Advances in Social Sciences Research Journal – Vol.7, No.12
Publication Date: December 25, 2020
DOI:10.14738/assrj.712.9532.
Baldwin, I. (2020). Discovery of Electricity and the Electromagnetic Force: Its Importance for Environmentalists, Educators, Physicians, Politicians, and Citizens. A*dvances in Social Sciences Research Journal,* 7*(12)* 362-383.

Discovery of Electricity and the Electromagnetic Force: Its Importance for Environmentalists, Educators, Physicians, Politicians, and Citizens

Ian Baldwin, M.A.
Publisher Emeritus, Chelsea Green
Craftsbury Common, Vermont, USA

ABSTRACT

The discovery of static electricity in the 18th century and electromagnetism in the 19th was one of the most momentous scientific-technological events in human history. In the 21st century our way of life depends on the electromagnetic force so totally that were our electromagnetic infrastructure to collapse, our civilization would collapse virtually simultaneously. Despite this situation of profound dependency, few citizens understand the electromagnetic force, how it was discovered, how it works, and what wonders of modern life it controls. Nor do citizens understand the roles that Earth's magnetosphere, ionosphere, and global electric circuit play in making electricity and life possible. Here, I review Earth's natural electric environment and how electricity first began to be scientifically understood with the innovation of the Leyden jar in the mid-18th century; Franklin's insights about electricity's positive and negative poles, and its movement (later named a "current"); Galvani's discovery of bioelectricity; and Volta's seminal invention of the bi-metallic electrochemical battery in 1800. Ørsted's discovery that an electric current affected a magnetized needle, causing it to swivel, in 1820 led to experiments with electromagnets by Schweigger, Arago, Ampère, Sturgeon, Henry, Faraday, and others over the course of the next decade. Observing how conducting wires induced magnetism in iron bars whenever the wires were electrified, Faraday and Henry separately discovered the principle of induction, whereby a moving magnetic field could reciprocally induce electricity in a coiled wire. Out of these momentous discoveries the "magneto-electric" telegraph was invented, and, within a single generation, the world was wired.

Keywords: Electromagnetism; Animal magnetism; Leyden jar; Battery; Voltaic Pile; Magnetic field; Induction, Telegraph.

INTRODUCTION

Electromagnetic energy not only surrounds us but is constantly at work at the most minute levels of our physical selves. As a large and growing scientific literature attests, every one of our cells is electrically sensitive [1]. Yet most of us are unaware of this all-pervasive invisible energy that orchestrates life's most fundamental rhythms. Some, on the order of 30 percent of us, are "*weather*

sensitive." Such individuals react to electrical changes in the atmosphere that travel much faster than the wind that carries the weather, arriving hours or even days before the weather itself finally arrives. Another five to ten percent of us are electromagnetically sensitive enough to be aware, often uncomfortably and even painfully aware, when artificial electromagnetic disturbances are suddenly introduced into the environment [2].

Earth is a giant magnet whose immense force lines—its magnetic "*field*"—deflect the ionizing particles that arrive without cease from deep space and most especially from the sun. Earth's magnetosphere forms a vast cocoon that shields life forms from these high-energy particles. Some of the particles have enough energy to penetrate the outer limits of the magnetosphere, both its frontal, sun-facing magnetosheath and behind that, the magnetopause. Particles that manage to penetrate these barriers are then captured by the outer and inner Van Allen radiation belts (named after the scientist who discovered them in 1958, at the dawn of the Space Age). The outer Van Allen belt extends some 64,400 km (40,000 mi) from Earth's surface, while the inner begins about 966 km (600 mi) from its surface. In fact, there is no clear gap between the inner and outer belts, which trap the highly energized particles and send them, spiraling back and forth between the north and south poles, along Earth's magnetic field lines. As Earth rotates on its axis, its magnetosphere remains stationary, its compressed, or bow side facing the onslaught of the sun's powerful "*winds*," while the opposite, nocturnal side stretches from Earth for millions of miles into space (the magnetotail).

The constantly changing amplitude of Earth's magnetic field, its night-and-day rhythm, informs fundamental biological rhythms, including the human circadian rhythm.

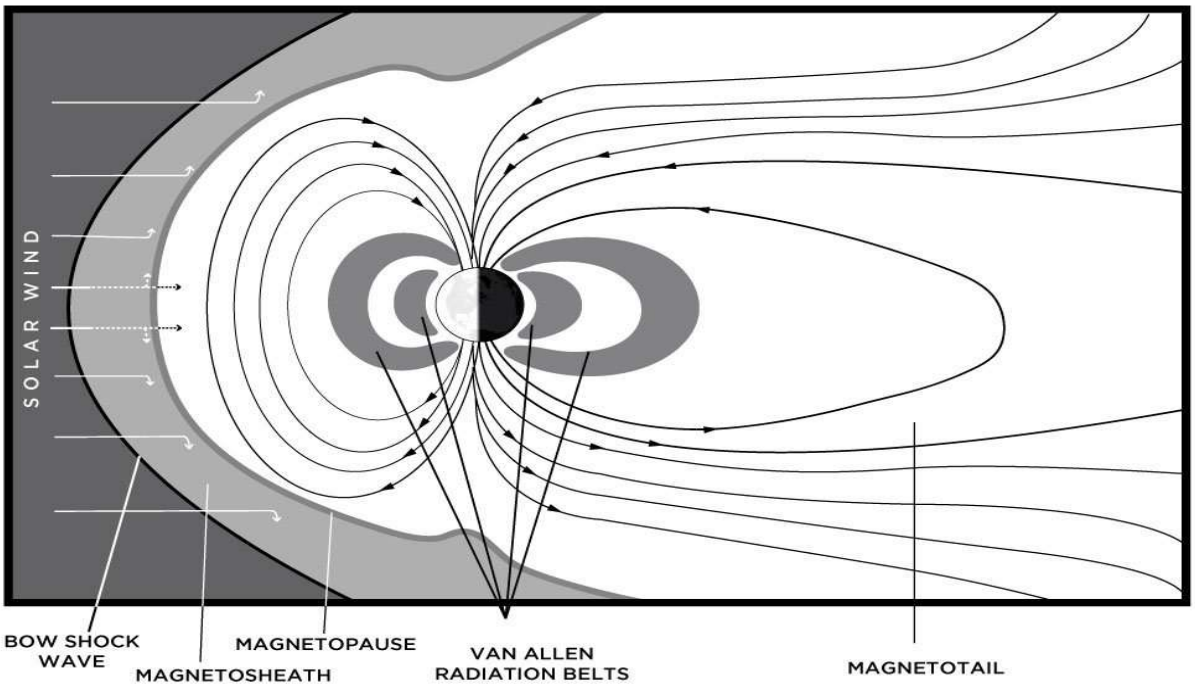


Figure 1. Earth's magnetosphere, partially depicted in this figure, is as essential to life as its atmosphere and its hydrosphere. Life would cease if the magnetosphere collapsed. Very little is known about anthropogenic influences on the magnetosphere.

Some particles not captured by the two shielding Van Allen belts rain into an almost 1000-km-deep atmospheric reservoir called the ionosphere. The ionosphere begins approximately 60 km above Earth's surface and terminates roughly at 1,000 km altitude, near the base of the inner Van Allen belts. It is not only a protective zone but a constantly replenished source of the electric energy that animates life on Earth.

The multi-leveled layer between the bottom portion of the ionosphere and Earth's surface forms what atmospheric physicists call the global electric circuit, or an "*electric envelope*," a roughly 90-km-deep aerial wilderness that wraps itself around our planet. It is the layered nest in which all life has evolved for billions of years. Relatively small amounts of cosmic, solar, and Earth radiation fill this reservoir with the polarized static electricity essential to life. The atmospheric layers are illustrated in Figure 2, with dimensional ranges shown in Table 1.

Table 1. Dimensional Ranges of Atmospheric Regions.

