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Elizabeth Cavicchi

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Introduction

This paper describes details of one electrical experiment that Charles Grafton Page conducted in Salem, Massachusetts, in 1836. This experiment – involving spiral conductors and batteries – was an important step in the development of the induction coil. Page's experiment ignored barriers present in modern science between body and knowledge, and exemplified a fluid and dynamic approach to knowledge that did not require or presuppose grounding in scientific theory. I explore Page's experiment from several angles, including historical accounts of the experiment, context provided by other accounts, and my own exploration of a spiral apparatus using modern equipment. These accounts combine to provide a story of science without barriers, a fluid attitude toward knowledge, and a sense of wonder and curiosity that eventually led to the development of the induction coil.

Routine outcomes trivialize complex means: tripping a switch that lights a room, we are oblivious to electrical behaviors, technologies and history that make this outcome possible. By contrast, outcomes and means merged confusingly in electrical experiments done early in the nineteenth century. How an experiment occurred mattered as much as what happened. Experimenters were literally inside the experiments that they devised, even to the extent that their bodies conducted some of the electricity.

FIG. 1. Charles Grafton Page. (Robert C. Post collection. Reproduced with permission)

Charles Grafton Page worked resourcefully within this complex environment and made substantial contributions to instruments, experimental practice and how people understood electromagnetism (fig. 1). Page was still a Harvard medical student when doing the 1836 experiment discussed here. With it, he detected electricity where no one had expected it to be. His bodily sensation of shock demonstrated its presence.

Inseparable from that surprising outcome were the innovative means by which he probed electricity and expanded his research. Page opened up an electrical circuit that others had treated as closed, and he did this in multiple ways. Many possibilities emerged, both for experimental tests, and for interpretation. By tolerating the ambiguity that went with all these possibilities, Page was able to continue noticing more. Thus he generated a broad base of experience that served him well in his subsequent work as U.S. Patent Examiner, and in projects such as his electromagnetically powered locomotive. [1]

For us to appreciate Page's experiment , it helps to recall what it is like when ways and means matter, and outcomes are uncertain. I put myself into such an environment by redoing Page's 1836 experiment. My interest was not to match his set-up literally, but rather to engage with the phenomena in ways that opened up experimental possibilities new to my experience, and that brought me into contact with ambiguity. Like Page, I found this ambiguity to be productive in extending my investigation and experience. Thus my redoing was parallel to the kind of experimental life in which Page excelled.

There is little mention of Charles Grafton Page in accounts of nineteenth-century American science and technology. Perhaps part of the reason for this is that standards for success in science and invention emphasized outcomes, status, and conformity with a code of behavior from which Page strayed. This study looks closely at one experiment and provides an alternative view of Page's contribution. Page's inventiveness with materials and scientific thinking depended upon his ability to work productively with ambiguity and uncertainty. Whereas the author found this process to be critical, the reader will need to adapt to it, too.

Physical and Cultural Boundaries involving the Body in Experiments

Page's 1836 experiment used his body in many ways.[2] He built most of the apparatus himself; he set it up and revised its setup with his hands. To activate the apparatus, either he, or an assistant, lowered a battery connector into a small cup of mercury. To find out what was going on, he visually looked for sparks and audibly listened to their crackling sound, and he qualitatively compared these. He put his body into the electrical circuit by holding metal handles that were connected to it. He felt shock in his hands and arms and compared its strength when the experiment was set up in different ways. When the shock became too feeble to sense with his hands, he poked needles through the skin of his finger tips. The needles connected to the circuit to apply shock to the fingers.

While Page introduced new kinds of observations involving the body and the circuit, his use of the body reflected common practices for observing the electricity produced in batteries. When Italian investigator Alessandro Volta announced his landmark chemical battery to the British Royal Society in 1800, he used only his body to link its two ends.[3] Immersing one hand in a basin of saltwater that connected to the battery's bottom, whenever he touched the other hand to its top, he felt shocks whose painful extent ranged from the fingertips to his elbow (fig. 2). Volta tested the response of every bodily sense to this new electricity. Applying it to an open wound, his tongue, his eyeball, his eardrum and the interior of his nose, he felt pain, tasted acid, sensed light, experienced a frightening noise, and smelled nothing. These sensations arose only when the circle between the bodily part and the chemical battery was fully complete. Any break or gap in that circle stopped the electricity, and the bodily response.

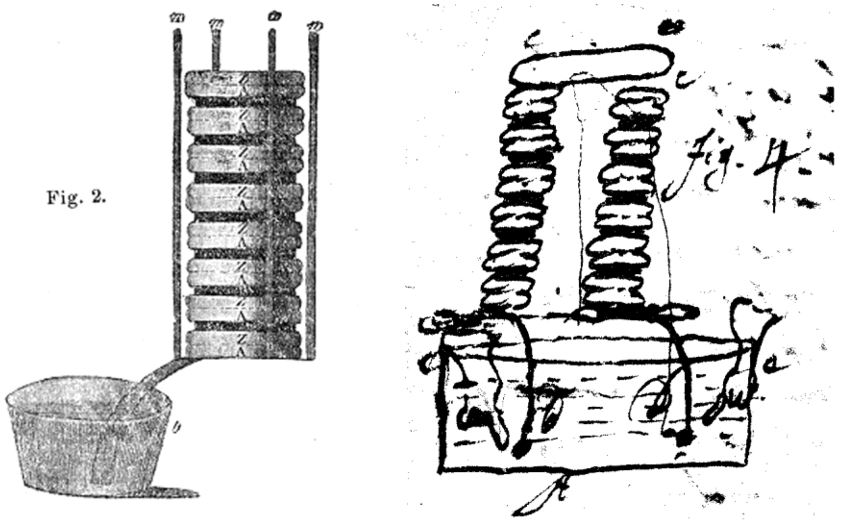

FIG. 2. Left: Volta's alternating pile of silver (A), zinc (Z), and moist cardboard, terminating in a salt water basin where he placed one hand, while putting the other at the top of the pile to receive a shock (Source: Volta, "On the Electricity Excited by the Mere Contact of Conducting Substances of Different Kinds," *Philosophical Transactions* 90 (1800): 403–31.) Right: Volta's sketch showing how his hands made contact with the two ends of a double pile. (Source: Volta, *Le Opere di Alessandro Volta*, vol. 1, [1918], pl. XXII, reproduced courtesy of the Instituto Lombardo Accademia di Scienze e Lettere, Cart. Volt. J68.)

Whereas Volta used the body to observe the physical property of the electric "circle,"[4] others saw in the body's response to electricity a venue for exploring the senses and medical therapy. Germans Alexander von Humboldt and Johann Ritter probed their body's limits to extremes of electrical stimulation by plunging electrodes into scalpel incisions, open wounds, and the eye.[5] By contrast, medical therapies were intended to heal the body; many disorders related to the nervous system were already treated with electricity discharged by eighteenth-century friction machines.[6] When voltaic electricity became available, it was tested as a treatment in similar contexts.

