Page's spiral experiment opened up options for electricity's paths; these paths showed themselves to be more complex than simple flow between two endpoints. Electricity arose interactively inside conductors: Page experienced it as shocks from spiral intervals where he did not expect electricity to be. His body was both a constituent of those new paths, and a reporter on what was going on. It filled in where no measuring apparatus then available could, by sensing momentary pulses induced in the spiral's many turns.

Body and circuit are partners, with each being a locus for inquiry and intervention, in the experimenting of Page and his peers, from Volta through Faraday, Henry and Sturgeon. The instruments bear out this partnership: medical acupuncture needles became electrodes, and coiled conductors, therapeutic aids. The analogy goes further; Page opening up the spiral to probe its interior resembles a physician looking into the body. His thought experiment to put a mercury cup on every spire applies surgical precision to circuitual intrusions. Once inside, both body and circuit were baffling; the sensational observations disclosed electrical activity, but left the workings obscure. Page communicated his observations in all their ambiguity, proffering no explanations until a community extended his findings with their own.

Multiple factors confounded in the effects Page used and detected, and these melded together for him. Only through his later extensive experimenting with circuit breakers, batteries, and electromagnets of varying construction and wiring, did he work out such characteristics as induction's enhancement under abrupt stimulus, lengthened coiling, and differentiated thick and thin wires. Change in both time and space matter to electromagnetic induction: Page's spiral exemplified this by the *timing* of its switching and by its spiral extent in *space*. Time, space and magnetic lines changing in that space came to have interactive roles in Faraday's more mature thinking about fields. Yet in the late 1830s, years before Faraday began investigating thoroughly what goes on in a powerful electromagnet's gap (Gooding, 1980, 1981; Cavicchi, 1997), Page, Sturgeon, Henry and others had already engaged directly with electromagnetic field phenomena. Although lacking the field analysis that pervades subsequent science

²³J. B. Zabriskie, physician in Flatbush, Long Island, reported on his experimental spirals (1837), but the spiral did not become a standard medical device. The electromagnetic coil's medical context is described in reference to physician Golding Bird in (Beard & Rockwell, 1871; Morus, 1998).

²⁴H. Hertz described his work with 'Reiss or Knochenhauer spirals' (1892/1900, p. 2). The experiment is discussed in (Buchwald, 1994, pp. 217-227). Further references to historical experimenting with spirals are given in (Gluckman, 1993).

and engineering, they worked productively with the whole web of electromagnetic effects and ambiguities to develop instruments that manifested and amplified inductive behaviours.

Faraday, Henry, Page, Sturgeon and I responded to instruments and reports of others through initiating experiences of our own with apparatus culled from whatever was ready at hand – including hands! None of these reconstructions of self-inductive phenomena literally redid effects of the others. Each engaged with ambiguity by differing forms: from those entangled with the phenomena, such as Page's 'equivocal' Leyden jar tests and my variable voltage traces; to others compounded by such sketchy communications as Henry's hasty notice or the Salem traveller's faulty memory; to the ambiguity of evolving one's sense of what is going on through proposing and doing new experimental work. As diverse as these instruments and experiences were, the experimenting interrelated, to retrace and open new options that kept extending the work. The participants' emerging understandings of electromagnetic induction were overlapping but not identical, enriched by the particular observations and paths of each.

My reconstruction of Page's experiment recovered something of those past experiences of dealing in the unknown. My observations following electrical effects across ever-wider spiral intervals did not readily confirm Page's sensations of heightened shock. If Page's experiment had translated directly into my improvisations and instruments, my project might have concluded as a success in replication while remaining unaware of the experience with ambiguity that was core to the original investigations. In this sense, my experimental journey re-expresses what Page's biographer, Robert Post, described as Page's engagement with 'the baffling complexity of things' (Post, 1976b, p. 26-7, quoting Beard, 1927, pp. 741-742). That complexity, both in nature and our curious responses, becomes hid from view by subsequent formalized and purpose-driven packaging that, like Davis' commercial coil, constrains the options for engaging it around a particular favoured outcome. Where such options are limited and ambiguity is masked, it is hard to explore; we suppose we know in advance where any path will go.

A challenge inherent in reconstructing a past experience lies in recovering our access to complexity and ambiguity sufficient that genuine opportunities for investigation emerge from options which under present practices and knowledge might be unnoticed, discounted or unexpected. Those options and inquiries may take on different forms for us – for example, here requirements of health and safety reframed the instrumental context. Our involvement with historical and reconstructive material deepens through coming upon passages in the work that open our vulnerability, such that we can find ourselves in ambiguity and begin to explore.

These reflections spiral back to my aspirations as a teacher seeking to facilitate exploratory experiences among students. Conventional practices in classrooms make daunting the challenge of engaging students in their own genuine, sustained experiences with the 'baffling complexity' of any subject matter. The prevalence of didactic explanations, along with students' expectations for such answers, closes down options, leaving nothing to explore. Historical reconstructions offer evidence of what an alternative pedagogy might encompass: on going into a material seemingly well-known, the learners find there the unknown, not just about what someone else already did, but also within their own understandings. For historical investigators like Page, widening personal experience supported by a community made possible their unique exploratory work; similarly there is a role for educators to bring about environments where each student's curiosity evolves by undertaking its own explorations in relation with a community of other explorers.

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