Atmosphere Region	Dimensional Range
Exosphere	600-10,000 km (372-6,200 mi)
Thermosphere	85-600 km (53-372 mi)
Mesosphere	50-85 km (31-53 mi)
Stratosphere	14.5-50 km (9-31 mi)
Troposphere	0-14.5 km (0-9 mi)
Ionosphere [green in Figure 2]	48-965 km (30-600 mi)
Electric Envelope [red in Figure 2]	0-85 km (0-55 mi)

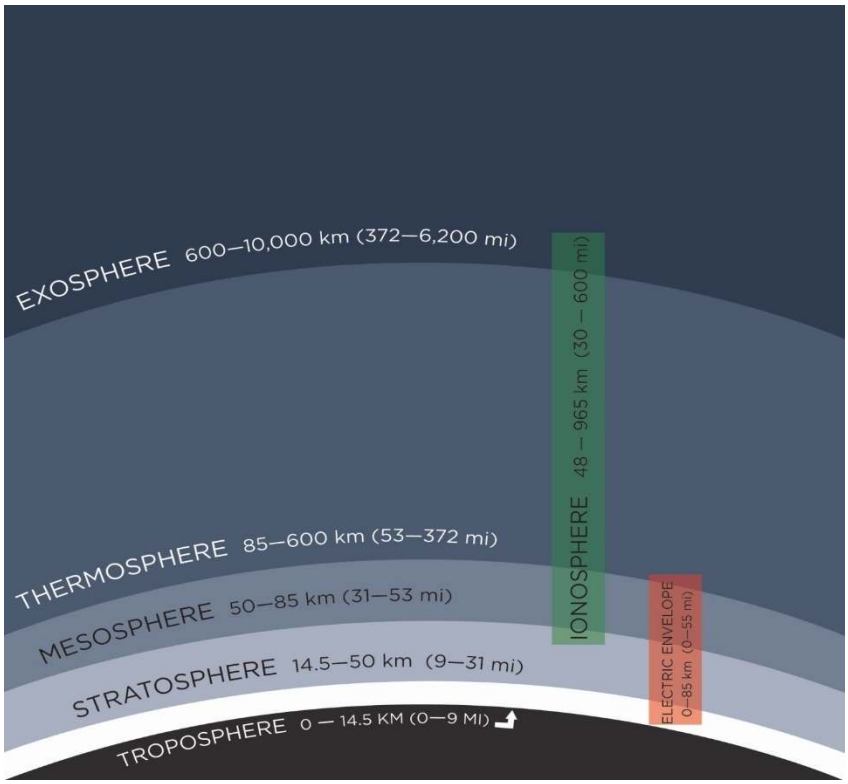


Figure 2. Earth's layered atmosphere, including the ionosphere, shown in green, and the global electric circuit or "electric envelope," shown in red.

> *"The most spectacular reminder that electricity is always playing around and through us is…of course, lightning. Electricity courses through the sky far above us, explodes downward in thunderstorms, rushes through the ground beneath us, and flows gently back up through the air in fair weather,"*

forming the global electric circuit [3]. Some two thousand thunderstorms continuously play across Earth's surface, and every second more than a hundred bolts of lightning, each delivering a trillion watts of energy, ceaselessly discharging the build-up of excess electric potential in the ionosphere somewhere on Earth, as the flow of ions from the solar wind and deep space keeps pouring in, recharging the circuit.

GLOBAL ELECTRIC CIRCUIT

All organisms are part of Earth's immense global circuit. "Each of us generates our own electric fields, which keep us vertically polarized like the atmosphere, with our feet and hands negative with respect to our spine and head. Our negative feet walk on the negative ground, as our positive heads point toward the positive sky. The complex electric circuits that course gently"—meaning in a very low frequency range—"through our bodies are completed by ground and sky," in a continuous life-endowing flow [4].

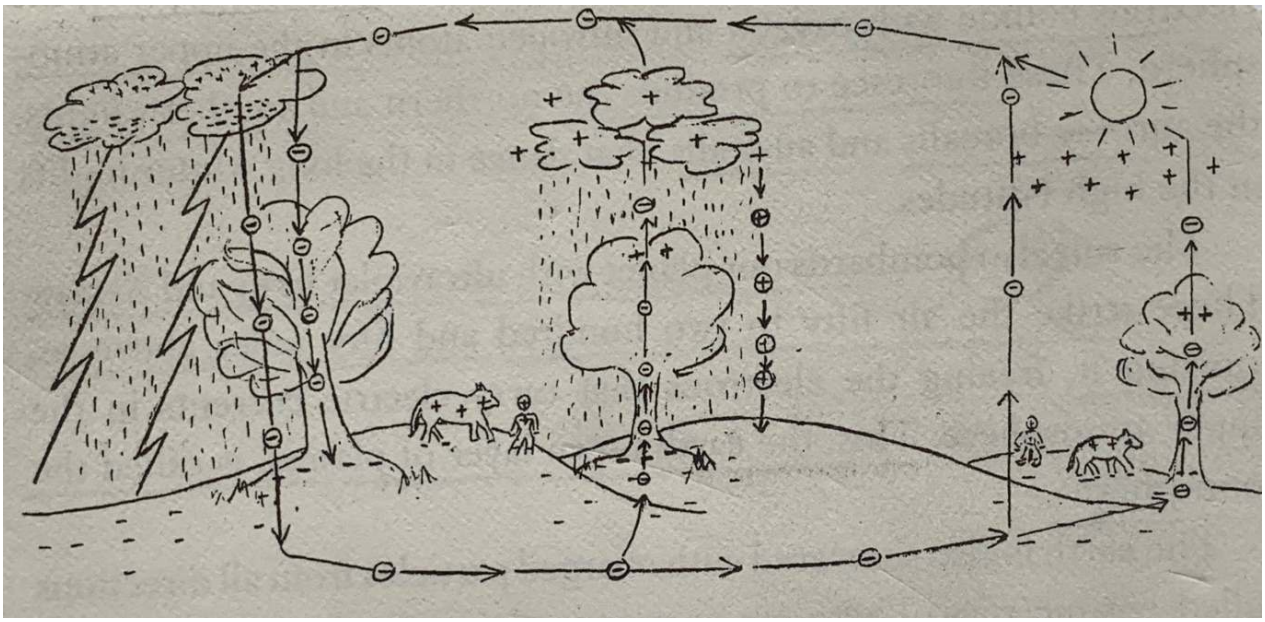


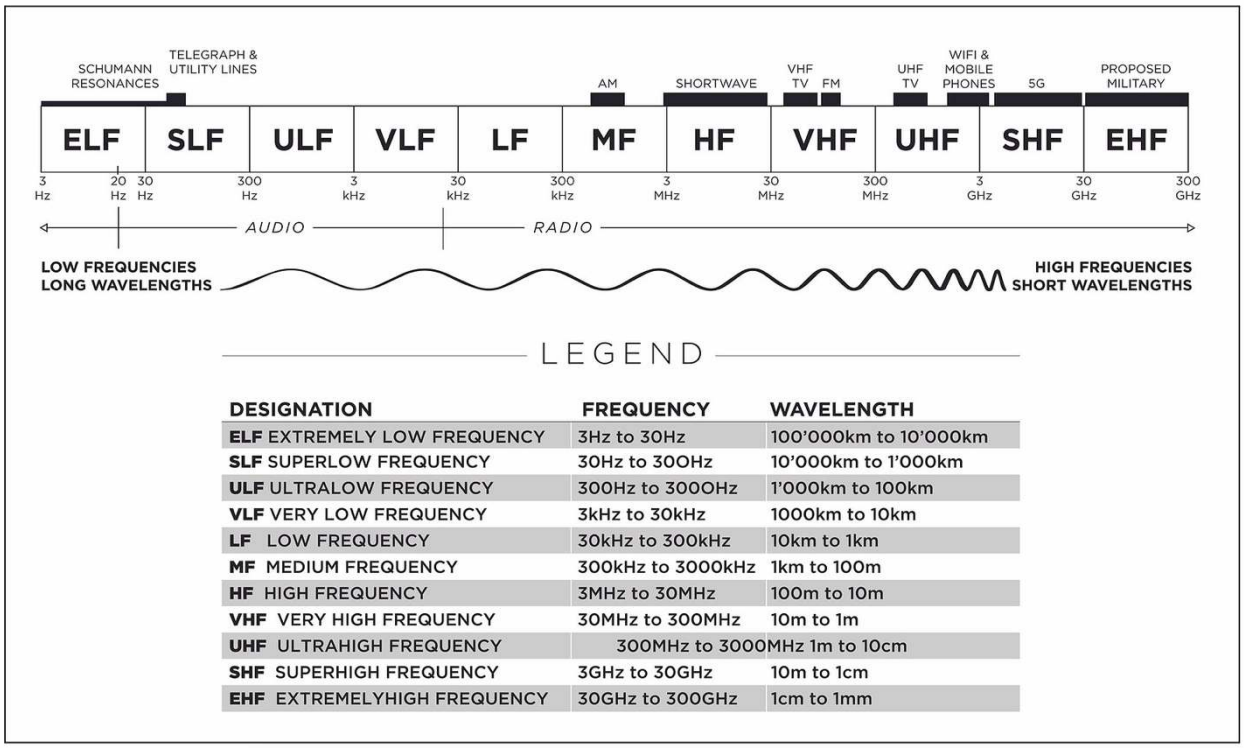
Figure 3. Both Earth and its atmosphere are good conductors of electricity and together form the global electric circuit. SOURCE: Hand-drawn by Arthur Firstenberg, *The Invisible Rainbow.*

The electric envelope forms "a resonant cavity" where ceaseless "lightning sets the biosphere ringing at the particularly low frequency tones" called the Schumann resonances. In the early 1950s the German physicist Winfried O Schumann predicted and then developed the first measurements of the frequencies caused by Earth's constant lightning discharges, occurring at 3 to 60 Hertz (Hz) in a sequence of tonal peaks. Later, scientists speculated that these Schumann "resonance signals" may "act like a tuning fork not just for the biological oscillators of the brain but for all processes of life," [5] including at the level of DNA processes [6].

We all live attuned to these very low spectrum frequencies. In a state of "awake relaxation, our brains tune into these precise frequencies," alpha and theta, that "pulsate, so far as is known, in all animals" [7]. Earth's natural electromagnetic field—its "heartbeat" or "background" base frequency—surrounds all life with a very low protective frequency of on average 7.83 Hz.