In contrast with friction-generated electricity, the lower "tension" (voltage) and greater quantity (current) of voltaic electricity made it more difficult and risky to administer. The body's skin has a high resistance to electricity that blocks low voltage currents. To get around this resistance, physicians cut under the patient's skin in order to put the electrodes into contact with receptive tissues. British surgeon Charles Wilkinson innovated the more humane placement of metal discs (attached to electrodes) over wet skin.[7] The wide area of the discs and the moist surface combined to improve electricity's transmission into the body. French physicians employed an alternative tactic of directly piercing the skin; this arose as part of their efforts to reintroduce the Chinese method of acupuncture into Western medical practice.[8] Since acupuncture sometimes felt like shocks, the French interpreted its needle "as a true lightning rod" accessing the body's inherent electricity. They extended traditional practice by attaching a voltaic battery's terminals to acupuncture needles that convulsed tissue intervening between them.[9] While Page was in medical school, these techniques gained notice in America. One physician wrote "acupuncture is entitled to far more attention than it has yet received in the United States."[10]

Analogous to the bodily boundary provided by the skin, which has to be transgressed to get electricity through it, other bodily boundaries are involved in experiments, and sometimes transgressed during them, that have cultural dimensions. In their edited volume *Science Incarnate*,[11] Christopher Lawrence and Steven Shapin offer biographical commentaries regarding the Western cultural convention to divide knowledge outcomes from the bodies and material processes that make knowledge, and to ascribe a higher status to knowledge than to the body. Under this cultural tradition, investigators' bodies impeded their search for truth. Ailments they suffered were regarded as testaments to their oblivious immersion in non-bodily, higher status pursuits. Cultural archetypes about workers' bodies reinforced this image, such as the emaciated scholar whose affairs are wholly of the mind or the rotund surgeon who attends to things of the flesh.[12]

These cultural conventions exerted real power on what people believed, favored, and admonished in regard to the body, knowledge, and how body and knowledge interrelate. As American science became a profession in the late nineteenth century, the pursuit of science became self-identified as an elite undertaking, not open to all. The cultural mores by which scientific status was conferred or removed functioned to widen the split between "pure" knowledge and base means of production (including the body). In *Suffering for Science*, Rebecca Herzig describes a culture in professional science that extolled and rewarded voluntary bodily sacrifice made in the service of higher, disembodied truth.[13] While the body was an inextricable part of the investigative activity, its subjugated role demonstrated the sharp cultural boundary between body and knowledge.

The culture of science that developed in the decades after Page's death lacked the means to acknowledge the usefulness of a fluid relation among body, experimental materials, and inferential thinking, such as Page, Volta, and others practiced. Given the cultural boundaries then in place, historians and scientists of this later era might not look to work such as Page's for meritorious examples. Lawrence and Shapin argue that present-day science and history also function under cultural boundaries that divide bodies from knowledge. However, today these boundaries reflect a situation different from the late nineteenth century. In their view, with the rise of expertise, boundaries that had privileged one kind of body or bodily involvement over another, are no longer (so) controlling of what it is believed it takes to do a job. Any body will do, and there is no longer a cultural value in denigrating the body's role.[14]

Both physical and cultural boundaries protect and regulate the body's participation in experimental activity. Page worked fluently among and through these boundaries in ways that others did not, and later often could not. Page's fluency in manipulating the boundaries between body and experiment was one means by which he extended the possibilities of his experimental work into new and fruitful areas.

Precedent Experiments by Henry and Faraday

The experiment that Page did in 1836 was a response to one that he read about in a brief notice appearing in the *American Journal of Science* in the preceding year. It said that Princeton professor Joseph Henry had produced a means of delivering electrical shocks whose maximal severity was "not yet determined."[15] The device was just a long wire or conductor with handles at either end, directly connected to the terminal poles of a large single cell battery (fig. 3, left). Anyone holding a handle in each hand would feel a shock whenever the contact broke between battery and wire. A spark also appeared at the spot where the disconnection occurred. That shock or spark was greater if the wire were coiled. Henry found that the shock was further intensified if the conductor, instead of a being a coiled wire, was a wide ribbon of copper, wound into a spiral (fig. 3, right).

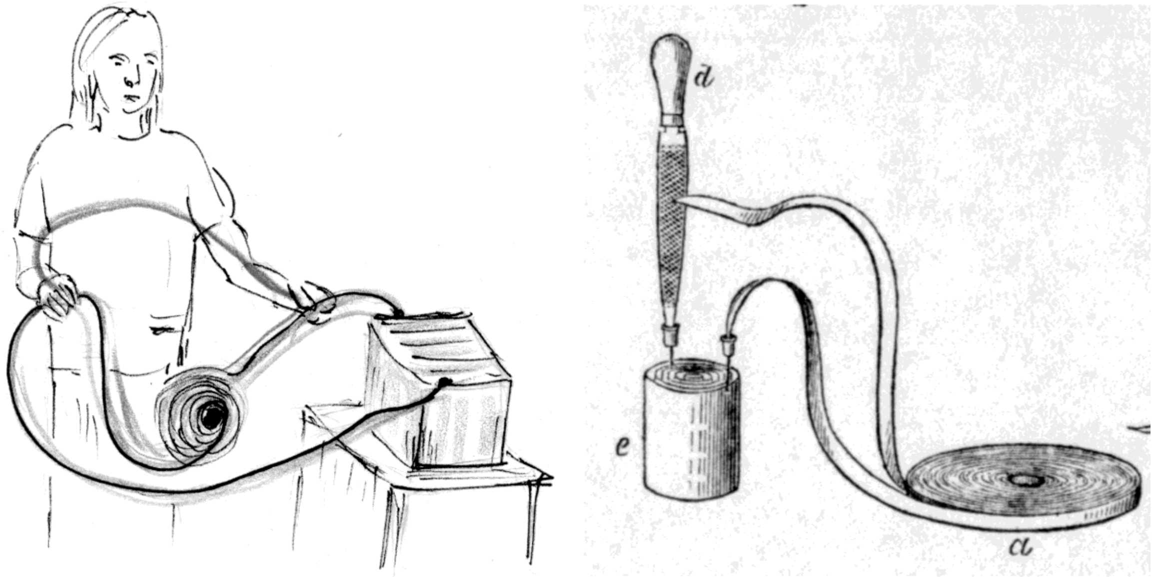

FIG. 3. Left: A person holding both ends of a coil feels shock when the coil breaks its connection to the battery (Source: author sketch). Right: Henry's sketch of his spiral, battery, and rasp interrupter. (Source: Henry, "Contributions to Electricity and Magnetism, No. III, On Electro-Dynamic Induction," ***Transactions of the American Philosophical Society*** **6 [1839], fig. 1, 304.)**

Henry announced these results before investigating the behavior more fully, because Michael Faraday of the Royal Institution in London had already published his work describing shocks that he felt when holding a wire coiled around an iron bar.[16] Faraday's report had not mentioned Henry's prior, but rudimentary, observation of it. Henry followed up on his old finding by doing some new experiments, by which he came upon the shock-enhancing property of the spiral conductor (fig. 4). Anxious not to lose more ground to Faraday while at the same time acknowledging Faraday's precedence, Henry gave a talk and sent out a hastily prepared abstract.[17]

Henry's shock results were surprising in several ways. Volta had felt shocks only while his bodily connection to the multi-cell battery was complete, not when it stopped, as observed here. Volta found it necessary to stack multiple cells (twenty or more) sequentially in order to feel a notable severity in those shocks. The large single cell batteries (called calorimotors[18]) that experimenters in Page's day used to observe electromagnetic behaviors, ordinarily did not shock experimenters even when current coming directly from a battery went through their hands. Battery current from a single cell (fig. 4, top right) was too low in "intensity" (voltage) for one to perceive a shock. Faraday interpreted the coil experiment as a variant on his landmark 1831 discovery that the stopping of current flow in one wire induces a brief current in a nearby independent wire.[19] The electricity that gave a shock *after* battery connection broke was different from the battery's output current. In Faraday's view, when that battery current suddenly stopped, a momentary electricity arose in the wire coil, going in the opposite direction from the battery's output. This new electricity had high enough intensity to shock someone or spark in air.

FIG. 4. Left: A spiral conductor used by Joseph Henry. Upper Right: A two-cell voltaic battery used by Joseph Henry. Lower Right: Close-up of the fabric insulating the turns in the Henry spiral on left. (Source: National Museum of American History. Henry spiral is catalogue number 181,540; Henry battery is catalogue number 181,746.)

Henry's claim, that a spiraled conductor gave strong shocks, caught the eye of twenty-four-year- old Page. Page improved it and sent his own brief four-page write-up to the *American Journal of Science* as a response to "Prof. Henry's apparatus."[20] He was unaware of the background in Faraday's research that had inspired Henry, or of Faraday's analysis of the currents. Thus, he worked in an environment of the unknown, where what he did, observed and wondered about were key to developing his experience.

