Kieran Murphy

Induction after Electromagnetism

Faraday, Einstein, Bachelard, and Balzac

Abstract: Faraday's discovery of electromagnetic induction transformed the world by providing the blueprint for the mass production of electricity and a new type of motor that replaced the steam engine as the main driving force of the global economy. Electromagnetic induction presented a new set of physical problems whose solutions undermined the theoretical framework of Newtonian physics and redefined the nature of inductive reasoning. As the main logical inference characterizing the natural sciences, induction has been the subject of numerous philosophical debates about its definition and scientific value. In this paper, I trace a lesser-known contribution to these debates that developed in the wake of the epistemological changes instigated by the phenomenon of electromagnetic induction and that, through Einstein's and Bachelard's achievements, changed the modern conceptions of science, discovery, and history. I also argue that these achievements are inscribed in a tradition that should include Balzac's pioneering use of electromagnetic induction to convey the elusive nature of scientific discovery.

1 Transformational motors and interdisciplinary practices

Michel Serres has shown how the steam engine marked the advent of *transformational motors* and impacted modern thought by redefining the origin of movement (1977, 1975, Ch. 2).¹ From Aristotle's *unmoved mover* to the neoclassical period, the ultimate cause of all movement in the universe remained metaphysical. Ancient motors such as a spring or a water mill relayed the motive force provided by human, animal, or natural actions, which themselves worked as the relays of the primordial motor. The steam engine did not simply transport and transmit movement; it appeared to generate its own motive force by transforming heat into mechanical work. This remarkable motor turned the age-old

¹ This essay is an early version of some of the ideas and arguments that I explore in greater details in my book *Electromagnetism and the Metonymic Imagination* (Penn State University Press, 2020).

metaphysical inquiries concerning the origin of movement into a physical problem. In 1824, the founder of thermodynamics, Sadi Carnot, began to provide the scientific explanation to this problem when he demonstrated that the motive force of the steam engine depended on a temperature difference between hot and cold sources. According to Carnot, a temperature difference displaces the metaphysical motor as the source of movement.

Beyond mines, factories, and locomotives, the steam engine embodied a shift from the metaphysical to the secular generation of movement transpiring concurrently in the sciences, arts, and humanities. Serres has traced how influential figures such as Hegel, Turner, Darwin, Marx, Zola, Nietzsche and Freud attempt to seize the means of production of their respective subject matters by displacing metaphysical intervention with the generative power of difference. Their wide-ranging works not only rely on analogies inspired by the steam engine; they themselves function as transformational motors.

In his interdisciplinary study of the rise of technological and conceptual transformational motors, Serres brings the steam engine to the fore due to the central role it played in the development of thermodynamics, and pays little attention to the electromagnetic motor, the other great catalyst of the Industrial Revolution. The discoveries of electromagnetism and electromagnetic induction unveiled a new kind of relation and difference between electricity and magnetism that became another source of movement and inventions. From Michael Faraday to Albert Einstein, the electromagnetic difference contributed to the groundbreaking development of physical concepts such as energy, field theory, and relativity. Beyond physics, however, the legacy of the electromagnetic difference has not attracted much scholarly attention, especially its early impact on literature, cognition, history, and language. As Serres has demonstrated in the case of the steam engine, all cultural formations – artistic, scientific, or otherwise – partook in the exploration of the conceptual shift embodied by transformational motors. The study of the transformative energies manifested throughout nineteenth-century cultural formations cannot then be limited to the stronghold of a single academic discipline without committing an usurpation of power. The main challenge in understanding the emergence of a new type of difference – in our case, the electromagnetic difference – consists therefore of recovering the interdisciplinary bridges where it initially spread and where it continues to thrive. This paper contributes to this vast undertaking by showing how the electromagnetic difference is at work in Balzac, Poe, Einstein, and Bachelard, and,

in turn, how it provides a critical connection between disciplines such as literature, physics, and the philosophy of science and history.

2 Electromagnetic interaction and induction

When Hans Christian Ørsted (1777–1851) discovered the existence of a connection between electricity and magnetism in 1820, it took the English and French speaking scientific community by surprise because, following Benjamin Franklin and Laplacian physics, it believed that these two forces were completely unrelated. Ørsted stumbled upon the proof of this affinity when he noticed that a current-carrying wire deflected a nearby compass needle. He also realized that the needle would point in the opposite direction whether it was above or below the wire. This strange behavior greatly intrigued the scientific community because it indicated the existence of a different kind of attraction and repulsion that did not simply follow a straight line, as in Newton's law of universal gravitation, but that operated through a kind of circular action. Ørsted argued that the electric current generated a magnetic effect in its vicinity spiraling along the length of the wire. He coined the adjective *electromagnetic* to characterize the new type of circular influence manifested by the interaction of the current-carrying wire and the compass needle (1998; Caneva 2005, 176–183). Ørsted's experimental proof of the connection between electricity and magnetism gave birth to a new field of research, electromagnetism, prompted by the necessity of studying the two forces together.