Hertz is a measure of the number of oscillations of a wave per second: Schumann resonances for the most part vary from 3 to 45 Hz, in the very low range. Cells respond to electromagnetic frequencies between 3 and 25 Hz. "Research has shown that the Schumann resonances can modulate human health indicators such as blood pressure, cardiac and neurological disease, reaction time, neuroendocrine sensitivities," and can also be used to induce violence [8].

In addition to these very low frequencies that "speak to our brains" and span the lower end of our auditory range, lightning also generates "a steady symphony of higher frequencies" in the 200 to 30,000 Hz (30 kHz) portion of the spectrum within which our hearing range is located and which includes "the frequencies of the impulses that our brains send to our muscles" [9]. All these high frequencies, nonetheless, belong to the very low frequency end of the radio spectrum.



DESIGNATION	FREQUENCY	WAVELENGTH
ELF EXTREMELY LOW FREQUENCY	3Hz to 30Hz	100'000km to 10'000km
SLF SUPERLOW FREQUENCY	30Hz to 300Hz	10'000km to 1'000km
ULF ULTRALOW FREQUENCY	300Hz to 3000Hz	1'000km to 100km
VLF VERY LOW FREQUENCY	3kHz to 30kHz	1000km to 10km
LF LOW FREQUENCY	30kHz to 300kHz	10km to 1km
MF MEDIUM FREQUENCY	300kHz to 3000kHz	1km to 100m
HF HIGH FREQUENCY	3MHz to 30MHz	100m to 10m
VHF VERY HIGH FREQUENCY	30MHz to 300MHz	10m to 1m
UHF ULTRAHIGH FREQUENCY	300MHz to 3000MHz	1m to 10cm
SHF SUPERHIGH FREQUENCY	3GHz to 30GHz	10m to 1cm
EHF EXTREMELYHIGH FREQUENCY	30GHz to 300GHz	1cm to 1mm

Figure 4. Non-ionizing portion of the electromagnetic spectrum. Ever since the telegraph, humanity has deployed technologies that use increasingly high frequencies of electromagnetic energy, whose medical and environmental risks remain largely unacknowledged.

The human brain and the atmosphere are thus tuned to each other, having evolved in electromagnetic synch for a very long time. And life generally has evolved tuned to and by these permanently ringing very low (VLF) Schumann frequencies.

By 1960 the first detailed map of an animal's polarity or "charge distribution" had been made by the pioneering orthopedic surgeon, Robert O Becker. Four years earlier, in 1956 at the dawn of the Space Age, two zoologists experimenting on crayfish were astonished to discover that extremely small currents "could cause an already firing nerve to alter its firing rate." In fact, an incredibly small current "of only 36 billionths of an ampere was enough to increase or decrease" the nerve's firing rate by 5 to 10 percent. A miniscule "current of 150 billionths of an ampere would…double the rate of firing, or silence the nerve altogether," depending on the direction in which the current was applied to the nerve [10].

The two zoologists' momentous discovery was ignored. It is still being ignored, well over a half century later. According to Firstenberg, such a miniscule current is *thousands of times less* than what today's developers of modern telecommunications safety codes believe is the minimum possible to have any biological effect [11].

Since birth of the telegraph in the middle of the 19th century, we have lived in an invisible, seemingly immaterial substance—an anthropogenic electromagnetic cloud—whose dimensions, complexity, and scope we keep expanding, all the while refusing to look at its possible environmental, medical, and mental effects. During those decades, spanning the lives of seven generations, from our great, great grandparents to our grandchildren, the diseases of civilization have sprouted, culminating most recently in a pandemic whose origins and behavior seem to completely befuddle us.

We have lived so long under this invisible radiative cloud we no longer appreciate how it grew and grew, spectacularly and without letup, to the point where it now comprehensively governs every moment of our lives. How did this come to pass?

DISCOVERY OF THE ELECTRIC FORCE

In 1746 two scientists working in a laboratory in Leyden, Holland, made "*an experiment that changed the world forever*" [12]. To a horizontal metal bar, the "*prime conductor*," one end of which nearly touched a friction machine's large spinning ball charged with static electricity, they added at its opposite end a sturdy wire that went into a glass jar of water, hoping to discover that the mysterious "*fluid*"—visible as sparks that leapt from the spinning orb onto the metal conductor—could be "*captured*" as it coursed along the prime conductor and, via the attached wire, into the bottled water, to be stored there for future use.

The experiment was a huge success. Within a year, in various laboratories all over Europe, "*Leyden jars*" were devised using metal foil on the inside and on the outside, each storing equal but opposite static electric charges, that did away with the need to use water. The Leyden jar was the world's first prototype electrical capacitor, able to store a limited quantity of electricity for limited use.

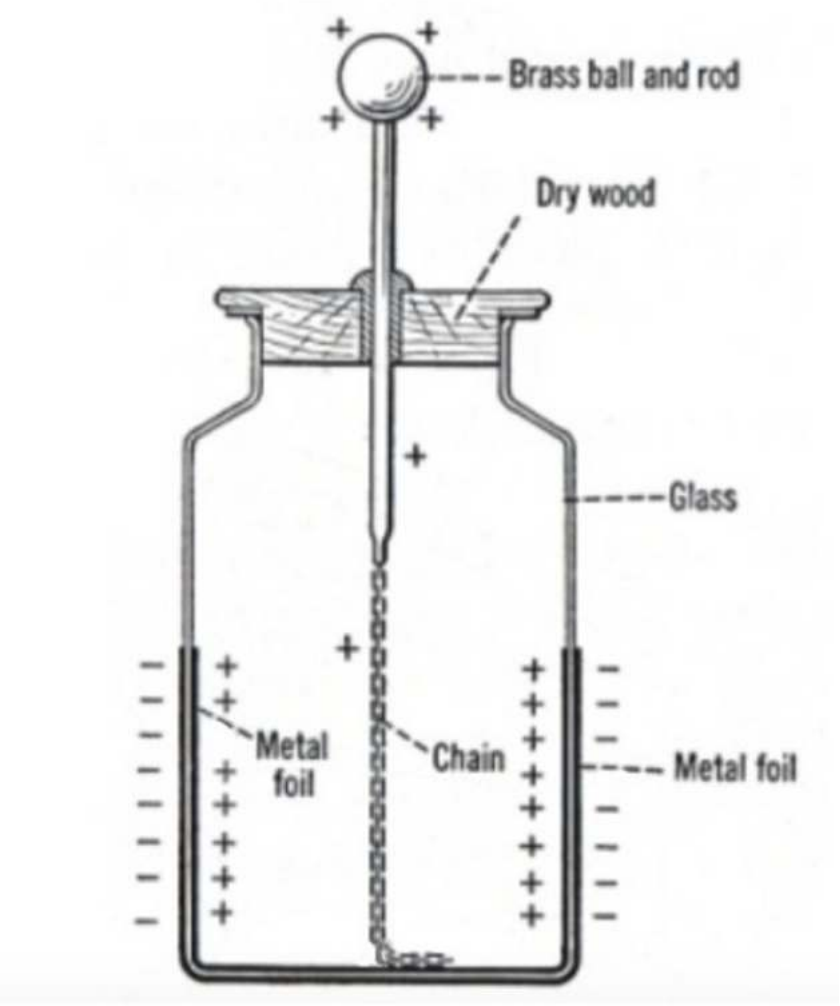


Figure 5. The brass bulb received the static charge flowing down a conductor placed near a friction machine (neither shown), which then flowed down the brass rod connected to the chain inside where the foil, charged positive inside and negative outside, affected the glass so as to store the electric charge, making the Leyden jar a primitive electrical capacitor. SOURCE: Wikipedia.

Ben Franklin conducted experiments in 1747 and 1748 that "*showed electricity consisted of a 'common element' which he named 'electric fire,'*" in effect, a "'*fluid' like a liquid*" that "*passed from one body to another*" and was "*never destroyed*," but "*only circulates*'" [13]. Franklin's use of the words "*electric fire*" was no accident, as he had experienced electric shock during one of his early experiments: *"'…a universal blow throughout my whole body from head to foot, which seemed within as well as without; after which the first thing I took notice of was a violent quick shaking of my body*,'" followed by a numbness in his arms and the back of his neck that gradually wore off [14].

In explaining his "*single fluid*" theory, Franklin maintained electricity flowed "*from a positive body, that with an excess charge, to a negative body, that with a negative charge*," a concept and nomenclature that has endured ever since [15]. His experiments further convinced him the Leyden jar's glass insulator, or dielectric, was the element that actually stored the charge: "*The whole force of the bottle, and the power of giving a shock, is in the glass itself,*" Franklin wrote in 1749 [16].

Almost immediately after the two Dutch scientists discovered the magical fluid could be stored, an intense, universal craze, a kind of "*electromania*," seized Europe and made the Leyden jar an overnight sensation: "…everywhere you went people would ask you if you had experienced its effects….Like a child prodigy making his debut, electricity had arrived, and the whole Western world turned out to hear his performance" [17].