FIG. 5. Left: The Salem, Massachusetts, home where Page performed his spiral experiments. (Photograph by the author, 2008.) Upper Right: A homemade glass bottle friction machine such as Page might have made as a child. (Photograph by the author, 2001). Lower Right: Plaques appearing on the former Page residence today. (Photographs by the author 2008)

Page's Experimental Instrument

Page's lab was at his parents' home in Salem, Massachusetts (fig. 5). He had been fascinated by electricity from childhood. The ten-year old Page turned his mother's lamp glass into a friction electrical machine (fig. 5, top right). While at Harvard College, a charismatic young Page organized a chemical club where he lectured peers on electricity. During his medical school studies, Page built and tested voltaic batteries at home.[21] Through these pursuits, he developed the expertise and workspace which provided the requisite resources for his ground-breaking experiments.

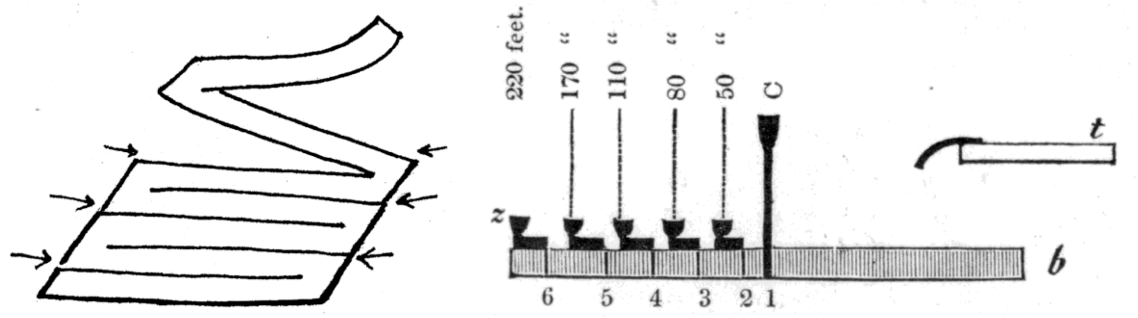

FIG. 6. Left: My diagram of the Page's method of slitting a copper sheet from opposite sides (arrows) so that it would open as a zigzag strip. Right: Side view of Page's spiral showing connector cups spaced across its length. (Source: C. G. Page, "Method of Increasing Shocks …," ***American Journal of Science*** **31 [1837]: 137.)**

Page improvised his spiral using materials at hand. Lacking a spool of copper ribbon, he constructed strips from flat sheets of copper. He did this by alternately cutting partway into each sheet from opposite ends and then unfolding from it a single zigzag 55-foot strip (fig. 6, left). The strip had to be bent over itself at each reversal to make it flat. Page preferred this irregular construction to what he saw as the alternative: soldering potentially fallible joints between many short segments.[22] Page joined the strips end to end. He wrapped the whole combined length in fabric insulation and then wound it into a compact spiral. At 220 feet in length, Page's first spiral was more than double the length of Henry's.

The distinctive feature in Page's spiral instrument was a series of conductive "taps" giving access to different points along the spiral's length (fig. 6, right).[23] At four unequally spaced places along its length, as well as at the two ends, Page soldered a metal post. At the top of each post went a thimble cup filled with mercury, commonly used at the time by researchers for electrical connections.

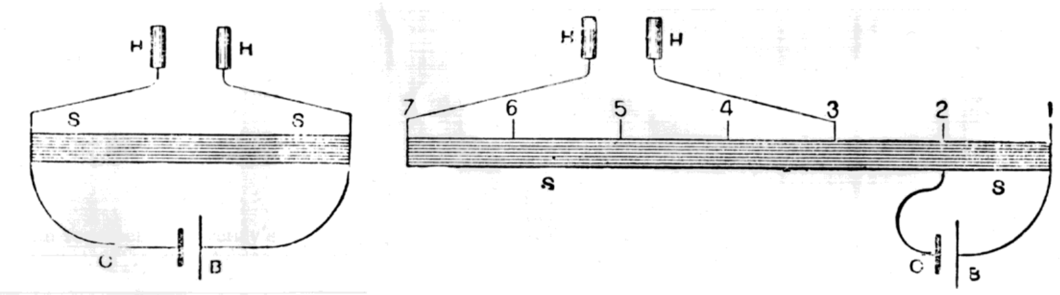

FIG. 7. Left: Henry's spiral unwound; the shock is taken across the handles *HH*, while the battery is applied across the same span. Right: Page's spiral unwound; the shock may be taken across parts of the spiral that may differ from the segment carrying the battery current. (Source: J. A. Fleming, *The Alternate Current Transformer*…, [London, 1892], vol. 2, fig. 1 and vol. 6, fig. 2.)

This design was innovative. Usually, each connector in an electrical device connected to one pre-specified battery terminal to complete a fixed circuit. In the circuits of Faraday and Henry, only the entire conductor (coil or spiral) could be connected to the battery and body (fig. 7, left). To test a longer (or shorter) conductor required substituting a different conductor. With Page's intermediately placed cups, the same conductor could bear current along either all or part of its length (fig. 7, right). Positioning cups at different radial positions provided diverse options for connecting the spiral with battery and body.

Page's Exploration of the Spiral

Page became aware of the diverse experimental options that his design allowed while experimenting with the instrument. Intriguing new electrical phenomena arose as he discovered and tested each option.

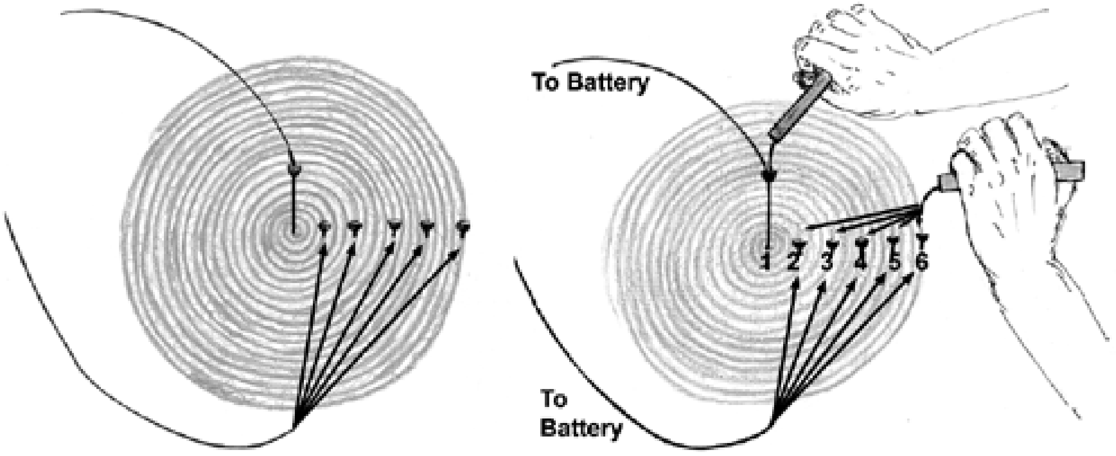

FIG. 8. Sketches of top view of spiral. Left: Battery current is applied by one wire to the central cup and by the other wire to each of the other cups in turn. Sparks appear when either connector is removed from its cup. Right: Battery current is applied between the central cup and each of the others in turn. The hand grips are inserted into the same pair of cups. A shock is felt when a battery connector is removed.

Page started by exploring the effect of extending the length of the spiral through which current passed. Fixing a connection from one battery terminal on the innermost cup (1), he immersed the other battery terminal's connector briefly in the next cup (2, fig. 8, left). On removing it, he observed sparks. Next, he repeated the same procedure by first placing, and then removing, the second terminal connector from each mercury cup in succession (cups 2 through 6). At cup 3, the sparks flared brightest and electricity snapped loudest. As he went on to add in more segments (at cups 4, 5, 6), the spark and snap diminished. In a footnote, Page suggested that if cups were soldered onto every turn of the spiral, it would be possible to "accurately" determine where the turnaround in spark brightness occurred.[24]

Setting up the apparatus to take shocks was more complicated than watching sparks, and the comparative findings came out differently. Page grasped in each hand a metal handle having a prong that dipped into a mercury cup. Since his hands were occupied, an assistant opened the circuit by removing the outermost battery terminal from its cup. Page kept one hand-held prong in cup 1, where the inner battery terminal was placed and remained. Page put the prong held in the other hand in each of the other mercury cups in succession (2 through 6, fig. 8, right). As the assistant raised the terminal from each of these cups, Page experienced shocks of increasing severity. Unlike sparks whose brightness peaked with half the spiral in the battery loop, shocks strengthened as that loop extended out to the entire spiral.