In 1821, Michael Faraday (1791–1867) provided an empirical validation of Ørsted's idea of circular action spiraling along the current-carrying wire by inventing a new type of transformational motor. Faraday used mercury, a liquid conductor, to design a flexible electrical circuit, and succeeded in making a current-carrying wire rotate about a magnet, and vice-versa. In addition to clearly illustrating the circular nature of the newly found electromagnetic attraction, Faraday's experiment displayed the first electromagnetic motor by showing that the interaction of an electric current and a magnet could produce a steady movement.

The steady movement resulting from the interaction of an electric current and magnetism suggested that the reverse effect was also possible and, throughout the 1820s, researchers looked for a way to convert movement and magnetism into an electric current. Following a series of experiments that showed various aspects of this conversion, Faraday finally announced in 1831 that a conductor generated an electric current by simply moving a magnet near

it. Now known as electromagnetic induction, he initially called this new phenomenon “*magneto-electric* or *magnelectric* induction.”² Through the progressive mastery of the conversion of heat into useful work, the steam engine powered the first cycle of the Industrial Revolution. Faraday’s discovery of electromagnetic induction proved that electricity, magnetism, and movement were interconvertible, and provided the blueprint for the next generation of transformational motors that, through electric motors powered by power plant dynamos, would eventually displace the steam engine as the main driving force of the global economy.

The link between the electric current and magnetism quickly led to new theories concerning the nature of these two forces. Soon after Ørsted’s discovery, André-Marie Ampère (1775–1836) began to consider magnetism only in terms of an effect generated by loops of electric current. The reduction of magnetism to an electric current led him to devise an effective approach to quantify the relation between the two forces. To distinguish his theory from Ørsted’s, Ampère rejected the term *electromagnetic* and introduced his own term, *electrodynamic action* (as opposed to *electrostatic* action) because he was confident that he could explain all magnetic effects in terms of an electric current.

At the time Ampère laid the foundation of electrodynamics, others such as Johann Joseph Prechtel (1778–1854) and Jöns Jacob Berzelius (1779–1848) took the opposite approach as they attempted to explain the electric current in terms of magnetism (Caneva 2005, 184–188). Although their failed and forgotten theories lacked the mathematical clarity of Ampère’s, they serve as a historical reminder that, despite its achievements, electrodynamics remains a convention. As discussed below, Einstein’s theory of special relativity will re-legitimize the use of the term *electromagnetism* by arguing that, in the phenomenon of electromagnetic induction, electric current and magnetism are manifestations of the same fundamental entity, the electromagnetic field, and that they appear different due to the frame of reference of the observer.

3 A new motor for analogical exploration

In the nineteenth century, due to the pioneering works of Ørsted, Ampère, and Faraday, electromagnetism also emerged as a new empirical model to explore

² Faraday’s italics. Faraday initially adopted this terminology to differentiate “magneto-electric” from “Volta-electric induction,” or the induction of a current by another current. He soon realized that they were just variations of the same electromagnetic effect, and stopped using the latter term (Faraday 1839a, 16).

other elusive, puzzling, or highly speculative connections and interactions. Honoré de Balzac was the first canonical literary author to exploit electromagnetic induction as a conceptual engine. Less than two years after Faraday's discovery, Balzac already sensed its epistemological importance when, in his philosophical novel *Louis Lambert*, he replaced a Newtonian image with an unprecedented electromagnetic image to describe how great discoveries come from involuntary intuition. In the 1832 edition of *Louis Lambert*, Balzac invokes the Newtonian model of gravity to express how an unexpected event can lead to such an *eureka* moment: "as the fall of a pear became the primary cause of Newton's discoveries" (Balzac 1832, 333).³ A year later, in the 1833 edition of *Louis Lambert*, Balzac replaces this Newtonian image with the new electromagnetic model: "as the electric sensation always felt by Mesmer at the approach of a particular servant was the starting-point of his discoveries in magnetism" (Balzac 1833, 111).⁴

Balzac was a staunch supporter of the proto-hypnotic psychotherapy invented by Franz Anton Mesmer and known back then as *animal magnetism*. According to this last citation, Mesmer discovered a kind of *magnetism* connecting his body to his servant's by feeling an *electric sensation*. For Balzac, there is then something akin to an electromagnetic induction occurring between Mesmer and his servant. The approaching servant recalls a moving magnet that induces electricity in a nearby conductor represented by Mesmer's body.

Sporadically in other novels, Balzac relies on electromagnetic phenomena to convey the invisible workings of cognitive and vital forces, and the way they can exert an influence on other bodies through space. Balzac was particularly attuned to the implications of Faraday's discovery because he believed in the same Romantic idea that had guided Ørsted on the path to his discovery of a connection between electricity and magnetism, namely, the unity of natural forces (Balzac 1976a, 16–17). Balzac was also a friend of André-Marie Ampère's son, Jean-Jacques Ampère. Jean-Jacques Ampère had an illustrious career as a literature professor, and reportedly joked that his two greatest achievements came down to having met Balzac when he was unknown and skinny (Balzac 1906, 366).

³ Transl. by KM. "comme la chute de la poire devint la cause première des découvertes de Newton" (Balzac 1832, 333).