Though of limited practical utility because they had to be recharged with cumbersome friction machines every time they were used, the Leyden jars were nonetheless employed not merely to titillate salon audiences but to provide the world's first shock treatments for medical purposes. (Often these had healing benefits; often they did not.) Tens of thousands of volts of static electricity could be stored in the jars and the maestros of the magical fluid delivered shocks "*that could take away your breath, boil your blood, [and] paralyze you*." No matter: "*eager men and women by the thousands, all over Europe, lined up to give themselves the pleasure of electricity*" [18].



Figure 6. Engraving c. 1750, Jürgen Teichmann, *From Bernstein to the Electron*, German Museum of Masterpieces of Science and Technology, Munich.

The romance with electricity had begun. Sober scientific warnings of its dangers did not dampen the public's infatuation then any more than it does today, early in the 21st century, when the latest miracle of cellular technology is unpacked for yet another triumphant improvement in how we live.

ANIMAL ELECTRICITY AND THE BI-METALLIC BATTERY

Toward the end of the 18th century, however, the genie was still bottled up. It required an intense scientific debate over the meaning of a scientific discovery, involving the behavior of frogs' legs, to set it free.

The debate was between two experimental scientists, a physician and a physicist. Italian physician and anatomist Luigi Galvani's experiments on the behavior of frogs' nerve and leg muscles stimulated by electric current—variously generated by Leyden jars, lightning storms, and metal objects—led him to conclude that the animal's leg (its muscle and nerve) "probably bears two opposite surfaces, internal and external, corresponding to the internal and external plate of the Leyden jar." Galvani discovered that the static electricity provided by the Leyden jar or by nearby lightning storms was not necessary to catalyze the frog leg's sudden extensions and contractions. It was "enough to connect leg nerves and muscles through metallic conductors, thus realizing [completing] a circuit similar to that which develops in a Leyden jar" [19].

Galvani believed he had proven "that the nervous principle was electrical," that he had discovered the "long-sought for 'vital force'…the most controversial subject of the time" [20]. He named the phenomenon he had meticulously observed over several years "animal electricity" and published his experimental results in 1791, simultaneously sending his paper to the soon-to-be renowned Italian physicist Alessandro Volta.

Volta replicated Galvani's experiments and decided the source of the visible results caused by electricity was not in the animal but in the differing metals that touched it, such as an iron scalpel or a brass hook from which it was sometimes suspended or the metal plate on which it sometimes lay. Volta believed "that the unusual electrical behavior observed by Galvani involved two different types of metals," and that the animal tissue was irrelevant: "any moist material between the two metals would produce electricity" [21].

In 1793 Volta published his theory of bi-metallic electricity in the Royal Society's Philosophical Transactions, "setting in motion both a major advance…as well as a particularly strident controversy that was to occupy the life sciences" throughout the following centuries (even to the present moment). He left no doubt there "was no electricity in living things—Galvani had simply misinterpreted his findings" [22]. Galvani then conducted an experiment that demonstrated his animal electricity without the intervention of metal, showing that when a nerve section of a frog's leg muscle touched the outside surface of the muscle, it contracted. Chary of controversy, he published his result anonymously in 1794. When Volta and others discounted this finding, Galvani followed the experiment with another in 1797, the year before he died, showing that when the nerves of a frog's two legs made contact, both legs contracted. (Figure 7)

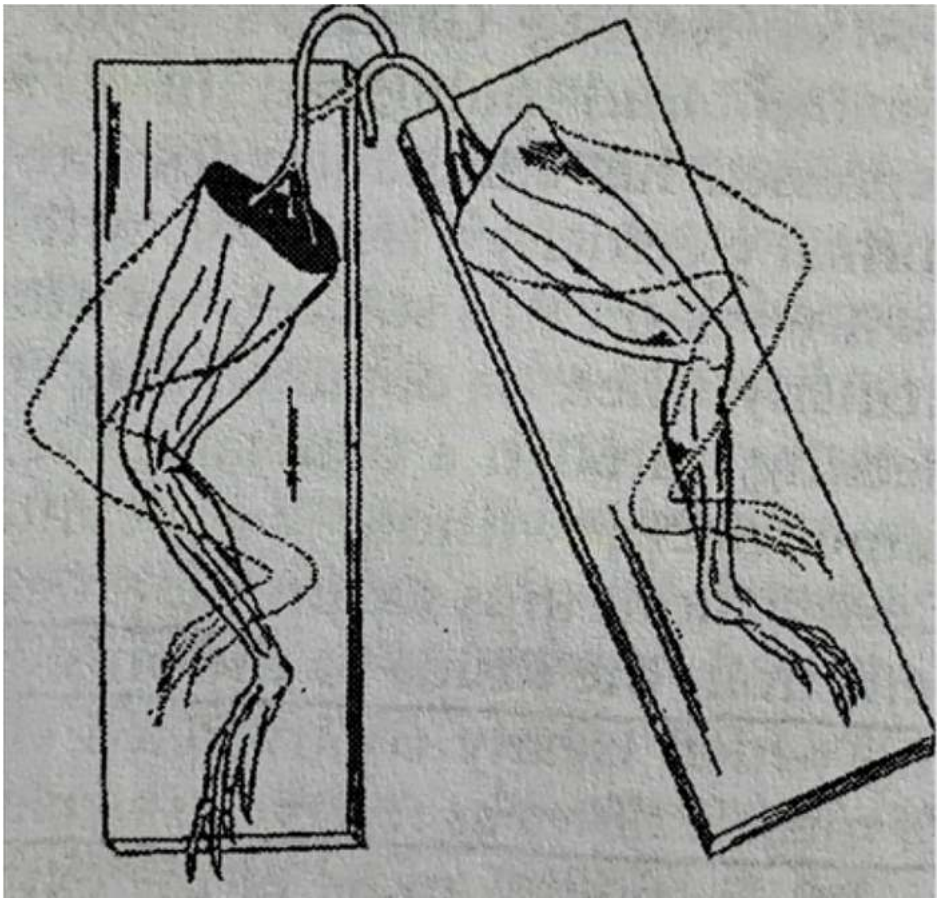


Figure 7. Galvani's 1797 experiment. When the surface of a section of the right sciatic nerve touches the intact surface of the left sciatic nerve, both legs contract. SOURCE: Marco Piccolino [19].

This experiment, considered foundational for the future discipline of electrophysiology, was also "passed by, practically unnoticed by the scientific community" [23]. Though decades later his work would be validated, Galvani died a disappointed man.

Meantime, Volta was continuously experimenting with various metals for his electric "pile," measuring and ranking each metal's conducting potential. Alternating discs of dissimilar metals, each pair separated by a dielectric plate such as cardboard, were themselves separated by brine-soaked cloth (the electrolyte) and stacked one on top of the other. When Volta connected a wire to each end of his "pile," one electrode positive, the other negative, an electric current flowed continuously. By simply disconnecting the wire at one or the other end of the stack, he halted the flow of electricity.

Volta's electricity appeared to be of a new kind, one that produced a steady, reliable current that "rushed forward like water in a river so that it was called an electric current." And it was storable, portable, and reusable [24].