Page then had the insight to explore another set of experimental options. The battery's connectors and the body's connectors could be inserted across different spans of the spiral, independent of each other. On testing these configurations, Page obtained outcomes that startled him even more: "curious …difficult to explain."[25]

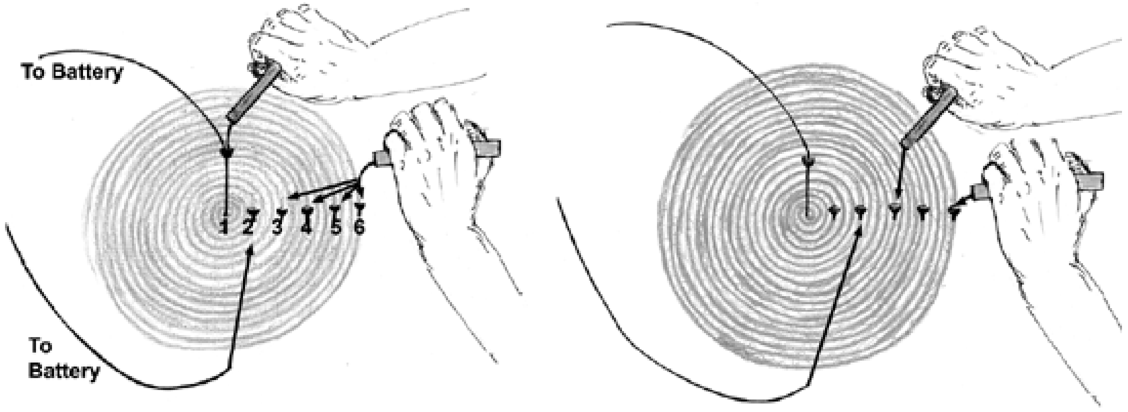

FIG. 9. Left: Battery current is applied between cups 1 and 2. Shocks are taken across cups 1 and 3 (4, 5, and 6) in succession. Right: Battery current is applied from the central cup to cup 3. A shock is felt when handgrips are placed at cups 4 and 6.

First, he put one battery connector at cup 1 and the other at cup 2. While the battery current was confined only to flow (or stop flowing) between cups 1 and 2, he connected the handgrip to cup 1 and the other handgrip to cup 3. When the battery connection broke, Page reported a greater shock than if his hands spanned just cups 1 and 2 to which the battery was connected. This shock increased when he relocated the second hand grip to the outer cups (4, 5, and 6; fig. 9, left), while leaving the battery connectors positioned in cups 1 and 2.

Next, Page tried out the effect of sending the battery current through longer spans of the spiral, such as from cup 1 to cup 3, or from cup 1 to cup 4 (covering half the spiral's length). While the battery current was applied in each of these configurations, he positioned one hand grip at cup 1, and put the second hand grip at cup 3 (or cup 4) to take the shock. Then he tried to feel the shock when the second hand grip was located at each of the outer cups (4, 5, 6; or 5, 6) in succession. He reported that the instrument delivered its greatest shock when the battery current traversed half the spiral (from cup 1 to cup 4) while his hands spanned it all (from cup 1 to cup 6). By comparison, when battery current passed through the entire spiral (from cup 1 to cup 6), its cessation produced a lesser shock for hand grips positioned at cup 1 and cup 6. This observation gave Page grounds to propose that spiral turns beyond the current's path operated electrically by some means which he termed "lateral cooperation."[26]

Page was further astonished by what happened next. "Contrary to expectation," upon stopping battery current flowing through the inner turns (cups 1 and 3), he felt shock while his hands spanned only the outer ones (one hand at cup 4; the other at cup 6; fig. 9, right). The shock was so feeble that Page amplified his sensitivity to an "extremely painful" level by piercing needle conductors into his thumb and finger.[27] This technique, adapted from acupuncture, allowed Page to use a battery of modest size, rather than a great calorimotor like Henry's that output high currents.[28]

Something was happening even in parts of the coil where no direct current had been connected. With each new phase of trials, Page looked yet more deeply into the spiral's function as a conductor, to uncover unexpected electrical activity. Electricity did not simply go from the battery's input point along the conductor to its output point, and it did not abruptly stop when the battery connection broke. It was somehow active throughout the conductor. Its intensity was differently expressed across various portions of the spiral after the main current ended. Recognizing that these behaviors did not agree with "the received theories of electromotion,"[29] Page experienced ambiguity and confusion. He did not rush to mask that confusion by speculating in print about an explanation. Instead, his wonderment and thoughtful curiosity acted as the stimulus to raise new experimental possibilities, such as where to probe the spiral, and ways to amplify its effect or his sensitivity to it.

I came upon the account of Page's experiment in the context of studying and recreating the development of the induction coil, a nineteenth-century instrument that produced electricity at high enough intensity to spark through significant air gaps, having only a low-intensity input battery.[30] Page's spiral conductor is unique in the early phase of the induction coil's history.[31] It is among the earliest devices to exhibit electricity of heightened intensity in a conductive path that is beyond the path of direct battery current. Page argued for recognition in this regard himself. At his life's end in 1868, Page successfully persuaded the U.S. Congress to grant him a retroactive patent as the induction coil's originator, based on his 1836 spiral and subsequent inventions.[32] In doing so, he ensured financial security for his heirs. However, by seeking monetary gain for intellectual work, he transgressed a cultural boundary and negatively impacted his legacy as a scientist.

Redoing Page's Experiment

For me, Page's paper linked to a fascinating phase in the induction coil's development. Evidences of new complex phenomena emerged interactively as investigators revised experiments and instruments in response to what they found.[33] Being flexible while experimenting facilitates notice of further physical behaviors which are unexpected, such as when Page took shocks from cups 4 and 6 that were outside the battery current's path. Historians have described similar experiences in the early research of electromagnetism around 1820. In accounts of investigations done by André-Marie Ampère and Faraday during that period, Friedrich Steinle identified characteristics of "exploratory experimentation," where an interlinked process of experiment and thought evolves without explicit theory.[34] Page's experiment exemplifies this process of exploration in the context of probing the electrical response of his spiral conductor.

Since exploration within an environment of ambiguous behaviors is distinctive in Page's experiment, my effort to understand and redo Page's experiment also needed to reflect that by some means. A reproduction of Page's experiment that took an unequivocal path to match his outcomes would not represent the core of what he did. Redoing an experiment for purposes other than literal verification of facts is a method of historical research.[35]

Not all experiments are alike. For historians practicing this method, ambiguity and other features distinctive to an experiment always arise in the course of redoing it. These features engender insights, whether or not the historical project produces more clarity about the specifics. For example, Klaus Staubermann found it more challenging to perform bodily motions in the complete darkness that is critical for astronomical observation, than to operate the nineteenth-century telescope photometer that was the formal topic of his study.[36] Peter Heering discerned differences in the underlying context of experiments conducted during different historical periods. While Enlightenment era experiments promoted audience participation and entertainment, subsequently the emphasis in experimenting shifted toward precise instrumental work aimed at verifying theories.[37] Staubermann and Herring had to adapt their understanding of these experiments while repeating them. Both for the historian-experimenter and for the original investigators, having a flexible outlook is a key asset in recognizing the relevance of features that may not be explicit and could be unexpected.