⁴ Transl. by KM. "comme la sensation électrique toujours ressentie par Mesmer à l'approche d'un valet fut l'origine de ses découvertes en magnétisme" (Balzac 1833, 111).

Another contemporary of Balzac, Edgar Allan Poe was also among the first major literary figures to create electromagnetic images. In the introduction of the little-known 1844 humorous tale, *The Spectacles*, Poe coins the term “magnetœsthetics” and defines it in terms of an electromagnetic interaction:

Modern discoveries, indeed, in what may be termed ethical magnetism or magnetœsthetics, render it probable that the most natural, and, consequently, the truest and most intense of the human affections are those which arise in the heart as if by electric sympathy [...].
(Poe 2000, 886–887)

As in Balzac, such passages should be considered as unconventional for this era, the norm being images relying solely on magnetism or electricity to describe romantic attraction (i.e. love as magnetic attraction, etc.). What makes the above passages from Balzac and Poe remarkable and cutting-edge, is how they use magnetism and electricity together, to convey the workings of invisible interaction behind scientific inspiration and “human affections.” The discovery of electromagnetic induction provided then a new analogical model, based on a new type of difference and relation, particularly suited for the exploration of other elusive and puzzling relations at work in phenomena such as involuntary cognition.

4 The term *induction* in electrical science

The electromagnetic difference also became a motor for exploration and discovery in physics. The various conceptual transformations undergone by the term *induction* from its initial meaning in electrostatics to Faraday’s redefinition provide an effective starting point for investigating the impact of this unprecedented motor in physics. Faraday begins the series of papers on his discovery of electromagnetic induction by defining the meaning of *induction*. The term comes from phenomena attributed to “electricity of tension,” or what we now call electrostatics:

The power which electricity of tension possesses of causing an opposite electrical state in its vicinity has been expressed by the general term Induction; which, as it has been received into scientific language, may also, with propriety, be used in the same general sense to express the power which electrical currents may possess of inducing any particular state upon matter in their immediate neighbourhood, otherwise indifferent. It is with this meaning that I purpose using it in the present paper.
(Faraday 1839a, 1)

Unlike conduction, or charging by contact, induction refers to how a negatively charged object causes a positive electrical state in another object, or vice-versa,

without apparent contact. Although they relied on different terminologies, historians credit Benjamin Franklin (1706–1790), John Canton (1718–1772), Johan Carl Wilcke (1732–1796), and Franz Aepinus (1724–1802) with the first formulation of the concept of electrostatic induction (Heilbron 1979).

From the second half of the eighteenth to the beginning of the nineteenth centuries, the term induction progressively made its way into the official terminology of electrical science. In 1777, Tiberius Cavallo (1749–1809) stated in his treatise on electricity, “The action of these plates depends upon the principle long ago discovered, viz. the power that an excited electric has to induce a contrary Electricity in a body brought within its sphere of action” (Cavallo 1777, 382).⁵ Cavallo does not explain his choice of the verb “to induce” for this electrical effect. He follows the verb’s typical eighteenth-century dictionary definition of producing or bringing into view by influence or exterior cause (Johnson 1785).⁶ The same meaning of the verb appears elsewhere in the treatise in the more familiar non-electrical contexts. At times, Cavallo also relies on “to induce” to refer to the logical inference characteristic of the scientific method associated with Francis Bacon (1561–1626), and consisting of generalizing observations into a law.

The introduction of the term *induction* in electrical science did not happen without controversy. In his often-cited 1814 treatise on electricity, George John Singer (1786–1817) writes on the subject of electrostatic induction: “Such phenomena are classed under the general term electrical influence; and positive and negative states so produced are called the electricities of position, or approximation, and by some writers induced electricity” (Singer 1814, 130). The main writer that Singer has in mind when he reluctantly mentions the term “induced electricity” is Humphry Davy (1778–1829), the great pioneer in electrochemistry, and Faraday’s old boss at the Royal Institution.

In 1812, Davy had advocated the use of the terms “induced electricity” and “induction” in his descriptions of electrical effects (Davy 1812, 74).⁷ In an article predating his treatise, Singer had criticized Davy’s indiscriminate use of the term *induction* for electrical effects that he thought were actually different and stated that “in its literal interpretation [induction] expresses nothing analogous

⁵ I could not find an eighteenth-century example that clearly signals the shift from old electrical terminologies to the verb “to induce.”

⁶ The Latin etymology of the verb “to induce” means to lead.

⁷ As noted by Singer, in Davy’s published works the apparition of the term “induction” for various electrical effects dates back at least to 1807 (Singer 1812, 219).

to any known electrical effect.”⁸ Singer also had his critics. For instance, a reviewer of Davy’s work aware of Singer’s terminological objection, stated, “As to the term induction, which is more familiar to metaphysical than physical language, it seems as convenient and applicable as any other” (“Notices Respecting New Books” 1812, 435). Although the debate on the value of the term *induction* in electrical science would go on throughout the nineteenth century,⁹ Davy’s usage quickly became the norm.