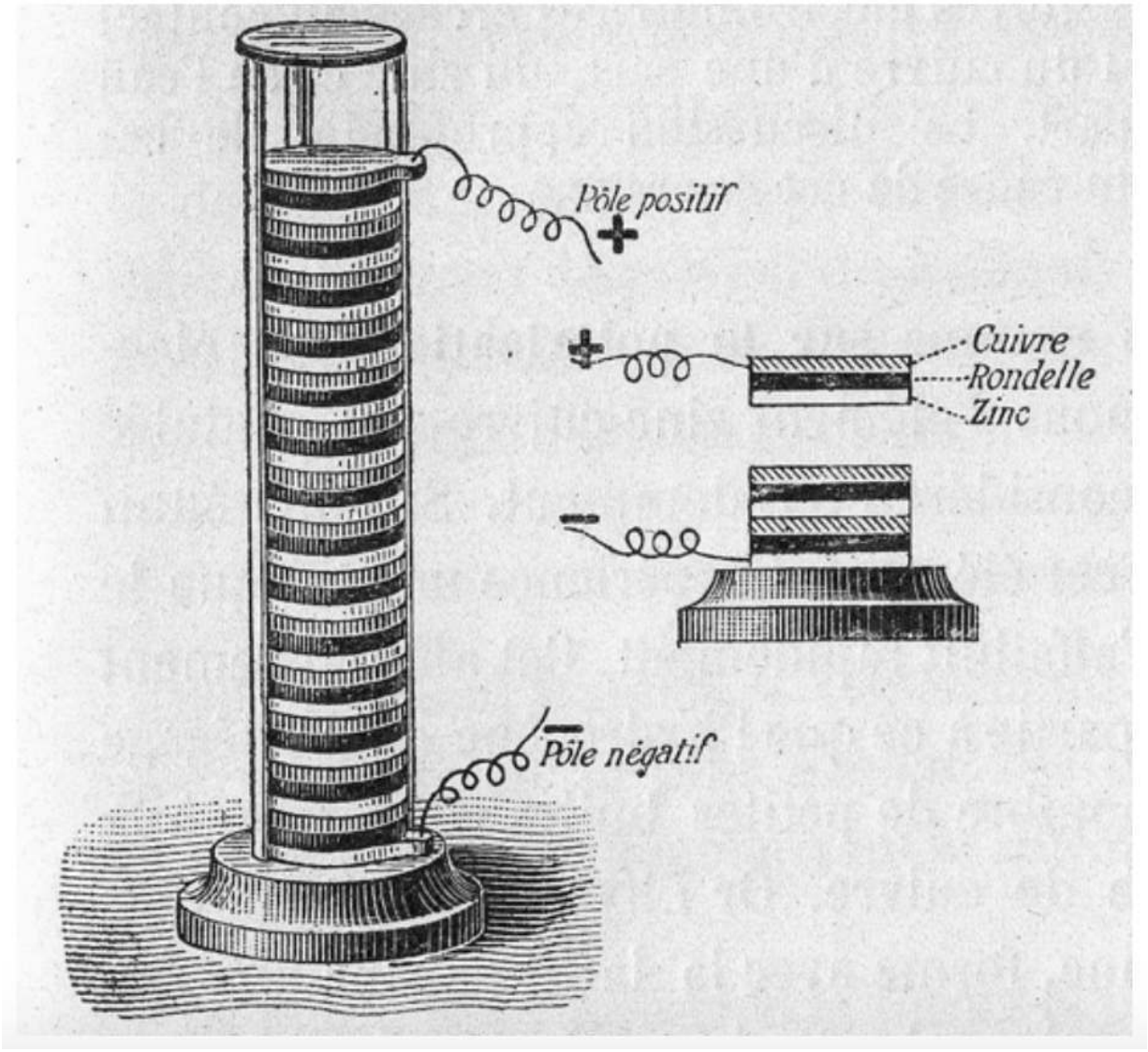


Figure 8. Schematic drawing of Volta's "*Pile*." *Cuivre* means copper; *rondelle*, slice or insluator. SOURCE: Wikipedia.

In 1800, Volta submitted his findings to the Royal Society's Proceedings. The impact of his article was immediate. Within a year he was called to demonstrate his invention to Napoleon and his court, gaining a life pension and the title of count for his trouble. Voltaic piles—the world's first batteries—were immediately built and put to experimental use in laboratories all over Europe and America.

Volta's invention utterly eclipsed Galvani's discovery of bioelectricity. Life and electricity were henceforth considered separate phenomena. Indeed, ordinary people "even forgot," unlike their 18th century forbears, "to wonder what the nature of electricity was," and the buildout of an electrical civilization proceeded "without [anyone] noticing, or thinking about, its [biological] consequences" [25]. In hindsight we could ask, was Volta's victory a Pyrrhic one? (The question is of course moot.)

DISCOVERY OF THE ELECTROMAGNETIC FORCE

Over the ensuing decades Volta's battery was constantly improved, as was the scientific understanding of electricity, with such basic properties as charge (*coulombs*), electric potential or voltage (*volts*), current or amperage (*amps*), resistance (*ohms*), and power (*watts*) rigorously stated in the form of mathematical-scientific laws.

The next major turning point in the scientific understanding of electricity arrived by chance in April 1820. A Danish physicist, Hans Christian Ørsted, was preparing a lecture on Voltaic electricity when he noticed that whenever he completed an electric circuit in a wire conductor, a nearby compass needle instantly and briefly deflected from its at-rest position pointing to magnetic north, and when he switched the current off, it again deflected, but in the opposite direction. Ørsted had accidentally confirmed electricity and magnetism were somehow related, despite the widespread belief they were separate phenomena. After further experimentation, he showed that the magnetic field produced by a moving electric current circled around the wire carrying the current. In July 1820 he published his revolutionary finding.

On reading Ørsted's paper a German chemist, Johann Schweigger, discovered that a coiled wire surrounding a compass needle (which was in effect a small magnet) caused the needle to deflect whenever the coil's circuit was closed (turned on) or opened (shut off). And the more turns in the coil, the greater the deflection. In September 1820 he presented his discovery of the "*multiplier*," so named because each additional coil multiplied the effect of an electric current on a magnetized needle.

Scientists all over Europe made double haste to understand the new "*electro-magnetic*" force. Meantime Schweigger's multiplier could also be used to detect electric currents, the sensitive magnetic needle deflecting whenever the weakest current coursed through the little wire cage (*the multiplier*) surrounding it. It enabled researchers to measure current and conduct scientifically meaningful experiments. The prototype galvanometer (so named in honor of Galvani) was immediately adopted and continuously improved on throughout most of the remainder of the century.

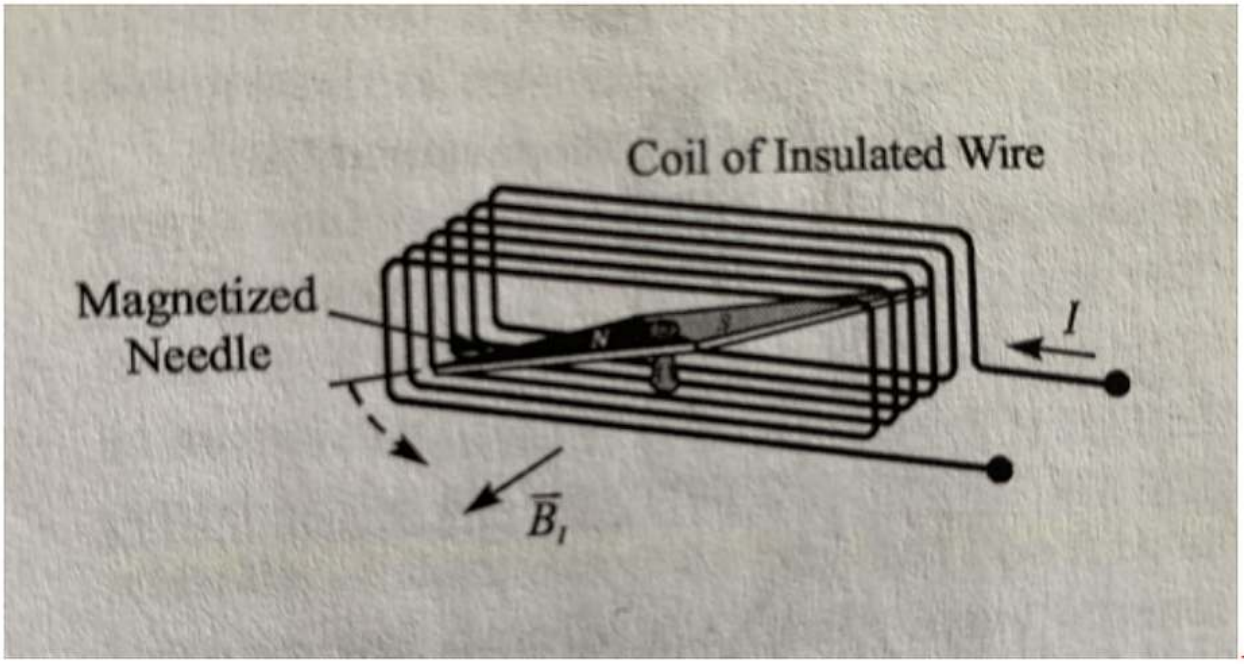


Figure 9. Schematic drawing of a galvanometer, based on Schweigger's design. *I* indicates the flow of current from a battery (not pictured) and B_1 indicates the deflection of the needle within the magnetic field. SOURCE: Glenn S Smith [38].

Ørsted's paper also inspired a brilliant young French mathematician, André-Marie Ampère, to set up his own experiments. Observing a demonstration of Ørsted's discovery, Ampère suspected magnetism was an inherent property of an electric currant. If so, a magnet was not needed for experimental proofs. In September 1820, Ampère showed that two parallel electrified metal conductors were attracted when their currents flowed in the same direction and repelled when they flowed in opposite directions. No magnetic needle was needed to prove that a moving electric current was an inherently electromagnetic phenomenon or force. Magnetism was, in effect, a fundamental property of a current of electricity in motion (as opposed to static electricity).

During this time Ampère's colleague François Arago demonstrated that a coiled electric wire attracted metal filings when electrified and dropped them as soon as the coil's circuit was broken. By putting an iron bar inside a wire coil and electrifying the coil Arago discovered that the bar would be temporarily magnetized, as Schweigger had shown, and that an electric current produced "*a cylinder of magnetism around the* [conducting] *wire*" [26]. Ampère had meanwhile demonstrated that the greater the intensity of the electric current, the greater the magnetic force, and that their relationship could be stated mathematically.

Ampère also theorized an "'*electrodynamic molecule' (the forerunner of the idea of the electron) served as the constituent element of electricity and magnetism*" [27]. Ampère believed all atoms (a purely hypothetical concept in the 1820s) possessed electromagnetism, and thus all matter (including life itself) was inherently electromagnetic, a belief shared by his English scientific correspondent, Michael Faraday.

Like Ampère and Arago, Faraday too was immediately inspired by Ørsted's discovery. Within months he had set up an experimental demonstration of electromagnetic rotary motion by suspending a freely moving wire in a container of conductive mercury surrounding a bar magnet. He then electrified the wire and thereby "*created a magnetic field around it, which interacted with the field of the magnet, pushing the wire around [the magnet] in a circular motion*" for as long as he maintained the wire's circuit. Faraday's was the first of many lab demonstrations and working prototypes of the electric motor, all of which were decades in advance of practical, commercial motors.