My Spiral Experiment

As with these prior studies, my outlook continually evolved during my project to redo Page's experiment. Initially, I assumed that it would be straightforward to demonstrate his basic electrical findings. It was not. In trying to uncover more about what was going on, I worked with techniques and instruments that were not available in his day and were new to me as well. My own instrument, and questions that arose for me in using it, became a focus that set off many series of experimental tests. While my experiment seemed to diverge from what Page literally did, it echoed the experience of working in ambiguity and opening up multiple options for investigation.[38]

While Page worked in a lab stocked with homemade apparatus, I worked in the Massachusetts Institute of Technology Edgerton Center with equipment that I either assembled or learned to use during my project. Just as Page started from materials that were on hand, similarly I started with items readily accessible today. Page constructed an electrical analog to Henry's spiral out of copper sheet; I devised an analogue to Page's spiral from copper tape intended as edging for panes of stained glass (fig. 10). This conductive foil spirals outward in an unbroken path. Its paper backing insulates successive turns from each other, similar to the effect of Page's fabric. At intervals along the spiral, I soldered copper strips like Page's cup supports. In place of mercury cups, I used alligator clips to connect my spiral to other apparatus. Where Page broke the flow of battery current by removing a terminal from a mercury cup, I initially used a mechanical switch and later tried many other techniques. I substituted two D-size flashlight batteries or a 3-volt power supply for Page's calorimotor.

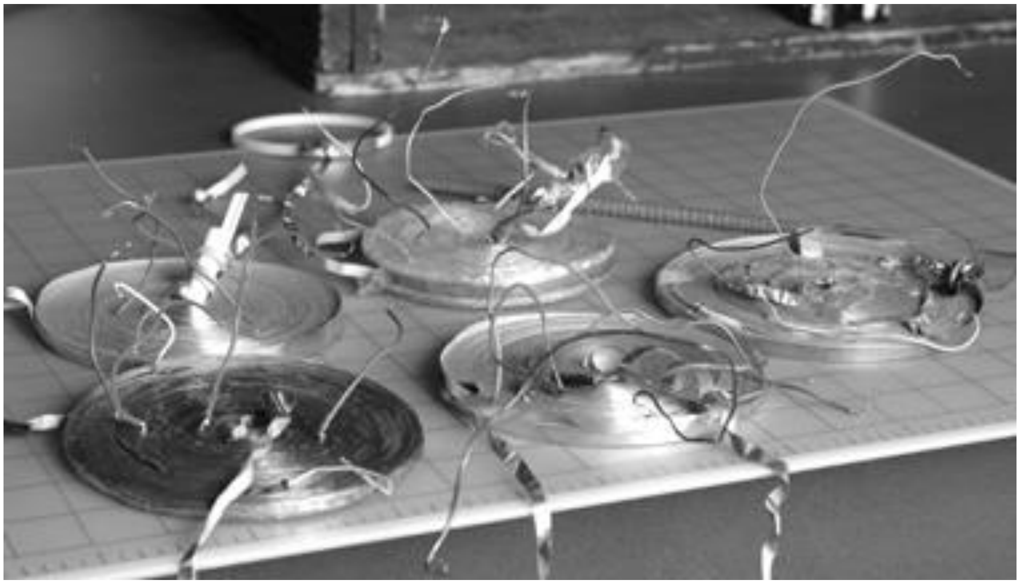

FIG. 10. Several spirals used in my project, made from copper tape used in stained glass art. (Photograph by Omari Stephens.)

Whereas Page relied on his bodily sense of shock to detect electricity, I did not. The boundaries regarding the body's use in lab work are defined differently in today's culture from those in Page's time. Bodily electric shock and liquid mercury exposure are now known to be dangerous and treated as safety hazards.[39] While I sometimes experienced shock accidentally, and once had the opportunity to use liquid mercury,[40] I do not employ these risks routinely. Similarly, I work with much lower electric currents than the amperes output by Page's calorimotors. Since my spirals were much smaller in scale than Page's, these lower (and safer) currents were adequate to produce interesting electrical effects.

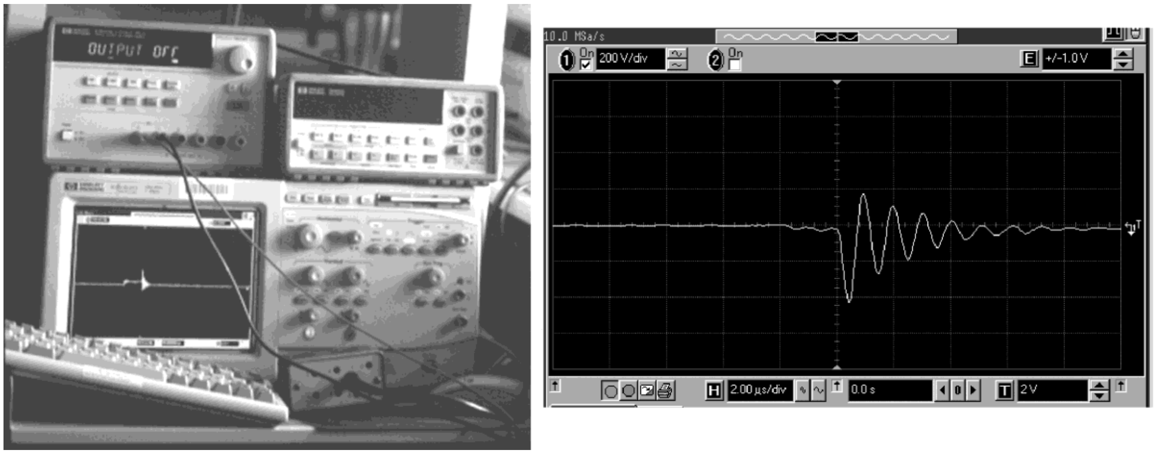

FIG. 11. Left: Digital oscilloscope with display screen; power supply and function generator are on top. Right: A trace from the oscilloscope, showing how the voltage (vertical) changes in time (horizontal) when the switch opens.

In analogue to the function that Page's body played in detecting electricity, I used a storage oscilloscope.[41] This instrument displays the signal voltage picked up by its probes, as a trace on a two-dimensional screen, where voltage is on the vertical axis and time is on the horizontal (fig. 11). As the trace is repeatedly redrawn across the screen, its excursions up and down indicate changes in voltage occurring during the time interval represented by the horizontal axis. This time scale can be varied across many orders of magnitude, as can the voltage scale applied to the vertical axis. Signals that are stable in voltage appear as straight horizontal lines on the screen. Signals that occur only sporadically or in one trace, such as those produced on breaking the spiral's battery connection, are obscured by the next trace unless a storage feature of an oscilloscope is used to retain it.

A typical trace produced within my spiral showed a voltage spike of several hundred volts, followed by lesser peaks spaced microseconds apart (fig. 11, right). Treating this trace as a proxy for Page's sense of shock, I interpreted traces showing greater excursions in voltage as representing circumstances where Page might have reported greater shock.

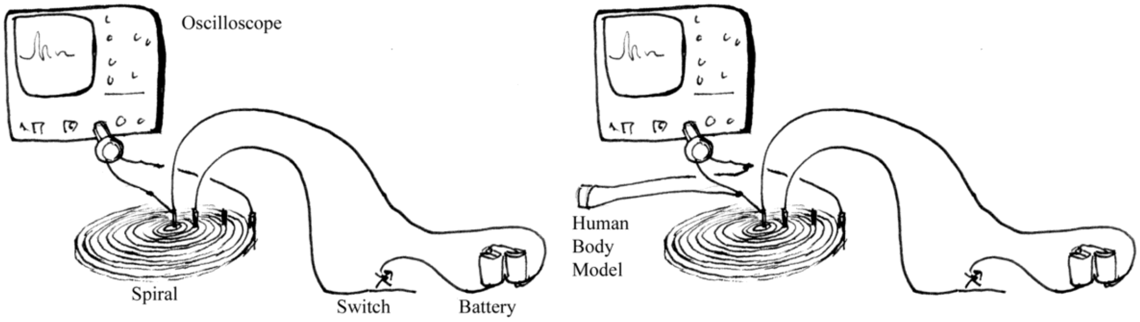

FIG. 12. Left: My circuit where a battery connects across part of the spiral via a switch, while a high voltage probe from the oscilloscope connects across another spiral interval. Right: The human body model (such as a resistor) is connected in parallel with the oscilloscope probe.

