H. C. Ørsted and the Discovery of Electromagnetism

During a lecture given in the spring of 1820 Hans Christian Ørsted decided to perform an experiment. As he described it years later,

> "The plan of the first experiment was, to make the current of a little galvanic trough apparatus, commonly used in his lectures, pass through a very thin platina wire, which was placed over a compass covered with glass. The preparations for the experiments were made, but some accident having hindered him from trying it before the lecture, he intended to defer it to another opportunity; yet during the lecture, the probability of its success appeared stronger, so that he made the first experiment in the presence of the audience. The magnetical needle, though included in a box, was disturbed; but as the effect was very feeble, and must, before its law was discovered, seem very irregular, the experiment made no strong impression on the audience. It may appear strange, that the discoverer made no further experiments upon the subject during three months; he himself finds it difficult enough to conceive it; but the extreme feebleness and seeming confusion of the phenomena in the first experiment, the remembrance of the numerous errors committed upon this subject by earlier philosophers, and particularly by his friend Ritter, the claim such a matter has to be treated with earnest attention, may have determined him to delay his researches to a more convenient time. In the month of July 1820, he again resumed the experiment, making use of a much more considerable galvanical apparatus."[1]

The effect that Ørsted observed may have been "very feeble". Its consequences were not. Ørsted's discovery of an unexpected connection between electricity and magnetism led to Michael Faraday's discovery of electromagnetic induction (1831) and to James Clerk Maxwell's famous equations (1865). The result was nothing less than an electromagnetic revolution that changed the world we live in. Few people can imagine a world without electricity, and even fewer would like to live in it. This 200th anniversary year for Ørsted's discovery seems to be a good time to recall the ideas and events that influenced Ørsted's thinking and ultimately led him to perform his historic lecture demonstration.

The present pages are intended to provide a brief description of some of the elements in Ørsted's background that made him uniquely prepared to discover electromagnetism. We will also consider the events immediately following his discovery that guaranteed both the rapid acceptance of his

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[1] *The Edinburgh Encyclopædia*, conducted by David Brewster, LL. D., Vol. 18, pp. 573–89. Edinburgh 1830. According to the editor's statement this article was written by H. C. Ørsted. KM II, pp. 351–398 and JJK, pp. 547.

results and the recognition of their significance. The story will be told by a physicist, but effort will be made to limit technical details to a level that will be acceptable to a broader readership.

Early years

Ørsted was born in 1777 in Rudkøbing, where his parents, Søren Christian and Karen (*née* Hermansdatter), owned the local pharmacy. His brother, Anders Sandøe, was born the following year. Since educational possibilities in Rudkøbing were limited, the boys were sent to a school run by an underemployed wig-maker, Christian Oldenburg, and his wife. As a consequence they first learned to read and write in Oldenburg's native German. Formal lessons ended when Ørsted was twelve, but learning continued. Since the brothers were seen to be gifted, the private libraries of local citizens were open to them. More formal lessons in chemistry and law were provided by a Norwegian student and a district judge, respectively. Hans Christian learned a more practical form of chemistry by helping in the pharmacy. A land surveyor, whose employment was largely seasonal, provided rudimentary instruction in mathematics, French and English in return for winter lodgings at the pharmacy guest house. By the spring of 1794, the brothers were ready to leave home in order to study at the University of Copenhagen. Housing for students in Copenhagen was as difficult then as it is now. Fortunately, they had a right of priority to lodge at Elers' Kollegium since their stepmother (Anna Dorothea Ørsted, *née* Borring) was related to its founder, Jørgen Elers. They took their evening meal with their aunt Engelke Møller, who had a boarding house[2].

Anders Sandøe was to study law, and Hans Christian was to study chemistry[3]. As was their habit, the brothers continued to share what they learned with one another. This was not necessary in the case of philosophy. They both attended the lectures of Professor Børge Riisbrigh (1731–1809), who was a great favorite of the students. Riisbrigh's lectures in these years dealt with the philosophy of Immanuel Kant. Both were impressed by Kant's ideas. Ander Sandøe was particularly interested in Kant's ideas regarding moral philosophy. Hans Christian was far more interested in Kant's views regarding the natural sciences, particularly as expressed in his *Metaphysische Anfangsgründe der Naturwissenschaft*[4] (1786). This work specifically determined the contents of his dissertation and profoundly influenced his general view of the natural sciences. More importantly — and perhaps

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[2] It was here that they met Adam Oehlenschläger (1779–1850), who remained a close friend.