His discovery of what he called "*electromagnetic rotation*" through the interaction of a magnet and a current in a conductor "*so excited Faraday that he spent the next decade, on and off, trying to understand the physics behind electromagnetism*," [28] even as he worked on other pressing scientific and technical problems assigned him in his role as the superintendent of the Royal Institution of London's research laboratory.

In 1824 an English inventor, William Sturgeon, decided to create a practical device that would enable the newly discovered electromagnetic force to perform work. He wound a coil of wire, insulated with varnish, loosely around an unmagnetized iron horseshoe and made a closed circuit in the wire, temporarily magnetizing the iron (as Schweigger and Arago had shown). By switching the current off the magnetic force was simultaneously shut off. Switching it on caused "*the ordinary iron*" to mysteriously "*come alive…as if an invisible force were jumping from the wire into the iron*," [29] enabling his seven-ounce electromagnet to lift a nine-pound weight, using the current of a single-cell battery. Sturgeon found he could regulate the magnet's power by adjusting the current's strength, exactly as Ampère had suggested.

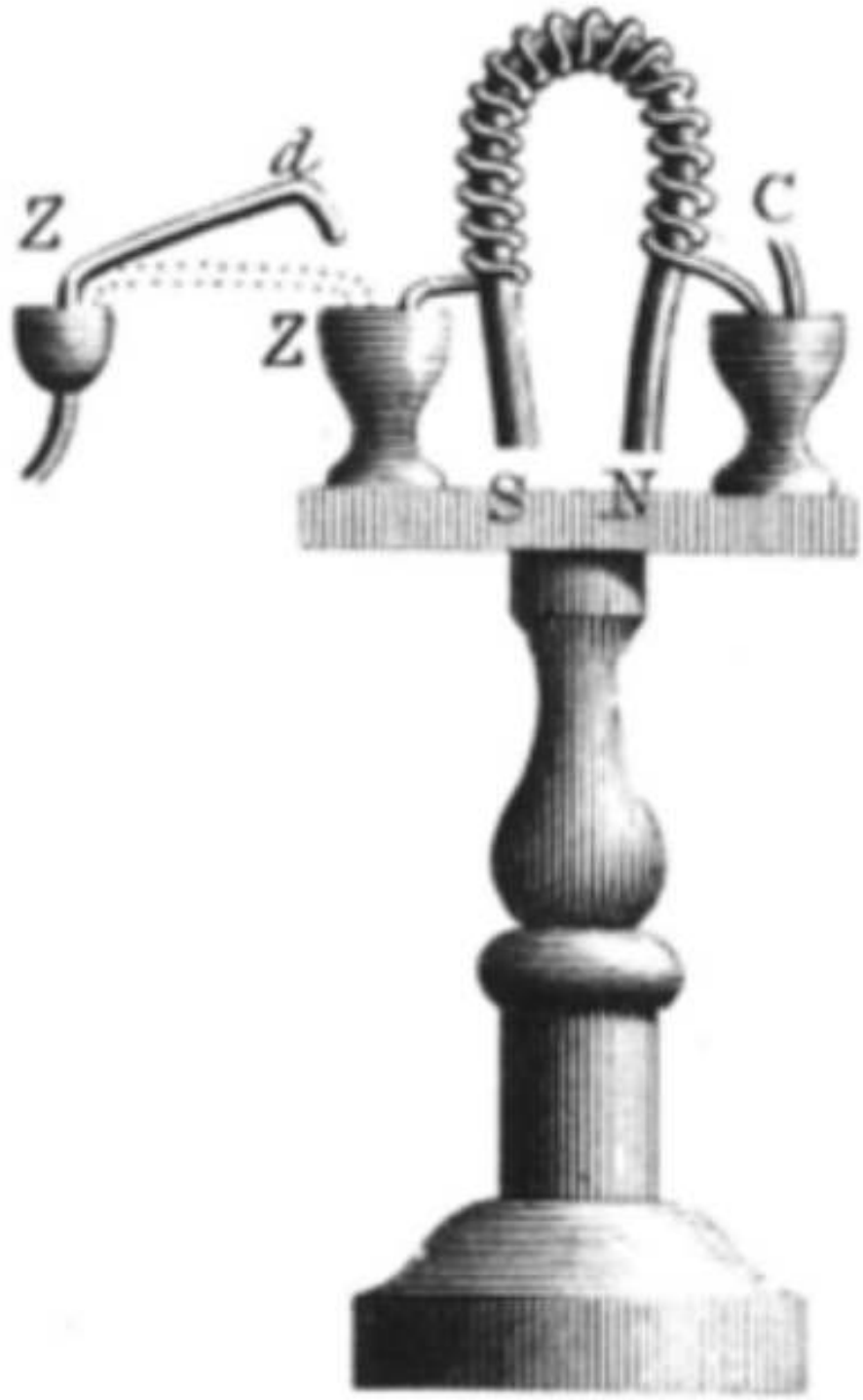


Figure 10. Sturgeon's horseshoe magnet. Z is conductive mercury in cups, d the switch, C the current. Battery not shown. SOURCE: Wikipedia.

A young American physicist, Joseph Henry, learned of Sturgeon's electromagnet in 1827. The following year he combined "*Schweigger's multiplier with Sturgeon's electromagnet*" and tightly wound a horseshoe-shaped iron bar with several layers of insulated wire. In 1829 he publicly "*demonstrated an electromagnet with 400 turns, or about 35 feet, of insulated wire*," making a magnet that "*possessed power superior to that of any before known*" [30].

Although Henry's magnets were capable of lifting hundreds and later thousands of pounds, he discovered that beyond a certain number of turns of wire magnetic power dropped off. (Ohm's theory of resistance, published in Germany in 1827, was unknown to most English-speaking scientists until his book about it was translated fourteen years later.)

The problem of electromagnetic energy loss over distance had been predicted in 1824 by the English mathematician and physicist Peter Barlow, who like many scientists of the time was intrigued by the prospect of electromagnetic communication, but had "'*found such a sensible diminution' of the needle's deflection through only 200 feet of wire*, '*as at once to convince me of the impracticability of the scheme*'" [31]. In other words, after travelling 200 feet, an electromagnetic circuit lost its power to deflect a galvanometer needle—to do work.

Intrigued by this difficulty, between 1828 and 1830 Henry conducted numerous experiments that demonstrated the effects of two different types of electromagnets used in combination with two different types of battery that he called "*quantity*" and "*intensity*" by virtue of their differing abilities to lift weight ("*quantity*") with a large low-voltage, high-current battery, or to transmit electromagnetic energy over long distances ("*intensity*") with a series of low-current batteries that generated the requisite high voltages to "*push*" the current over long distances. Henry's results were in his own words, "*directly applicable to Mr. Barlow's project of forming an electro-magnetic telegraph*" [32]. He published his findings in January 1831. They were to prove revolutionary for the development of the long-distance electric telegraph, which despite decades of experimentation, had never left inventors' workshops and laboratories.

INDUCTION

In December 1831, the prodigious experimentalist Michael Faraday read the first of what would become a long series of papers to a Royal Institution audience. He reported on his experiments, conducted during the prior summer and early fall, which showed magnetism induced electric current in a conducting wire. His historic paper was published later, in April 1832. Many scientists, including Ampère and Ørsted, were convinced that if an electric current possessed magnetism as an inherent property, *magnetism should as well possess an electric force*. But the indissoluble connection between electricity and magnetism had eluded scientists. For ten years no one had been able to prove it.

> *In his talk that December, Faraday provided the first experimental proofs that "induction" was possible. In one of his early experiments he wound a carefully insulated wire tightly around one side of an unmagnetized iron ring and connected both its ends to a battery; on the opposite side of the ring he did the same thing, connecting its wires to a galvanometer. The two coils were carefully separated on the ring. When the battery-connected coil's circuit was made on its side of the iron ring, the iron was magnetized*

and induced a current in the coiled wire on the opposite side, registered by the galvanometer needle's immediate deflection. In Faraday's words, "the impulse at the galvanometer, when contact was completed or broken, was so great as to make the needle spin round rapidly four or five times before the air and terrestrial magnetism could reduce its motion to mere oscillations" [33].