5 Thinking with magnetic curves: Faraday’s law of induction

Whether its “literal interpretation” fails to convey the nature of electrical effects or is as good “as any other,” the early controversy surrounding Davy’s choice of “induction” manifests a more profound epistemological issue linked at the time to the Newtonian framework of electrostatics. As Newton’s classical mechanics rose to prominence in the eighteenth century, it became the paramount physical elucidation of the universe. In 1785, Charles-Augustin de Coulomb (1736–1806) published the law uncovering the mathematical relation between electrostatic force and the interaction of electrically charged particles. Coulomb’s law ($F = kqq'/r^2$) looks structurally the same as the law of universal gravitation ($F = Gmm'/r^2$), suggesting that the fundamental principles of Newtonian physics were at work in all natural forces. However, as in Newton’s law, Coulomb’s law implied a type of action at a distance that occurs without delay or mediation. The actual way electricity produced an action through space remained a mystery (Balibar 1992). The debate as to whether Davy’s “induction” provided the most accurate term for a kind of electrostatic influence sidestepped the critical issue since, regardless of what word was used, it could only refer to a vague action at a distance.

During the first half of the nineteenth century, Coulomb’s achievement prompted other natural philosophers to apply Newtonian physics to magnetic and electromagnetic phenomena without conclusive success. As Faraday struggled

⁸ For Singer, Davy conflated two fundamentally different types of electrical effects, namely, the redistribution and the communication of charges that an electrically charged object could provoke in a nearby conductor (Singer 1812, 217–219).

⁹ “Amid such varying adaptations of the word *induction* there is much to gain in allotting to the electrostatic induction of charges by charges the distinguishing name of *influence*, as suggested by Priestley” (Thompson 1898, 153).

to formulate a simple rule to account for the electromagnetic effects he had identified through systematic experimenting and subsumed under the electrostatic term *induction*, he reached the first conceptual breakthrough that would eventually lead to the rejection of the theoretical framework informing Newtonian physics. Following an initial failed attempt to account for the interaction of magnetism, motion, and the induced electrical current in terms of Ampère's electrodynamics, he began to consider and develop a new concept based on the "magnetic curves" drawn by iron filings around a magnet (Steinle 1996, 152–153). He realized that he could consistently predict the electromagnetic effects of induction by focusing on the way a conductor in relative motion to a source of magnetism "cuts" its "magnetic curves" (Faraday 1839a, 32; 1839b, 66–67). By shifting the attention to the previously ignored "magnetic curves," this first formulation of what textbooks now call Faraday's law of induction was a theoretical leap whose far-reaching epistemological impact would only much later concretize (Steinle 1996).

Historians have differed widely on the main methodological factors that led Faraday to his revolutionary discoveries. Some have portrayed him as a "Baconian empiricist," others as "driven solely by theoretical and metaphysical speculations" (Steinle 1996, 144). More recently, Friedrich Steinle has described his approach in terms of "exploratory experimentation."¹⁰ The unorthodox and puzzling nature of electromagnetic induction prompted Faraday's exploratory experimentation, where, instead of designing experiments to test a pre-established idea or theory, he systematically varied experimental parameters in order to reduce the inductive effects to their essential features. Once this empirical reduction was achieved, Faraday realized that these features did not comply

10 "Far from being a mindless playing around with an apparatus, exploratory experimentation may well be characterized by definite guidelines and epistemic goals. The most prominent characteristic of the experimental procedure is the systematic variation of experimental parameters. The first aim here is to find out which of them are essential. Closely connected, there is the central goal of formulating empirical regularities about these dependencies and correlations. Typically they have the form of 'if – then' propositions, where both the if- and the then-clauses refer to the empirical level. In many cases, however, the attempt to reformulate regularities requires the revision of existing concepts and categories, and the formation of new ones, which allow a stable and general formulation of the experimental results. It is here, in the realm of concept-formation, where exploratory experimentation has its most unique power and importance. There is, finally, often the attempt to develop experimental arrangements that involve only the necessary conditions for the effect in question and thus represent the general regularity or law in a most obvious way. Those experiments are attributed a particular status in that they serve as core effects to which all other phenomena of the field can be 'reduced'" (Steinle 2002, 419).

with existing concepts and categories, and proceeded to revise them by putting forth a radically new theoretical framework based on the idea of “magnetic curves.” Faraday’s exploratory experimentation highlights the effectiveness of a methodological approach that depends much more on process than theory. Although the variation of experimental parameters is systematic, its main purpose does not consist in confirming theoretical expectation. The outcome of this process remains then more open-ended and, in turn, more attuned to the need for conceptual change.