[3] It should be noted that the University of Copenhagen did not have a science faculty until 1850. It was, however, possible to study chemistry, which was taught along with pharmacology in the Faculty of Medicine.

[4] Metaphysical Foundations of Natural Science.

surprisingly given their level of abstraction — Kant's ideas proved to be absolutely crucial for Ørsted's discovery of electromagnetism.

Figure 1: Børge Riisbrigh (1731–1809) and Immanuel Kant (1724–1804).

In Ørsted's time, each faculty of the University of Copenhagen was allowed to pose an annual prize question. The reward for the best answer was a gold medal. This is still the case. Jacob Baden, the professor of rhetoric, set the following prize question for 1796: "How can prosaic language be corrupted by moving too close to the poetic; and where are the boundaries between poetic and prosaic expression?"[5]. Ørsted had a life-long interest in poetry and, if measured by the quantity of his own lyric efforts, was himself a poet. As a result, he was already familiar with the relevant literature and soon received his first gold medal. His second gold medal is of greater interest here.

The prize essay for 1797 posed by the Faculty of Medicine had the title "On the Origin and Use of Amniotic Fluid"[6]. The topic was ideal for Ørsted. He reviewed the available literature and was shocked by what he found. Regarding purported measurements of chemical composition, he notes that "[I]t is truly exceptional to see experiments, made by the most astute men, which are so completely at variance with each other as the ones concerning amniotic fluid." After describing a number of experiments he had performed himself using samples of amniotic fluid obtained from a nearby hospital, he turned to the question of "origin". Here, too, he found a bewildering myriad of possibilities including sweat, urine, and "a mixture of spit, snot, and urine"[7]. None of them had empirical support. He observed that

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[5] Hvorledes kan det prosaiske Sprog fordærves ved at komme det poetiske for nær; og hvor er Grændserne mellem de poetiske og det prosaiske Udtryk?

[6] Om Modervandets Oprindelse og Nytte. KM I, pp. 3–31 and JJK, p. 6.

[7] JJK, p. 11.

Figure 2: The 2018 Gold Medal of the University of Copenhagen

“[E]xperience, this ever-faithful guide, abandoned us while we, surrounded by a chaos of hypotheses, did not know where to turn”[8]. Divergent theories regarding the use of amniotic fluid did not fare better. As we shall see, the critical views that Ørsted expresses here were unavoidable in view of his growing acceptance of the stringencies of Kant’s natural science. The judges of the competition were impressed. In their view:

> The author of this paper presents a treatise of brilliant clarity and perspicacity, composed with great skill. He has treated the chemical analysis particularly thoroughly and has splendidly solved and completed the proposed task. In addition, he has displayed a modesty which is unusual and singular in our time and in this way endeavoured to reconcile divergent opinions of various writers.[9]

Ørsted had won his second gold medal.

It is of some interest to note that Hans Christian was not the only Ørsted to win a University gold medal. The prize question for 1797 for the Faculty of Philosophy was set (and judged) by Professors Riisbrigh and Gamborg[10]. Anders Sandøe’s essay, entitled “On the the Connection between the Principles of Virtue and Jurisprudence”[11], was written with close adherence to the principles of Kantian moral philosophy and was deemed by the judges to be worthy of the gold medal.

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[8] JJK, p. 14.

[9] JJK, p. 3.

[10] Anders Gamborg (1753–1833)

[11] Sammenhængen mellem Dydelærens og Retslærens Princip.

We have now reached 1799, the year in which Ørsted defended his dissertation. Written in Latin, this work was entitled “Dissertation on the Structure of the Elementary Metaphysics of External Nature”. As the name suggests, it was directly inspired by Kant. The dissertation is partly a restatement of Kant’s ideas and partly a sketch of how they might be extended to provide a more solid foundation for chemistry. It seems likely that this second mission was inspired by Ørsted’s experience with the prize question on amniotic fluid. The many irreproducible and conflicting experimental results and the bewildering number of unfounded speculations that he encountered must have impressed him with the need for fundamental changes. For present purposes, it is not essential to understand either the details of Kant’s views or the accuracy with which Ørsted reproduces them[12]. What is important is to see what Ørsted *believed* that Kant said, and how this belief affected his future scientific development.