Working with these materials, I followed Page's practice by connecting a battery across part of the spiral and putting the oscilloscope probes across that same part, or some other part (fig. 12, left). Upon disconnecting the battery, I observed the trace and noted its peak value. Then I changed the connections, switched the battery on and off, and observed the next trace. In the first phase of my project, I sketched these traces by hand; later I used a digital storage oscilloscope to save each trace into a computer file for later analysis.

I expected that the voltage peaks of these traces would be greater when the oscilloscope probe covered more of the spiral and when the battery connected more of it. But this kind of trend did not appear consistently. Finding it hard to recall and compare the signals taken across different parts of the spiral, I tried using two probes at once, placed across different parts. However, adding the second probe changed the signal on the first.

In discussing with others what might be going on, an overlooked difference between my circuit and Page's emerged. What if Page's body contributed to the electrical behaviors he described? Oscilloscope probes present very high resistance to electric current, but the body does not.[42] Through the confusion raised by my experimental outcomes, I came to consider that the body might be an active part of the circuit, not an uninvolved detector like the oscilloscope. In this way, my thinking about the historical experiment crossed a boundary regarding bodies and circuits – between perception and participation – that I had previously treated as closed.

Having modern and safer means, I did not need to put myself into the circuit in order to explore this possibility. I looked into various measurements and models of the human body's electrical properties.[43] The simplest model represents the body as posing a resistance to the flow of current. This resistance is high for dry skin, low for tissue. To simulate this, I inserted an electrical resistor into my circuit, across the oscilloscope probe (fig. 12, right).[44] Still, the voltage did not always increase where I expected it to, and it was confusing to remember and compare subsequent traces.

For a time, I suspended experimenting with my spiral; experimenting stalled due to unmet expectations. Instead I wound multilayer iron-core coils having connection points at the different layers. When I connected battery and oscilloscope to these coils in configurations like those I used with the spiral, the trace voltages increased over greater coil length.[45]

On resuming experiments with the spiral, I doubled the spiral's length, improved connections, and employed a digital storage oscilloscope.[46] The digital oscilloscope immediately transformed my data collection. Values of voltage and time saved from more than one trace could be plotted on the same axes, allowing a direct overlay comparison between traces taken in different trials. I used this method to compare the trace produced when a low-valued resistor was in the circuit (like Page's body), with a trace produced without one (fig. 13, left). With the low resistor, the trace exhibited one major peak, without the declining oscillations that characterize the trace taken from that same circuit without the resistor.

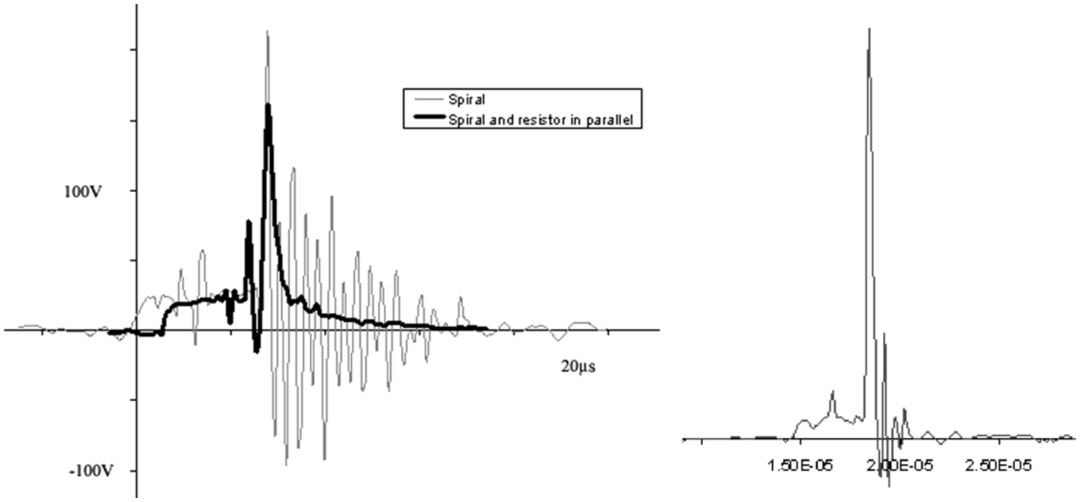

FIG. 13. Left: The light gray line represents the voltage induced across a part of the spiral when the switch opens. The dark line shows the voltage induced across the same portion of the spiral when a resistor (1kΩ) is put in parallel with the probe. Right: The voltage trace

produced when a human volunteer connected across my spiral, in place of the resistor. The peak voltage is 300 V.

The resistor affected the shape of the electrical signal when it was included in the circuit, suggesting that the body plays an active part in the circuit. The single spike of this resistor test corroborated with the narrow spike trace that resulted when a human volunteer put himself into my spiral circuit where the resistor had been (fig. 13, right). However, while I found that the human body affects the circuit, further tests showed that its inclusion (through an electrical substitute) did not remove the ambiguity which motivated my questions. I still lacked a consistent demonstration of voltage increase when the probe covers more of the spiral's length.

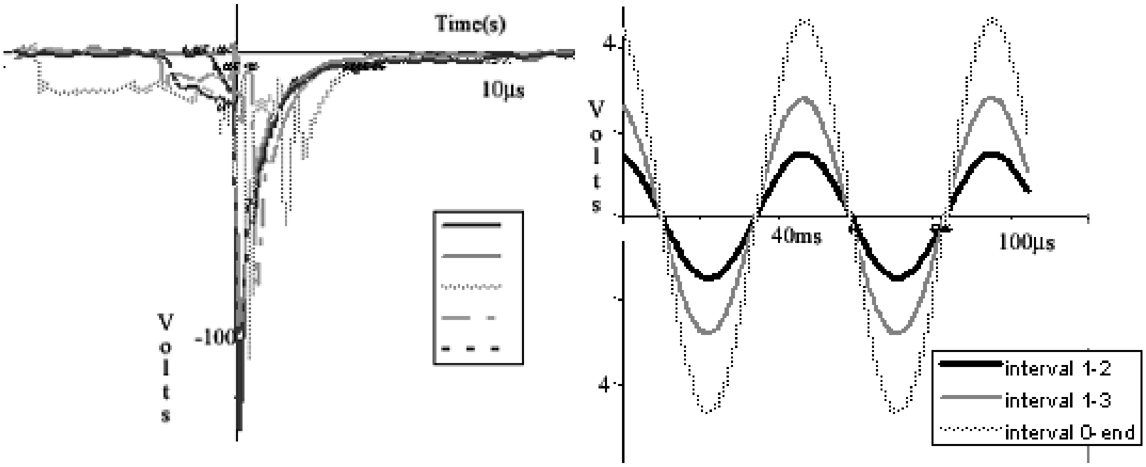

FIG. 14. Left: An overlay plot showing variation in voltage traces taken across one spiral interval (with a resistor in parallel) when the circuit is mechanically switched. Right: A constant frequency of 20kHz was applied to three intervals of the spiral in succession (inner, middle, outer). The observed voltage is superimposed, showing an increase in peak voltage across the spiral.

As I analyzed more data using the technique of plotting traces taken from separate trials onto one graph, I ascertained more about the signals that were giving me such confusion. Previously, I noticed that when I simply repeated an experiment without changing anything about the setup, the voltage trace looked different. Now I collected a series of traces that were produced when I changed nothing in the experiment's connections, but repeatedly closed and opened the switch that lets battery current into the circuit, under what I thought were identical conditions. When I superposed on one plot these traces taken from successive switching events, their peak values varied over a wide range (fig. 14, left). This pronounced variability contrasts sharply with the repeatable signals put out by my iron core coils when I activated them using the same battery and switch.