Steinle’s description of exploratory experimentation downplays other factors that constitute an integral part of the process of discovery. As discussed above, Balzac saw early on in electromagnetic induction a new type of difference and relation that helped him convey the complex nature of the eureka moment. Balzac’s initial Newtonian image conveys a straightforward experience where the detached scientist discovers universal gravity by witnessing the fall of a fruit. By replacing gravity with electromagnetic induction, Balzac creates an image that conveys a much more complex experience. Mesmer’s discovery of *animal magnetism* proceeds indirectly via the *electric sensation* he feels as his servant is approaching. Furthermore, Mesmer’s personal experience is not detached from the event that led to his discovery. He intimately partakes in it through an involuntary cognitive action described as the sensation of an “electric” effect. For Balzac, then, and in contradistinction to Steinle’s account of exploratory experimentation, the process of discovery cannot exclude involuntary actions, which, in the case of Faraday, might be termed intuition. This latter term is notoriously vague and usually associated with poetics. However, as an open-ended process, exploratory experimentation must involve crucial decision making and theoretical leaps based on both voluntary and involuntary influences. Balzac considered intuition central to understanding the process of discovery, and perceived early on in electromagnetic induction a new and more accurate way to convey its elusive nature.

Balzac’s image also provides a hint that the singular nature of the electromagnetic interaction Ørsted and Faraday had uncovered influenced the latter’s experimental approach. Ørsted’s compass and conductor apparatus and Faraday’s invention of the first electromagnetic motor displayed a circular attraction that did not fit with the straight-line model of Newtonian action at a distance. This indirect or, more precisely, roundabout electromagnetic action provided empirical justification for practicing open-ended methods such as exploratory experimentation that do not simply depend of the straightforward application of theory. This circular motion must also have inspired Faraday in his groundbreaking choice of *magnetic curves* as an effective means to visualize and in turn formulate the law of induction.

6 Electromagnetic induction as a motor for scientific discovery

The discovery of electromagnetism and its circular action came with a new set of difficulties concerning the nature of the universe that would lead to the reconceptualization of its spatiotemporal fabric. This profound epistemological shift stemmed from Faraday's struggle to find an effective rule to explain electromagnetic induction, which prompted him to elaborate a new physical framework based on the *magnetic curves* drawn by iron filings around a magnet. In later works, Faraday renamed "*magnetic curves*" to "*lines of force*," and used them as an alternative to the seemingly unmediated influence implied by the Newtonian model of action at a distance.¹¹ James Clerk Maxwell perceived the physico-mathematical value of Faraday's lines of force, and relied on them to derive the classical laws of electromagnetism. Faraday's and Maxwell's work on electromagnetic induction and lines of force provided conceptual tools that brought about *field theory*, revolutionized the understanding of radiations, and enabled the exploration of the atom. It also played a central role in 1905, when Albert Einstein published a series of epoch-making articles that would displace the theoretical framework of Newtonian physics (Balibar 1992). In what follows, I will focus on Einstein's description of the thought process behind the article most closely associated with the conceptual breakthroughs of electromagnetic induction, "On the Electrodynamics of Moving Bodies," where he first postulated the special theory of relativity.¹²

In this article, Einstein, similarly to Balzac before him, would exploit the electromagnetic difference to elaborate new theories. Einstein's article starts with

¹¹ Faraday criticized such action at a distance with a thought experiment: "The notion of the gravitating force is, with those who admit Newton's law, but go with him no further, that matter attracts matter with a strength which is inversely as the square of the distance. Consider, then, a mass of matter (or a particle), for which present purpose the sun will serve, and consider a globe like one of the planets, as our earth, either created or taken from distant space and placed near the sun as our earth is; – the attraction of gravity is then exerted, and we say that the sun attracts the earth, and also that the earth attracts the sun. But if the sun attracts the earth, that force of attraction must either arise *because* of the presence of the earth near the sun; or it must have *pre-existed* in the sun when the earth was not there. If we consider the first case, I think it will be exceedingly difficult to conceive that the sudden presence of the earth, 95 millions of miles from the sun, and having no previous physical connexion with it, nor any physical connexion caused by the mere circumstance of juxtaposition, should be able to raise up in the sun a power having no previous existence" (Faraday 1855, 571–572).

¹² Cf. Aura Heydenreich's paper "Albert Einstein's 'Physics and Reality' and 'The Electrodynamics of Moving Bodies'" in this volume.

a description of electromagnetic induction where, as Faraday had shown, the induced current depends on the interaction of a magnet and a conductor:

It is well known that Maxwell's electrodynamics – as usually understood at present – when applied to moving bodies, leads to asymmetries that do not seem to attach to the phenomena. Let us recall, for example, the electrodynamic interaction between a magnet and a conductor. The observable phenomenon depends here only on the relative motion of conductor and magnet, while according to the customary conception the two cases, in which, respectively, either the one or the other of the two bodies is the one in motion, are to be strictly differentiated from each other. (1989 [1905], 140)

Einstein notes that the mathematical laws James Clerk Maxwell devised to quantify electromagnetic interaction distinguish between whether it is the conductor or the magnet that moves. However, for Einstein this distinction must be artificial because the induced electrical current only depends on the relative motion of the conductor and the magnet. In later writings, Einstein provides a more detailed account of the thought experiment that prompted him to apply the principle of Galilean relativity to electromagnetic induction:

The difference between [the electric and magnetic fields] could not be a real difference, but rather, in my conviction, could only be a difference in the choice of reference point. Judged from the magnet there certainly were no electric fields; judged from the conducting circuit there certainly was one. The existence of an electric field was therefore a relative one, depending on the state of motion of the coordinate system being used, and a kind of objective reality could be granted only to the electric and magnetic field together, quite apart from the state of relative motion of the observer or the coordinate system. The phenomenon of the electromagnetic induction forced me to postulate the (special) relativity principle.¹³ (1972, 32)

Einstein found in electromagnetic induction the clues that paved the way for the theory of special relativity. The application of Galilean relativity to electromagnetic induction “forced” him to recast the foundation of physics on new relativist grounds that attributed a special status to the electromagnetic field. This application yielded new concepts such as *time dilation* and *length contraction* that would undermine the notions of absolute space and time that informed the theoretical framework of Newtonian physics (Balibar 1992).