In rough terms, Kant says (i) that “true” science must be based on a number of “necessary” facts of unquestioned validity, and (ii) that it must be possible to deal with these facts mathematically. This means that his approach could not be applied to every field of natural science. When *Metaphysical Foundations* was published in 1786, physics was the only field that could possibly be considered as a candidate. Kant was aware of this and wrote explicitly in the preface that his methods could *not* be applied to chemistry as it was understood in 1786. This was undoubtedly true since it is generally acknowledged that the birth of modern (i.e. antiphlogistic) chemistry was heralded by the publication of Antoine Lavoisier’s *Méthode de nomenclature chimique* in 1787[13]. Thus, Kant proceeds to illustrate his ideas by “deriving” a number of relations that are familiar from Newtonian mechanics. These include Newton’s first[14] and third[15] laws of motion. Apparently unaware that Newton had gotten there first, Ørsted describes the latter as “the Kantian theorem that ‘the action is equal to the reaction’ ”[16]. Kant was prepared to accept the notion of momentum (i.e. the product of a particle’s mass and its velocity), which he chose to call the ‘quantity of motion’. But it is striking that neither Kant nor Ørsted addresses Newton’s second law (i.e. $F = ma$), which really represents the dynamic content of Newtonian mechanics. In Ørsted’s case, it appears that his mathematical knowledge was not sufficient to deal with problems in Newtonian mechanics.

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[12] This is fortunate since contemporary physicists are not likely to find Kant’s arguments of much value in the practice of science.

[13] This work introduced a new system in which the classical elements of earth, air, fire, and water were replaced by 55 substances that could not be decomposed by known chemical means.

[14] The velocity of a body is unaltered unless a force acts on it.

[15] When one body exerts a force on a second body, the second body exerts an equal and opposite force on the first.

[16] JJK, p. 90.

Unfortunately, the Rudkøbing surveyor had not taught him calculus.

Kant also asserts that there must be a fundamental repulsive force to prevent matter from collapsing and a fundamental attractive force to hold matter together. There is no suggestion as to what either of these forces might be. It is then claimed that "matter can be divided, and can be so *ad infinitum*, i.e. in the division of a portion of matter we shall never reach a simple part, for matter is something real, and this can be divided *ad infinitum*"[17]. Whether one is convinced by the argument or not, this was assumed to mean that atoms do not exist. Thus, in Kant's view, natural science should be based on forces and not on atoms — dynamism rather than atomism. While this idea may seem silly, one should not be too hasty to judge. Opposition to the notion of atoms persisted far longer than one might expect. The physicist Ernst Mach (1838–1916) and the chemist Wilhelm Ostwald (1853–1932) vigorously opposed the notion of atoms until Jean Perrin (1870–1942) used Einstein's theory of Brownian motion to determine Avogadro's number and prove their existence in 1908. It should also be noted that modern condensed matter physics as well as quantum field theory often find it useful to maintain a "duality" in which there are two theories with identical content even though one is based on interacting particles, and the other is based exclusively on fields (i.e. forces)[18]. Ørsted's dissertation gives us clear indications of the direction that his future science was to take. He is convinced that atoms do not exist and manages to convince himself that the resulting infinite divisibility of matter has observable consequences. Specifically, he believed that this implied that the relation between the volume of any form of matter and the external pressure exerted on it should be universal and should be identical to that for perfect gases. In other words, the product of the volume and the applied pressure for a given quantity of matter (at fixed temperature) should be constant for all pressures. This was the initial (and primary) motivation for the many often brilliantly ingenious experiments on the compressibility of gases and liquids that Ørsted performed during his career.

Of greater importance, Ørsted adopts Kant's idea of the two fundamental forces of repulsion and attraction without reservation. Indeed, he adds the notion that each of the many forces actually observed in nature must be due to some mixture of these two forces. He fully expected that it would be possible to understand the details of this common origin. As he put it in his *Materials for a Chemistry of the Nineteenth Century* (1803)[19]

> "Our physics, therefore, will no longer be a collection of fragments on motion, on heat, on air, on light, on electricity, on magnetism, and

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[17] JJK, p. 83.