Whereas before I responded to the discrepancy between my spiral's output and Page's by looking to a component – the body—that differed in the two cases, subsequently I considered an element in common between Page's experiment and mine: the mechanical switch. With a mechanical switch, electric contacts break irregularly so that each switching is different. By contrast, electronic pulse generators produce events that are virtually the same each time. I began investigating my spiral by both means.

I explored my spiral's response to both mechanical and periodic stimuli in more than ninety lab sessions across five years. In doing this, I constructed new apparatus, such as a rotary wheel switch like one Page used, and additional spirals.[47] I probed the circuit with an array of electrical test equipment.[48] For data collection and analysis, I learned to use features of the oscilloscope and software that were unfamiliar to me. These techniques opened up multiple views to me on what was going on within my spirals, just as Page's intermediate taps opened up the spiral's internal electricity to him. In some of these experimental contexts, I observe voltages to increase in accord with what Page reported (fig. 14, right).[49]

Such confirmatory findings do not end my exploration. There are always more ways to probe the spiral and analyze its variable signals. The observation that ambiguities remain, even under examination by diverse techniques, shows how ambiguities – including from the human body – are intrinsic to experimenting. Ambiguity drives our curiosity to keep exploring, in some analogy to the electrical stimulus that rings across spiraled conductors, from Page's time to ours.

Conclusion

Encountering behaviors that genuinely surprised him, Page explored them without requiring or depending upon explanations or other guides. Starting with a circuit which was already the forefront research of Faraday and Henry, Page took it further by opening it up and investigating its internal and external paths. The knowledge that Page generated kept his experiment going. This knowledge, instead of gelling into definitive outcomes, provided the means by which he tried new tests, invented apparatus, and compared observations. Although it might seem that our present instrumentation and analyses would rule out ambiguities such as Page experienced, my lab project demonstrates otherwise. Ambiguities arise even with modern equipment. The process of responding to ambiguities without removing or resolving them brings to light questions and observations that were not apparent before. A key strategy in working productively with ambiguity lies in opening up multiple possibilities, entry points and perspectives,[50] as Page did by soldering intermediate taps into his spiral.

Physical and cultural boundaries tend to circumscribe and resist the fluid kind of investigation in which Page engaged. Page's inclusion of his body in the circuit illustrates how boundaries function to create ambiguities. Page's body not only sensed shock; it also affected the electrical signal giving rise to that shock. Permeability in the body's physical boundary allowed for knowledge about a new phenomenon.[51] Our cultural boundaries regarding lab safety initially obscured from me that Page's body took the double role of detecting and conducting electricity. Although cultural boundaries shift in time, at any particular time the force of their barrier may be immense. These cultural boundaries may be defined with such impermeable specificity, that there is no space available for work that depends on tolerating ambiguity, in order to proceed. Under these circumstances, it may then be untenable for a culture to appreciate the contributions of someone like Page, who worked innovatively without bounding outcomes neatly from means and without building understanding by excising ambiguity.

Historical neglect of Charles Grafton Page is one product of the limiting action of such cultural boundaries. But that neglect of Page is a symptom of a much larger and more pervasive cultural pattern. This pattern consists in boundaries that inhibit us from exploratory means of learning in our everyday lives and communities. The story of the spiral experiment, where opening up physical and cultural boundaries brought unexpected effects and fascinating ambiguities into human experience, has potential to help us crack the boundaries that restrain our curiosity at any time.

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[1] Robert C. Post, *Physics, Patents & Politics: A Biography of Charles Grafton Page* (New York, 1976); Post, "The Page Locomotive: Federal Sponsorship of Invention in Mid-19th-Century America," *Technology and Culture* 13 (1972): 140-69.

[2] C. G. Page, "Method of Increasing Shocks, and Experiments, with Prof. Henry's Apparatus for Obtaining

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Sparks and Shocks from the Calorimotor," *American Journal of Science* 31 (1837): 137-41. All articles cited from the *American Journal of Science* are available in the Proquest digital resource American Periodical Series (APS) online.

[3] Alessandro Volta, "On the Electricity Excited by the Mere Contact of Conducting Substances…," (1800), trans. Bern Dibner, in Dibner, *Alessandro Volta and the Electric Battery* (New York, 1964), 111-31. .

[4] Volta, in Dibner 120.

[5] For the self-experimenting of Humboldt and Ritter, see Stuart Strickland, "The Ideology of Self-Knowledge and the Practice of Self-Experimentation," *Eighteenth-Century Studies* 31 (1998): 453-71; Michael Dettelbach, "The Face of Nature: Precise Measurement, Mapping, and Sensibility in the Work of Alexander von Humboldt," *Studies in History and Philosophy of Biology and Biomedical Science* 30 (1999): 473-504; Roberto de Andrade Martins, "Orsted, Ritter and Magnetochemistry," in R.M. Brain and O. Knudsen, eds., *Hans Christian Oersted and the Romantic Quest for Unity: Ideas, Disciplines, Practices*, Boston Studies in the Philosophy of Science 241 (Dordrecht, 2007).

[6] Paola Bertucci and Giuliano Pancaldi, eds., *Electric Bodies: Episodes in the History of Medical Electricity* (Bologna, 2001).

[7] "Shilling"-sized electrodes are described in Charles H. Wilkinson, *Elements of Galvanism in Theory and Practice* (London, 1804) vol. 2: 444.

[8] Lu Gwei-Djen and Joseph Needham, *Celestial Lancets: A History and Rationale of Acupuncture and Moxa* (1980; repr., London 2002), 295-302.

[9] M. Morand, *Memoir on Acupuncturation*, trans. Franklin Bache (Paris and Philadelphia, 1825), 30.

[10] Quote in William Markley Lee, "Acupuncture as a Remedy for Rheumatism," *Boston Medical and Surgical Journal,* 14 September, 1836, 85-87. Available through APS online (see n. 2 above).

[11] Steven Shapin, "The Philosopher and the Chicken: On the Dietetics of Disembodied Knowledge," Christopher Lawrence, "Medical Minds, Surgical Bodies: Corporeality and the Doctors," and Janet Browne, "I Could Have Retched All Night: Charles Darwin and His Body," in Christopher Lawrence and Steven Shapin, *Science Incarnate: Historical Embodiments of Natural Knowledge* (Chicago, 1998), 21-50, 156-201, 240-87.

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[12] The actual situation might be otherwise, some researchers could be frail; others, like Charles Darwin, might use their maladies to secure the solitude needed for work; see Lawrence, "Medical Minds" and Browne, "I Could Have Retched."

[13] Rebecca Herzig, *Suffering for Science: Reason and Sacrifice in Modern America*, (New Brunswick, N.J., 2005).

[14] Lawrence and Shapin, 15-16, 45-46.

[15] Alexander Bache composed an abstract – "Facts in Reference to the Spark, &c. from a Long Conductor Uniting the Poles of a Galvanic Battery" – on Joseph Henry's experiment, and published it immediately in the *Journal of the Franklin Institute* (1835): 169-70; and the *American Journal of Science* 28 (1835): 327-29 (328). In the *American Journal of Science*, Bache's abstract was followed by an additional discussion by Henry, titled "Appendix to the Above," 329-31.

[16] Michael Faraday, "On the Magneto-Electric Spark and Shock, and on a Peculiar Condition of Electric and Magneto-Electric Induction," *Philosophical Magazine* 5 (1834): 349-54.

[17] Joseph Henry (later the Smithsonian's first director) first observed the heightened electricity occurring when a coil's battery connection broke during work with his great electromagnet: see "On the Production of Currents and Sparks of Electricity from Magnetism," *American Journal of Science* 22 (1832): 403-408. Henry's formal publication is titled, "On the Influence of a Spiral Conductor in Increasing the Intensity of Electricity from a Galvanic Arrangement of a Single Pair," *American Philosophical Society Transactions* (1837): 223-31. Henry presented his work with the spiral on 6 February 1835, his complete paper was not published until 1837.