¹³ This excerpt is from an unpublished essay entitled *The Fundamental Idea of General Relativity in its Original Form*, written about 1919 (Einstein 1972).

In 1907, two years after publishing his special theory of relativity, Einstein had “the happiest thought of [his] life” when he made an analogy between the gravitational field and his relativist interpretation of electromagnetic induction:

Just as in the case where an electric field is produced by electromagnetic induction, the gravitational field similarly has only a relative existence. Thus, for an observer in free fall from the roof of a house there exists, during his fall, no gravitational field – at least not in his immediate vicinity. If the observer releases any objects, they will remain, relative to him, in a state of rest [...]. (1972, 32)

As with the electric and magnetic fields, the gravitational field is relative. Einstein’s “happiest thought” marked the beginning of years of work that culminated in 1916 with the inclusion of gravity in the theory of relativity, or *the general theory of relativity*.

7 Bachelard’s electromagnetic epistemology

Einstein’s supersession of Newtonian physics would profoundly influence the intellectual climate of the twentieth century by providing an exemplary case study for reevaluating the process of scientific discovery. Bachelard was one of the first epistemologists to develop a new philosophy of science and history that drew extensively on Einstein’s example. Along with Einstein’s theory of relativity, he refers to Faraday’s electromagnetic science as “epistemological breaks [ruptures]” (1952, 15 and 25–26). The bachelardian idea of an *epistemological break* greatly contributed to the development of *historical epistemologies* during the twentieth century (Rheinberger 2010). It particularly influenced the historical approaches of thinkers such as Louis Althusser and Michel Foucault, who adapted it for their own purposes. It also paved the way for Thomas Kuhn’s *paradigm shift* theory. Like Einstein, Bachelard, who knew about the instrumental role electromagnetic induction had played in the discovery of the theory of relativity (1934, 125), implemented the electromagnetic difference to elaborate his critical ideas on the nature of discovery and history.

Bachelard considers the conceptual breakthroughs instigated by the discoveries of electromagnetism and Einstein’s theory of relativity as scientific revolutions that not only transformed our conception of the universe but also signaled a “new scientific spirit” (1938). According to Bachelard, before Einstein came to the fore, scientific practices derived mainly from empirical evidence and common sense. However, what the theory of relativity revealed about the nature of the universe had very little to do with everyday experience. The

counter-intuitive outcomes of the theory of relativity could not have been derived from the accepted empirical framework of its day. For instance, before being tested and confirmed, Einstein's prediction of the phenomena of *length contraction* and *time dilation* stood in sharp opposition to the notion of absolute space and time that had informed physics since Newton. For Bachelard, Einstein constructed a new and more accurate physical reality through bold reasoning and rigorous mathematical exploration that only later turned to empirical validation. Electromagnetic science and Einstein's theory of relativity proved that scientific revolutions do not occur through the continuous accumulation of knowledge, but abruptly, through epistemological breaks triggered by unheralded theories that stood fundamentally at odds with the accepted scientific framework of their time (1934, 42 and 146–147).

As it did in Balzac's description of the *eureka* moment and in Einstein's thought experiment, the model of electromagnetic induction plays a central role in Bachelard's historical epistemology. Charles Alunni (1999) has shown the emergence in Bachelard's work of a new concept of cognitive *induction* informed by the phenomenon of electromagnetic induction and the formative role it played in Einstein's discoveries.¹⁴ Alunni has also demonstrated how, in Bachelard, this new type of induction becomes a model to conceive a cognitive manifestation common to scientific, philosophical, and literary inventions. Bachelard called such cognitive induction, "dynamic intuitions" (1951, 214), and thought that electromagnetic induction best describes its elusive mode of operation.

Alunni's work on the new electromagnetic meaning of induction in Bachelard's philosophy of science also helps clarify the latter's early formulation of *epistemological break*. Bachelard actually uses the expression *epistemological break* on rare occasions. Following Althusser's and Foucault's reformulations, the expression has endured as a way to refer to Bachelard's contribution to epistemology and the philosophy of history, and as the name of one of the most influential ideas of the twentieth century. Through its canonization and subsequent reinterpretations, the term *epistemological break* lost track of the electromagnetic model Bachelard implemented to conceptualize the discontinuities that marked the evolution of science. The idea of *epistemological break* in Bachelard's philosophy of science hinged initially on a new interpretation of cognitive *induction* that took into account Faraday's and Einstein's discoveries. Bachelard writes:

¹⁴ See also Bontems 2010, 22–24 and 124–126.