[18] In the latter case, there exist topological field configurations (i.e. "knots" in the field lines) that have properties identical to those usually ascribed to particles.

[19] KM I., pp. 133–210 and JJK pp. 120–165.

> who knows what else, but with one system we shall embrace the entire world. Everyone must do what is in his power to nurture the great task of completion."[20]

Ørsted expected that such unification had consequences. Thus, he believed that the various forces of nature should have a measurable effect on one another. This is stated even more clearly in an article in Thomson's *Annals of Philosophy* in 1821[21]:

> "Having for a long time considered the powers which are developed by electricity as the general powers of nature, it necessarily followed that I should derive magnetic effects from them. In order to prove that I admitted this consequence to the utmost extent, I cite the following passage from my *Researches into the Identity of Electrical and Chemical Powers*, printed at Paris in 1813, "it must be determined whether electricity in its most latent state has any action upon the magnet as such." I wrote this during a journey, so that I could not easily perform the experiments, besides which, the manner of making them was not at that time at all clear to me."

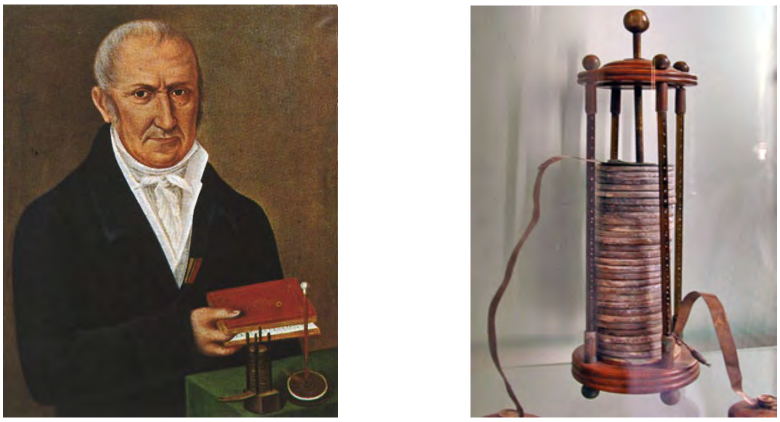

Figure 3: Alessandro Volta (1745–1827) and his voltaic cell

Volta's discovery

It is easy for us to forget that before 1800, "electricity" meant "static electricity". The very name was a 17th-century construct from the Greek "elektron" for "amber", a substance that produced static electricity when rubbed with wool. Currents of electricity were simply unknown. The situation changed dramatically in 1800 when Alessandro Volta constructed the first voltaic pile. The availability of a steady and stable source of electric

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[20] JJK, p. 164.

[21] KM II, pp. 223–45 and JJK, p. 430.

current created a revolution in physics and chemistry. The study of the decomposition of substances into their more fundamental constituents provided a clearer distinction between “elements” and their compounds. When the resulting elements were gases, the rational relations between their volumes offered strong support for the existence of atoms.

Ørsted’s journeyman years

From August 1801 to January 1804 Ørsted travelled in Germany and France. Support for this journey in the form of a stipend from the Cappel Fund was arranged by his mentor, Professor Johan Georg Manthey (1769–1842), who was a member of the board of the Fund. The stated purpose was for Ørsted to learn more about technical chemistry (especially porcelain manufacture) and the brewing of beer. The young Ørsted devoured a wealth of new impressions of society and the arts as well as of scientific matters. Armed with innocent enthusiasm and a portable voltaic cell, he was warmly received in both social and academic circles. The most important of his new German acquaintances was undoubtedly Johann Wilhelm Ritter, a young physicist of considerable ability[22]. Ritter, like Ørsted, was a disciple of Kant’s *Naturphilosophie.* Together, they studied the works of the Hungarian chemist Jacob Joseph Winterl (1739–1809). Winterl had taken the Kantian polarities to their extreme and claimed to have discovered two substances, “andronia” and “thelyke”, which were supposedly the physical embodiment of acidity and alkalinity, respectively. Ørsted’s uncritical and continuing support for Winterl’s irreproducible experimental discoveries created difficulties for him in Paris and later in Copenhagen. There was also time for scientific work during Ørsted’s extended stay in Germany using borrowed laboratory facilities, and he prepared his *Materials for a Chemistry of the Nineteenth Century*, a piece of Winterl advocacy, during this period.