[18] Philadelphia professor Robert Hare constructed a massive calorimotor consisting of many voltaic pairs connected in parallel, so as to be equivalent to a single cell; see Hare, "A New Theory of Galvanism ... by Means of the Calorimotor, a New Galvanic Instrument," *American Journal of Science* 1 (1818): 412-23.

[19] Michael Faraday, "On the Induction of Electric Currents," First Series (24 November 1831), *Experimental Researches in Electricity*, vol. 1, (1839; repr. Santa Fe, N.Mex., 2000) , ¶27-32.

[20] Page (n. 2 above), 137; Post 1976 (n. 1 above).

[21] [Jonathan Homer Lane], "Charles Grafton Page," *American Journal of Science* 48 (1869): 1-17.

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[22] On this way of configuring the sheet, Page wrote: "in this way the integrity of the circuit is better preserved than by numerous solderings" (Page, 138).

[23] Perhaps the composite assembly of the spiral's length from separate segments suggested to Page the possibility of using intermediate locations on the spiral for electrical input.

[24] Page, 138.

[25] Ibid., 139.

[26] Ibid., 139.

[27] Ibid., 139.

[28] Page, who did not specify the dimensions of his initial calorimotor, followed Henry's preliminary notice, which was vaguely worded in recommending "one of Dr. Hare's Calorimotors"; Henry, "Appendix" (n. 15 above), 329) Henry later stated that he employed one pair of large plates having 1.5 square feet of zinc surface area; Henry, "On the Influence of a Spiral Conductor" (n. 17 above), 224. See Elizabeth Cavicchi, "Sparks, Shocks and Voltage Traces as Windows into Experience: The Spiraled Conductor and Star Wheel Interrupter of Charles Grafton Page," in special issue, *Archives des Sciences* 28 (2005): 123-36. For more background on Page's experiment and electrical acupuncture, see Elizabeth Cavicchi, "Opening the spiral conductor to the body, more options, and ambiguity", February 2008, http://www.eecs.tufts.edu/~cavicchi/publications.html

[29] Page (n. 2 above), 139.

[30] Elizabeth Cavicchi, "Experimenting with Wires, Batteries, Bulbs and the Induction Coil: Narratives of Teaching and Learning Physics in the Electrical Investigations of Laura, David, Jamie, Myself and the Nineteenth Century Investigators – Our Developments and Instruments" (PhD diss., Harvard University, 1999); "Experiences with the Magnetism of Conducting Loops: Historical Instruments, Experimental Replications, and Productive Confusions," *American Journal of Physics* 71 (2003): 156-67; "Nineteenth Century Developments in Coiled Instruments and Experiences with Electromagnetic Induction," *Annals of Science* 63 (2006): 319-61.

[31] J. A. Fleming*, The Alternate Current Transformer in Theory and Practice*, vol. 2 (London, 1892).

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[32] [Charles Grafton Page], *The American Claim to the Induction Coil and its Electrostatic Developments* (Washington, D.C., 1867); Robert C. Post, "Stray Sparks from the Induction Coil: The Volta Prize and the Page Patent," *Proceedings of the IEEE* 64 (1976): 1279-286.

[33] Cavicchi, "Nineteenth Century Developments"; Wilhelm Hackmann, "The Induction Coil in Medicine and Physics: 1835-1877," in C. Blondel et al., eds., *Studies in the History of Scientific Instruments* (London, 1989), 235-50

[34] Friedrich Steinle, "Entering New Fields: Exploratory Uses of Experimentation," *Philosophy of Science* 64 (1996): S65-S74; Neil Ribe and Friedrich Steinle, "Exploratory Experimentation: Goethe, Land and Color Theory," *Physics Today*, July 2002, 43-49. For related discussions of Faraday's exploratory work, see David Gooding, *Experiment and the Making of Meaning: Human Agency in Scientific Observation and Experiment* (Dordrecht 1990); Elizabeth Cavicchi, "Faraday and Piaget: Experimenting in Relation with the World," *Perspectives on Science*, 14 (2006): 66-96.

[35] See "The Replication Method in History of Science," special issue, *Archives des Sciences* 58 (2005), esp. Jan Lacki, "Editorial," 93-95; Peter Heering and Christian Sichau, "Instruments and Experiments between the Laboratory and the Museum," 97-112; Cavicchi, "Sparks, Shocks and Voltage Traces" (n. 28 above); Ryan Tweney, "On Replicating Faraday: Experiencing Historical Procedures in Science," 137-48.

[36] Klaus Staubermann, "Controlling Vision – The Photometry of Karl Friedrich Zöllner" (PhD diss., Darwin College, Cambridge University, 1998); *Astronomers at Work: A Study of the Replicability of 19th Century Astronomical Practice,* Acta Historica Astronomiae 32 (2007).

[37] Peter Heering, "Educating and Entertaining: Using Enlightenment Experiments for Teacher Training," in Peter Heering and Daniel Osewold, eds., *Constructing Scientific Understanding through Contextual Teaching* (Berlin, 2007) 65-81; Heering, "Weighing the Heat: The Replication of the Experiments with the Ice-Calorimeter of Lavoisier and Laplace," in Marco Beretta, ed., *Lavoisier in Perspective* (Munich, 2005) 27-42.

[38] For more detail about my experiment, see Cavicchi, "Sparks, Shocks and Voltage Traces," and "Opening the Circuit to the Body" (n. 28 above).

[39] On safety issues with shock, see William Butterfield, "Electric Shock – Safety Factors when Used for the Aversive Conditioning of Humans," *Behavior Therapy* 6 (1975): 98-110. For United States Environmental

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Protection Agency assessments of health risks and policies associated with mercury, see http://www.epa.gov/mercury/effects.htm

[40] The Bakken Museum of Electricity and Life, Minneapolis, Minn., provided mercury for my demonstration talk, **"**Finding the Body – and Ambiguity – in the Circuit: Historical and Reconstructive Experiments with a Spiraled Conductor," 10 December 2003; see http://www.thebakken.org/research/Cavicchi-talk.htm I thank Ellen Kuffeld, Elizabeth Ihrig and David Rhees for support in my presentation on the Page spiral and related study at the Bakken Museum.

[41] I worked with the following storage oscilloscopes in successive phases of my study: HP 54600B, Lecroy 9450A, and HP Infinium 54810A. I used a high-voltage probe (Textronix P6015) to protect these instruments from high voltages induced in my circuits.

[42] Presenting 1MΩ to the test circuit, the oscilloscope is designed not to perturb it. However, I found that signals were affected (diminished) when two probes were applied at once to overlapping parts of the spiral.

[43] See J. Patrick Reiley, *Applied Bioelectricity: From Electrical Stimulation to Electropathology* (New York, 1998).

[44] 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; for example, see "Biological effects of electric shock," Thomas Jefferson National Accelerator Facility, Newport News VA, http://www.jlab.org/ehs/manual/EHSbook-440.html.

[45] see Cavicchi, "Nineteenth Century Developments" (n. 30 above), 346, fig. 14.

[46] HP Infinium 54810A.

[47] For more description of the reconstructed spiral and wheeled switch, see , "Sparks, Shocks and Voltage Traces" (n. 28 above), 131-34.

[48] I used 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 manufactured by Grass Medical Instruments, Quincy, Mass.

[49] See Cavicchi, "Sparks, Shocks and Voltage Traces" (n. 28 above), and "Opening the spiral conductor …" (n. 28 above).

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[50] Jean Piaget, *Possibility and Necessity*; trans. Helga Feider (Minneapolis, 1987); Eleanor Duckworth, "Inventing Density," in E. Duckworth, ed., *"Tell Me More": Listening to Learners Explain* (New York, 2001); Elizabeth Cavicchi, "Opening Possibilities in Experimental Science and Its History: Critical Explorations with Pendulums and Singing Tubes," *Interchange* 39, no. 4 (2008, in press).

[51] The body's permeability to electricity is not essential for producing this phenomenon, as demonstrated by the experiments of both Page and myself, where no body was included; Cavicchi, "Sparks, Shocks and Voltage Traces" (n. 28 above), and "Opening the spiral conductor …" (n. 28 above).