There is no transition from the system of Newton to the system of Einstein. One does not proceed from the first to the second by amassing data, perfecting measurements, and making slight adjustments to first principles. What is needed is some totally new ingredient. It is a 'transcendental induction' and not an 'amplifying induction' that leads the way from classical to relativistic physics.¹⁵ (1984, 44)

"Ampliative induction" or, more broadly, inductive reasoning refers to the Baconian scientific method. It stands as the quintessential empiricist's logical inference of generalizing observations into a law. Inductive reasoning has been particularly at home in the natural sciences, but it depends too much on observable facts to trigger an *epistemological break*. Einstein transcended the empirical constraint imposed by the physics of his time through a different type of *induction*. As Einstein makes known, a thought experiment that consisted of applying the principle of Galilean relativity to electromagnetic induction is at the source of his *transcendental induction*.

8 Conclusion

The interaction of electricity, magnetism and movement did not just induce the electric current that transformed the world at the turn of the twentieth century; it also *induced* a new scientific spirit. In physics, Einstein became one of the most outstanding manifestations of this new type of thought when he drew an analogy between electromagnetic induction and the laws of mechanics in order to move the physics of his time beyond its own limits. In philosophy, Bachelard also relied on the electromagnetic difference and relation and the historical significance of its discovery in order to conceptualize the non-linear evolution of science. By identifying a new type of cognitive induction rendered manifest by the occurrence of *epistemological breaks*, he showed that epistemology itself was subject to change and, in turn, paved the way for the subsequent historical epistemologies that would shape the intellectual landscape of the second half of the twentieth century.

Bachelard's attraction to the multipurpose term *induction* to describe the *dynamic intuitions* at work in discovery echoes Faraday's aforementioned series

¹⁵ "Il n'y a donc pas de transition entre le système de Newton et le système d'Einstein. On ne va pas du premier au second en amassant des connaissances, en redoublant de soins dans les mesures, en rectifiant légèrement des principes. Il faut au contraire un effort de nouveauté totale. On suit donc une induction transcendante et non pas une induction amplifiante en allant de la pensée classique à la pensée relativiste" (Bachelard 1934, 42).

of papers on his discovery of electromagnetic induction. In addition to defining the new electromagnetic meaning of *induction*, Faraday also relies in these texts on the verb “to induce” in the Baconian sense.¹⁶ In retrospect, Faraday’s indiscriminating and wide-ranging applications of induction begin to resonate with each other but, unlike Bachelard, he does not make an explicit link between the new physical phenomenon and the logical inference.¹⁷ As discussed above, it is a contemporary of Faraday, Balzac, who pioneered that link when in his description of the eureka moment he substituted the traditional Newtonian image of the falling fruit for the new electromagnetic model. Balzac’s unprecedented image conveys a much more roundabout experience of discovery where a cognitive reaction akin to intuition is set in motion by the interaction of Mesmer’s *electric sensation* and his servant’s *magnetism*. Balzac therefore prefigures Bachelard’s electromagnetic model of Faraday’s and Einstein’s *dynamic intuitions* and *epistemological breaks* by a century.¹⁸

Reference List

- Alunni, Charles. “Relativités et puissances spectrales chez Gaston Bachelard.” *Revue de synthèse* 120.1 (1999): 73–110.
- Bachelard, Gaston. *Le Nouvel esprit scientifique*. Paris: F. Alcan, 1934.
- Bachelard, Gaston. *L’Activité rationaliste de la physique contemporaine*. Paris: Presses universitaires de France, 1951.
- Bachelard, Gaston. “La Vocation scientifique et l’âme humaine.” *L’Homme devant la science*. Neuchâtel: Les Éditions de la Baconnière, 1952.
- Bachelard, Gaston. *Le Droit de rêver*. Paris: Presses Universitaires de France, 1970.
- Bachelard, Gaston. *The New Scientific Spirit*. Boston: Beacon Press, 1984.
- Bachelard, Gaston. *La Formation de l’esprit scientifique: Contribution à une psychanalyse de la connaissance*. Paris: Vrin, 2004 [1938].

16 “[...] but later investigations [...] of the laws governing these phenomena, induce me to think that [...]” (Faraday 1839a, 16). “Thus the reasons which induce me to suppose a particular state in wire (60.) have disappeared [...]” (Faraday 1839b, 69). As discussed above, similar wide-range uses of “to induce” appeared in Cavallo’s early treatise on electrostatics.

17 A similar implicit resonance occurs when the proper interpretation of the discovery of electromagnetic induction becomes a point of contention between William Whewell, who frequently collaborated with Faraday on the creation of new scientific terms, and John Stuart Mill in their debate on the nature of the inductive sciences. Cf. Whewell 1849, 48–51.

18 Bachelard himself lends support to this last claim in the preface he wrote for Balzac’s *Séraphita*. In this novel, where some of the earliest instances of electromagnetic images appear (Balzac 1976b, 737 and 823), Bachelard describes the power that Balzac’s literary images can have on the reader in terms of “dynamic induction” (Bachelard 1970, 128).