Ørsted finally arrived in Paris in December 1802. Although proficient in German from childhood, his first task was to improve his inadequate French. His routine in Paris differed considerably from that in Germany. His time was generally spent more passively by attending lectures and exploring the rich social and artistic opportunities. Above all, he had to adjust to the rationalism of French scientific culture, which placed a high value on experimental results and none whatsoever on *Naturphilosophie.* Ørsted used his newly-acquired language skills to promote the discoveries of Ritter in learned Parisian circles and, as a consequence, was invited by Jean Baptiste Biot to nominate Ritter for a Napoleonic prize for an important galvanic discovery. When consulted by Ørsted, Ritter chose to ignore his own unde-

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[22] In 1802 Ritter used ingenious chemical techniques to confirm Herschel’s 1801 discovery (by physical means) of the existence of infrared light and immediately used the same techniques to discover ultraviolet light. In the same year Ritter constructed the first dry cell, and in 1803 he constructed the first storage battery.

Figure 4: Ørsted in Paris (1803) and Johann Wilhelm Ritter (1776–1810)

niable scientific contributions and instead insisted on being nominated for two more questionable achievements. The first of these was his “discovery” that the earth has two electric poles. The second was the observation that a “compass needle”, constructed with one half of zinc and the other of silver, would point toward magnetic north. Ørsted had such a needle produced in the hope of reproducing Ritter’s results. While Ørsted won praise for his advocacy of a friend, he also gained a reputation for having more enthusiasm than judgment. Ritter received no prize. News of Ørsted’s role in the Ritter fiasco was quick to reach Copenhagen and probably contributed to the fact that he was unable to secure a university appointment immediately upon his return home.

Die Akustik,

von

Ernst Florens Friedrich Chladni,

Figure 5: Ernst Chladni

In attempting to understand the circumstances that led Ørsted to his monumental discovery of electromagnetism, it is fortunate that he considered himself to be a man of letters to the extent that he could describe his scientific production as his "literary career"[23]. His scientific prose is florid in comparison with that of many of his contemporaries. With philosophical and religious references and even bits of poetry, his writing would certainly not meet with the approval of contemporary editors. However, this freedom of style was accompanied by a freedom of content. As a result, Ørsted is often prepared to provide us with his personal views about science and clues to the sources of his own scientific inspiration. In 1803, some seventeen years before his discovery of electromagnetism, Ørsted stated his fundamental belief that

> "[t]he constituent principles of heat, which are important in alkalis and acids, in electricity, and in light, are also the principles of magnetism, and thus we would have the unity of all the forces which act together to govern the entire universe, . . . for do friction and impact not produce both heat and electricity, and are dynamics and mechanics not thereby perfectly intertwined?"[24]

The indebtedness to Immanuel Kant's ideas as expressed in his *Metaphysische Anfangsgründe* is apparent. If there are two fundamental forces (of attraction and repulsion), and if all the other forces of nature are derived from them, we should expect to find relations and interactions between them. The search for these connections provided a primary motivation for Ørsted's science. As we shall see, it led him to consider such apparently disparate topics as acoustic figures and the compressibility of fluids. It shaped his conviction that there must be a connection between electricity and magnetism.

Acoustic figures

By 1806, Ørsted's career was developing nicely. He had been appointed to the inferior position of *professor extraordinarius* of physics in the philosophical faculty of the University of Copenhagen in 1806 and been elected member of the Royal Danish Academy of Sciences and Letters. Professionally, his scientific studies now included a thorough investigation of acoustic figures[25], which had received a broad and positive reception in Copenhagen intellectual circles. The purpose of Ørsted's experiments was not an idle

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[23] KM II, p. 356 and JJK, p. 546.

[24] *Materials for a Chemistry of the Nineteenth Century* (1803), KM I, pp. 209–10 and JJK, p. 164.