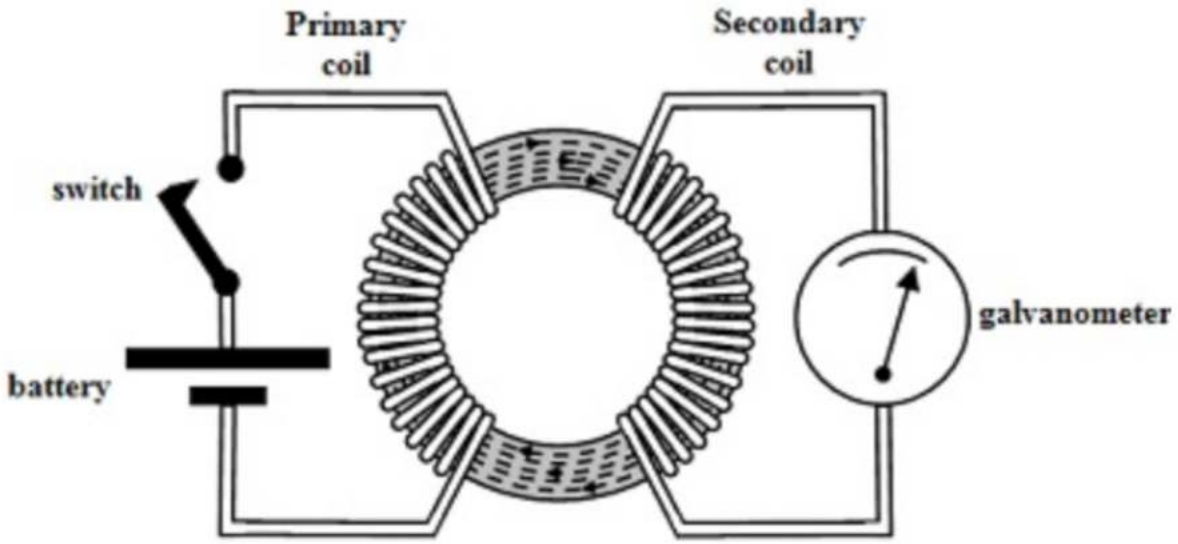


Figure 11. The ends of the wire coil on the left were connected to a battery; those on the right, to a galvanometer. The two coils were separated on the iron ring. SOURCE: Wikipedia.

Joseph Henry independently discovered induction and shares the honor of its discovery with Faraday. Henry published his experimental results later in 1832, after Faraday.

In his 1831 experiments proving induction, Faraday discovered that in addition to electric current and magnetism, motion was a third factor that influenced the generation of a continuous electromagnetic current. In another of his induction experiments, he attached the ends of a wire coil to a galvanometer and then plunged a bar magnet into the coil. Each time he moved the magnet in or pulled it out of the wire coil, the galvanometer registered a current first in one direction and then the other. "*Then, by constantly moving the bar magnet in and out of the coil he could make the galvanometer needle vibrate from side to side in phase with the motion of the magnet*" [34]. Increased velocity of the magnet's motions in and out of the coil induced an increased voltage in the coil, measured by the spin of the galvanometer's needle. But if neither the coil nor the magnet was moved in relation to one another, no current registered. Relative motion was necessary to induce a persistent current.

"Something was traveling from the magnet into the wire." With this experiment Faraday showed "that electricity wasn't some hissing liquid that could only be funneled along inside a wire," like a current of water, but "could be brought into existence by an invisible force that spread from a moving magnet," a force that "stretched across empty space" [35].

Faraday had been inspired by Arago's famous 1824 rotating disc experiment. Arago manually rotated an unelectrified copper disc, above which he suspended a magnetic needle. The needle spun whenever he rotated the disc. No electric current was used, only mechanical motion. Copper was, furthermore, non-magnetic. The effect had proved inexplicable. To solve the riddle posed by Arago's "rotations," Faraday decided to design "an improved version of Arago's disc experiment. He mounted a copper disc on a brass axes [sic] so that it could freely rotate between two poles of a permanent [horseshoe] magnet. He then connected the disc to a galvanometer by attaching one wire to its centre and another touching its rim" [36]. When the crank was turned to rotate the disc, the disc's motion cut through the magnet's field and induced a radial flow of current in the disc from its axle, or center, to its outer edge. Turning the crank in the opposite direction reversed the flow of induced electric current from rim to axle.

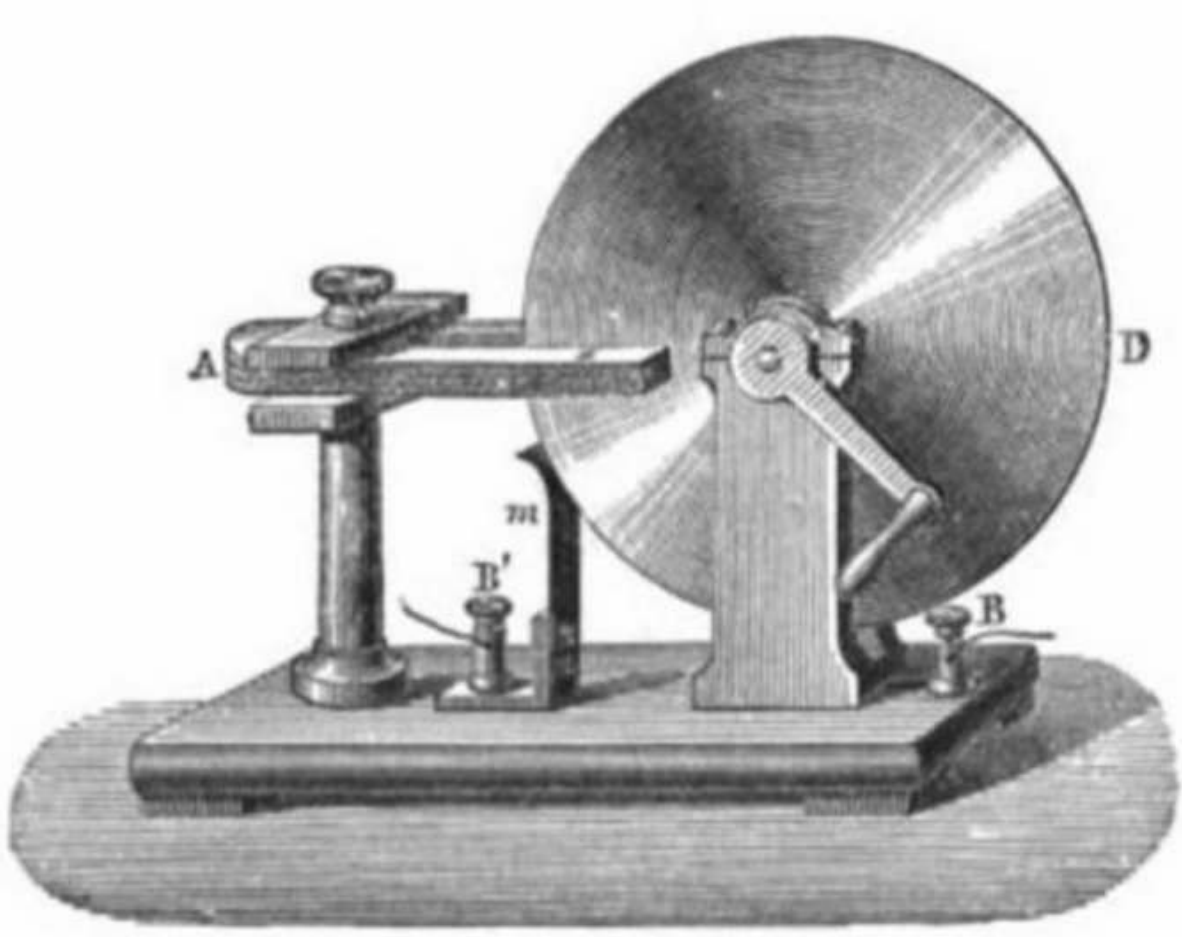


Figure 12. The copper disc D is located between the two poles of a horseshoe magnet A. The wire-binding post B is connected by wire (not shown) to the center of the copper disc and the wire-binding post B' by wire to the outer edge of the disc via the sliding contact m. Both wires led to a galvanometer (not shown). SOURCE: Wikipedia.

Faraday wrote, "Here therefore was demonstrated the production of a permanent current of electricity by ordinary magnets." And: "If a terminated wire [or disc] is moved so as to cut a magnetic curve [line of force], a power is called into action which tends to urge an electric current through it" [37]. In sum, Faraday had shown "how a magnetic field and continuous mechanical motion would

produce a continuous electric current" [37]. He had solved Arrago's riddle and provided definitive proof of electromagnetic induction, "one of the greatest scientific achievements of all time," a discovery with "tremendous technological consequences" [38].

Faraday's induction ring was the first prototype of what later became an electrical transformer, improved continuously by others ever since he first demonstrated it, which proved essential to the long-distance alternating current (AC) electric power grids toward the end of the century. Faraday's copper disc rotating in a magnetic field demonstrated the operating principle of the direct current (DC) generator, or dynamo, that (after many iterations) over the next four decades, powered industry and lit up residences and offices around the world.

Later, Faraday experimentally showed that all substances—whether solid, liquid, or gas—reacted to 'magnetic forces' and were mostly "diamagnetic" or repelled by either magnetic pole, aligning at right angles, while a few, such as iron, nickel, and cobalt, were "paramagnetic" or attracted by either magnetic pole, aligning parallel. He summarized his discovery with a telling image: "If a man could be suspended with sufficient delicacy…and placed in the magnetic field, he would point equatorially, for all the substances of which he is formed, including the blood, possess this property" of diamagnetism, or repulsion [39].

By the mid-1840s, when the commercial development of the electric or "magneto-electric" telegraph was underway, Faraday had come to believe three-dimensional "lines of force…were the vehicle that conveyed the [electromagnetic] forces and were physically present in space." He eschewed straight lines for curves and "curved paths" and introduced the terms "electro-motive force" and even more significantly for the future of physics, "lines of force" and "magnetic field," which conveyed the "idea that space itself could be the seat of [electromagnetic] forces." Defying Newtonian "action at a distance" in empty space, all Faraday's careful experimental findings suggested "that nothing happened at a distance, that all forces and all induction" acted "along paths that were rarely straight" [40].