- Balibar, Françoise. *Einstein 1905: de l'éther aux quanta*. Paris: Presses universitaires de France, 1992.
- Balzac, Honoré de. *Nouveaux contes philosophiques, par M. de Balzac: Maître Cornélius; Madame Firmiani; L'Auberge rouge; Louis Lambert*. Paris: Charles Gosselin, 1832.
- Balzac, Honoré de. *Histoire intellectuelle de Louis Lambert, par M. de Balzac, fragment extrait des "Romans et contes philosophiques."* Paris: Charles Gosselin, 1833.
- Balzac, Honoré de. *Lettres à l'étrangère*. Paris: Calmann-Lévy, 1906.
- Balzac, Honoré de. Avant-Propos/Foreword. *La Comédie Humaine*. Vol 1. Ed. Bibliothèque de la Pléiade. Paris: Gallimard, 1976a.
- Balzac, Honoré de. *Louis Lambert: Séraphita*. Ed. Bibliothèque de la Pléiade. Paris: Gallimard, 1976b.
- Bontems, Vincent. *Bachelard*. Paris: Les Belles lettres, 2010.
- Caneva, Kenneth L. "'Discovery' as a site for the collective construction of scientific knowledge." *Historical Studies in the Physical and Biological Sciences* 35.2 (2005): 175–291.
- Carnot, Sadi. *Réflexions sur la puissance motrice du feu et sur les machines propres à développer cette puissance*. Paris: Bachelier, 1824.
- Cavallo, Tiberius. *A Complete Treatise of Electricity in Theory and Practice: With Original Experiments*. London: Edward and Charles Dilly, 1777.
- Davy, Humphry. *Elements of Chemical Philosophy*. Vol. 1. Philadelphia: Bradford and Inskeep, 1812.
- Einstein, Albert. "Excerpt from Essay by Einstein on 'Happiest Thought' in his Life." *New York Times* (28 March 1972): 32.
- Einstein, Albert. "On the Electrodynamics of Moving Bodies." 1905. *The Swiss Years: Writings, 1900–1909* (English translation supplement). *The Collected Papers of Albert Einstein*. Vol. 2. Transl. Anna Beck. Princeton: Princeton University Press, 1989. 140–171.
- Faraday, Michael. "On Some New Electro-Magnetical Motions, and on the Theory of Magnetism." *The Quarterly Journal of Science* 12 (1821): 74–96.
- Faraday, Michael. "On the Induction of Electric Currents [...]." *Experimental Researches in Electricity*. Vol. 1. London: R. and J. E. Taylor, 1839a. 1–41.
- Faraday, Michael. "Terrestrial Magneto-electric Induction [...]." *Experimental Researches in Electricity*. Vol. 1. London: R. and J. E. Taylor, 1839b. 42–75.
- Faraday, Michael. "On some Points of Magnetic Philosophy." *Experimental Researches in Electricity*. Vol. 3. London: R. and J. E. Taylor, 1855. 566–574.
- Heilbron, John L. *Electricity in the 17th and 18th Centuries: A Study of Early Modern Physics*. Berkeley: University of California Press, 1979.
- Johnson, Samuel. *A Dictionary of the English Language*. Vol. 1. London: J. F. And C. Rivington, 1785.
- Murphy, Kieran. *Electromagnetism and the Metonymic Imagination*. Penn State University Press, 2020.
- "Notices Respecting New Books: Sir Humphry Davy's 'Elements of Chemical Philosophy.'" *Philosophical Magazine* 40.176 (1812): 434–444.
- Ørsted, Hans Christian. *Selected Scientific Works of Hans Christian Ørsted*. Princeton: Princeton University Press, 1998.
- Poe, Edgar Allan. "The Spectacles." *Tales and Sketches*. Vol 2. Ed. Thomas Ollive Mabbott. Urbana: University of Illinois Press, 2000. 883–918.

- Rheinberger, Hans-Jörg. *On Historicizing Epistemology: An Essay*. Stanford: Stanford University Press, 2010.
- Serres, Michel. *Feux et signaux de brume, Zola*. Paris: Grasset, 1975.
- Serres, Michel. *Hermès IV: La Distribution*. Paris: Editions de Minuit, 1977.
- Singer, George John. "Remarks on some Electrical and Electrochemical Phenomena." *Journal of Natural Philosophy, Chemistry and the Arts* 31 (1812): 216–221.
- Singer, George John. *Elements of Electricity and Electro-Chemistry*. London: Longman, Hurst, Rees, Orme, Brown, and R. Triphook, 1814.
- Steinle, Friedrich. "Work, Finish, Publish? The Formation of the Second Series of Faraday's 'Experimental Researches in Electricity.'" *Physis* 33 (1996): 141–220.
- Steinle, Friedrich. "Experiments in History and Philosophy of Science." *Perspectives on Science* 10.4 (2002): 408–432.
- Thompson, Silvanus P. *Michael Faraday: His Life and Work*. London: Cassell, 1898.
- Whewell, William. *Of Induction: With Especial Reference to Mr. J. Stuart Mill's System of Logic*. London: J.W. Parker, 1849.