[25] See KM II, pp. 11-34 and JJK pp. 264–81. Ernst Florens Friedrich Chladni (1756–1827) was a German physicist often regarded as the "father of acoustics". He is best know for his studies on the resonant properties of plates (1787). A century earlier, Robert Hooke had discovered that, when excited at a given frequency, glass plates had regions where they vibrated in opposite directions. These regions were defined by "nodal lines" along which there is no vibration. The normal modes of glass or metal plates can be excited by stroking the edge with a violin bow, and the nodal line can be made visible by covering the plates with flour or sand. Chladni made numerous detailed experiments with acoustic figures and was remarkably successful in popularizing them. In 1808 Chladni demonstrated his acoustic figures to an audience that included Napoleon. Napoleon offered a prize for the

attempt to reproduce what had been done before. Rather, it was a well-considered element in his desire to provide support for the Kantian dynamic view of nature: Since all natural forces are related, the mechanical oscillations of the plates should produce static electrical effects. Thus he wrote the following in an 1805 letter to Ritter:

> "I believed that I would also be able to discover electrical phenomena in the production of the acoustic figures and therefore chose *semen lycopodii* to strew on the glass plate instead of sand, in the hope that the dust would adhere to the positively charged places and would easily fall off the negatively charged ones."[26]

This work is described in far greater detail in his article *Experiments on Acoustic Figures* (1810)[27]. It is amusing to note one technical aspect of this paper:

> "[A] fine film of dust, in all its parts like the outline of the acoustic figure, covers the plate after we have removed what could easily be knocked off. This property can be used to obtain prints of the acoustic figures. A sheet of black paper is coated with a solution of gum Arabic, and when this has dried to the extent that it is still sticky, we put the plate, from which we have knocked the superfluous dust, on top of it. When we have pressed it hard, we remove the plate and stick the paper, while it is still moist, on to glass; we can then be sure of preserving a print which, when successful, is more accurate than the best drawing."[28]

Here, Ørsted is telling us that he used static electricity to create an image on a metal plate and then transferred it to a sheet of paper. This sounds remarkably like a Xerox machine. It's a shame that Ørsted did not think to patent it — particularly because his advice to the government in the 1840s shaped all Danish legislation regarding the granting of patents and the establishment of monopolies.

Although more than 200 years have passed, acoustic figures are still a matter of interest in contemporary physics. They continue to play an important role in helping us to understand the consequences of chaos in quantum mechanical systems. In this case, the acoustic figure is made on a small aluminium plate resting on 3 gramophone needles — one serves to excite the plate; the other two measure the acoustic "wave function". The analogy to quantum mechanics is perfect.

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mathematical description of the phenomenon. The prize was never awarded. The only correct answer was submitted by Sophie Germain (1776–1831).

[26] See KM I, pp. 261–62 and JJK, p. 180.

[27] See KM II, pp. 11–34 and JJK, pp. 264–281.

[28] JJK, p. 277.

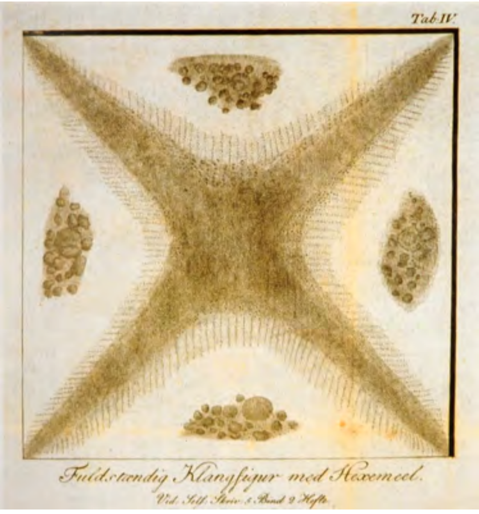

Figure 6: From Ørsted's *Experiments on Acoustic Figures* (1810).

Compressibility

The compressibility of both gases and liquids was a major theme in Ørsted's scientific research. His first paper on the subject was published in 1817 and the last in 1845. This was an old problem. Robert Boyle (1627–1691) and Edme Mariotte (1620–1684) had shown empirically that, for a fixed quantity of gas at a constant temperature, pressure and volume are inversely proportional. This is known as Boyle's Law or as the Boyle-Mariotte Law. At roughly the same time, Newton himself had shown how the measured speed of sound in any medium could be used to calculated its compression modulus. Ørsted was one of a number of physicists interested in the *direct* measurement of the compression modulus of gases and liquids. It was Ørsted's belief that the validity of the Mariotte's Law (as he called it) for *all* liquids and gases at *all* pressures would be sufficient to disprove the existence of atoms[29]. This is somewhat difficult to understand since, in 1737, Daniel Bernoulli (1700–1782) had shown that this law could be derived theoretically for an ideal gas composed of atoms. This would suggest that the verification of Mariotte's Law would constitute a proof rather than a disproof of the existence of atoms.