Since his experiments with polarized light in 1845 had showed him that magnetism "could affect a ray of light," Faraday had become convinced "magnetism was a universal property of matter" [41]. In an extemporaneous talk before a Royal Institution audience in April 1846, Faraday shared his radical vision with a surprised audience: "[T]he universe was crisscrossed by lines of force—electric, magnetic, and possibly other kinds….'atoms' were merely the centers of forces that extended through all space. When disturbed, the lines of force vibrated laterally and sent waves of energy along their lengths, like waves along a [shaken] rope, at a rapid but finite speed. Light," Faraday suggested, "was probably one manifestation of these vibrations," which were "vibrations of the lines of forces themselves" [42].

Faraday had, in effect, outlined scientific ideas that would in due course revolutionize physics and transform human life in the 20th century. Humanity was poised to bathe itself in new electromagnetic fields that did not "act at a distance," but made direct physical contact with objects, both inanimate and animate.

BIRTH OF THE TELEGRAPH

Immediately after his paper on electromagnets was published in 1831, Joseph Henry "set out to demonstrate the practicability of an electromagnetic telegraph…[using] a small battery and an 'intensity' magnet connected through a mile of copper bell-wire strung throughout a lecture hall" at New York's Albany Academy, where he taught [43]. He placed a permanent bar magnet in the space between the two poles of a horseshoe electromagnet next to a bell. When he closed the mile-long circuit, the bar magnet deflected and rang the nearby bell, returning to its position when the circuit was shut off. The following year, when he moved to teach at Princeton, he repeated the experiment, connecting his lab to his home by using a remote electromagnet to activate a local circuit that rang a bell in his house, alerting his wife he was coming home for lunch.

"Henry realized it would be easy to communicate just by agreeing that different arrangements" of the ringing could "represent different letters." And when one of his students "switched the battery on and off, his friends in the next room or even down the hall would hear the ringer sound in short bursts, just as fast as the hand could move" [44]. In 1838, when a frustrated Samuel Morse showed up at the professor's doorstep and was welcomed in, he began to take notes that would change the world.

The telegraph was the first commercially significant electromagnetic technology to be globally deployed. "Within thirty years," of Morse and Vail's 1845 launch of their telegraphic system in the US, "there were over 650,000 miles of wire, 30,000 miles of submarine cable" linking all inhabited continents, and "20,000 towns and villages were on-line" [45]. The "Victorian Internet" had spread "with astonishing speed" according to one historian, "more rapidly than today's Internet," and "by 1870 formed a world-wide telecommunications system" [46] that remained in use until the 1950s.

CONCLUSIONS

In the mid-19th century human beings began to alter Earth's natural electromagnetic environment by rolling out wired electric technology on a global scale. We do not understand the environmental effects of this rollout, which ramped up in the late 1870s with the invention of the telephone, the light bulb, the dynamo, the alternator, and the modern transformer, permitting AC current to power industry, make skyscrapers, and light up the world. By the end of the 19th century Hertz's discovery of radio waves was being put to use, and after World War I electromagnetic energy was freed to travel across space without the inconvenience and expense of wires, creating wholly new applications and industries, including radio, radar, TV, computers, and cell phones.

Nearly two centuries after the discovery of electromagnetism, environmentalists, educators, and medical professionals remain largely uninformed about how it functions either theoretically or practically, and therefore ignorant of what risks it might pose to our natural environment, to human health, or to the immense planetary structures governed by the electromagnetic force: the global electric circuit, the ionosphere, and the magnetosphere. How much longer can such willful ignorance about risk continue to run consistently parallel to the immense scientific and technical knowledge needed to maintain and keep constructing the electric edifice of 21st century civilization?

Acknowledgements

Thanks to Abigail Stone for creating the illustrations in Figures 1, 2, and 4. Thanks to Rob Williams for critical reading and advice.

References

1. See 137-page "Bibliography" in Arthur Firstenberg, *The Invisible Rainbow: A History of Electricity and Life* (White River Junction, VT & London: Chelsea Green, 2020), 413–551.
2. Firstenberg, *Op. Cit.*, 39–41 and 365–377.
3. *Ibid*., 115–116.
4. *Ibid*., *Op. Cit.*, 116.
5. Elizabeth Pastor Guzman, "Tuning in to the Earth's Natural Rhythm," *Brain World Magazine*, Summer 2014. https://brainworldmagazine.com/tuning-in-to-the-earths-natural-rhythm/. Accessed December 15, 2020.
6. Martin Blank & Reba Goodman, "DNA is a fractal antenna in electromagnetic fields," *International Journal of Radiation Biology*, 87,4 (2011). https://www.tandfonline.com/doi/full/10.3109/09553002.2011.538130. Accessed July 21, 2020.
7. Firstenberg, *Op. Cit.*, 118.
8. Iona Miller, "Schumann Resonances, Psychophysical Regulation & Psi (Part 1)," *Journal of Consciousness Exploration & Research*, 4, 6 (July 2013). https://quwave.com/316-971-1-PB.pdf Accessed December 15, 2020.
9. Firstenberg, *Op. Cit.*, 120.
10. *Ibid*., 153–154.
11. *Ibid*.
12. Arthur Firstenberg, *7*.
13. "The Electric Ben Franklin," Undated. https://www.ushistory.org/franklin/science/electricity.htm Accessed September 28, 2020.
14. "Franklin's Lightning Rod," The Franklin Institute. Undated. https://www.fi.edu/history-resources/franklins-lightning-rod Accessed September 28, 2020.
15. "The Electric Ben Franklin," *Op. Cit.*
16. "Benjamin Franklin Explains the Leyden Jar," The Atlas Society. February 22, 2012. https://www.atlassociety.org/post/benjamin-franklin-explains-the-leyden-jar Accessed July 23, 2020.
17. Firstenberg, *Op. Cit.*, 5.
18. *Ibid.*, 5, 8.
19. Marco Piccolino, "Luigi Galvani and animal electricity: two centuries after the foundation of electrophysiology," *Trends in Neuroscience*, 20, 10, 1997. https://www.sciencedirect.com/science/article/abs/pii/S0166223697011016 Accessed July 27, 2020.
20. Robert O Becker & Andrew M Marino, *Electromagnetism & Life* (Belcher, LA: Cassandra Publishing, 2010; originally published by State University of New York Press, 1982), 9.
21. "Voltaic Pile—1800," National MagLab. December 10, 2014. https://nationalmaglab.org/education/magnet-academy/history-of-electricity-magnetism/museum/voltaic-pile-1800 Accessed August 3, 2020.
22. Becker & Marino, *Op. Cit.*, 10.
23. Piccolino, *Op. Cit*.
24. David Bodanis, *Electric Universe: How Electricity Switched On the Modern World*, (New York: Three Rivers Press/Random House, 2005), 5.
25. Firstenberg, *Op. Cit.*, 46.

26. "Michael Faraday's electric magnetic rotation apparatus (motor)," The Royal Institution. Undated. https://www.rigb.org/our-history/iconic-objects/iconic-objects-list/faradays-motor Accessed August 6, 2020.
27. J B Shank, "André-Marie Ampère," Britannica Online Encyclopedia, updated https://www.britannica.com/biography/Andre-Marie-Ampere Accessed August 20, 2020.
28. Jim Al-Khalili, "The birth of the electric machines: a commentary on Faraday (1832) 'Experimental researches in electricity'," *Philosophical Transactions* A, 2015. http://europepmc.org/article/PMC/4360079 Accessed August 04, 2020.
29. Bodanis, *Op. Cit.*, 16.
30. David Hochfelder, "Joseph Henry: Inventor of the Telegraph?" The Smithsonian Institution, 1998–2007. https://siarchives.si.edu/sites/default/files/pdfs/jhpp/JHP_Inventor_of_the_Telegraph.pdf Accessed September 03, 2020.
31. *Ibid.*
32. *Ibid.*
33. Al-Khalili, *Op. Cit*.
34. *Ibid.*
35. Bodanis, *Op. Cit.*, 66.
36. *Ibid.*
37. *Ibid.*
38. Glenn S Smith, "Joseph Henry's role in the discovery of electromagnetic induction," *European Journal of Physics*, 38 (2017). https://iopscience.iop.org/article/10.1088/0143-0807/38/1/015207 Accessed September 14, 2020.
39. Nancy Forbes and Basil Mahon, *Faraday, Maxwell, and the Electromagnetic Field: How Two Men Revolutionized Physics* (Amherst, NY: Prometheus Books, 2019), 100.
40. *Ibid.*, 109.
41. *Ibid.*, 101.
42. *Ibid.*, 102.
43. Hochfelder, *Op.Cit.*
44. Bodanis, *Op. Cit.*, 19-20.
45. Tom Standage, *The Victorian Internet* (New York & London: Bloomsbury, 1998), 102.
46. J B Calvert, "The Electromagnetic Telegraph," April 7, 2007, University of Denver archives. https://mysite.du.edu/~jcalvert/tel/morse/morse.htm Accessed December 16, 2020.