It seems likely that Ørsted's argument went something like this: If atoms exist, it would be possible to compress a substance until the distance between its atoms approaches a size characteristic of the atoms themselves. At such densities, Mariotte's Law *must* fail. Conversely, if Mariotte's Law

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[29] As Ørsted put it, "the compression is in proportion to the compressing forces". See JJK, p.493.

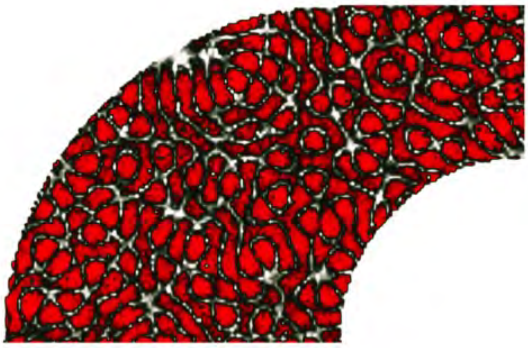

Figure 7: A modern acoustic figure produced by Clive Ellegaard.

does *not* fail, there can be no such characteristic size, and therefore atoms do not exist. What is seen thus depends on the degree of compression that can be achieved and the actual size of atoms. In fact, Benjamin Franklin already had a remarkably good idea of just how big atoms are[30].

Ørsted's initial remarks in 1817 regarding the compressibility of water were very brief and limited to criticism of previous measurements[31]. The results obtained by John Canton (1717–1782) were grossly inconsistent with the results calculated, as Newton had suggested, using the known speed of sound in water. Those of R. A. Abich (1738–1809) and E. A. W. Zimmermann (1743–1815) were found to be unreliable due to significant calculational errors. By the time he returned to this topic in 1822[32], Ørsted realized that there had been a flaw in the design of these experiments: As he put it,

> "[I]n spite of the great strength of the brass cylinder in which the water is compressed, it was possible that its walls might have

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[30] While in England in 1773 Benjamin Franklin made a measurement that provides a quite serviceable estimate of atomic size. As he wrote to William Brownrigg on 7 November 1773, "Being at Clapham, where there is, on the Common, a large Pond, which I observed to be one Day very rough with the Wind, I fetched out a Cruet of Oil, and dropt a little of it on the Water. …[T]ho' not more than a Tea Spoonful [it] produced an instant Calm, over a Space several yards square, which spread amazingly, and extended itself gradually till it reached the Lee Side, making all that Quarter of the Pond, perhaps half an Acre, as smooth as a Looking Glass." Given that 1 acre = $4000\,\mathrm{m}^2$ and 1 teaspoon = $5\,\mathrm{cm}^3$ and making the assumption that the oil forms a layer that is one molecule thick, we immediately conclude that one molecule of oil has a characteristic size of about 4 Å. This estimate is remarkably accurate!

[31] See KM II, pp. 211–12 and JJK pp. 407.

[32] See KM II, pp. 254–263 and JJK p. 453–461.

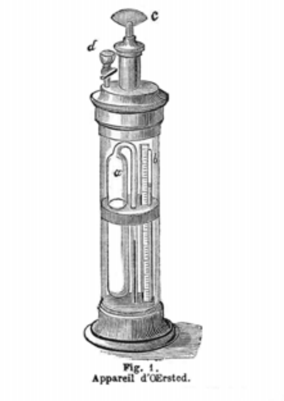

Figure 8: An early version of Ørsted's piezometer.

> given way so that not only the compression of the water would have been measured, but the combined effect of that and the expansion of the vessel."[33]

This was a serious concern since extremely large pressures were required to change the volume of liquids by a measurable amount. In order to avoid this problem, Ørsted constructed a greatly improved piezometer which allowed for identical pressures both inside and outside the confining cylinder[34]. Experiments with the new apparatus confirmed his belief in the general validity of Mariotte's Law. Subsequent experiments on gases as well as liquids with an improved piezometer changed the situation. Specifically, experiments with "sulphurous acid gas" (i.e. sulphur dioxide) showed significant deviations from expectations in conjunction with signs of liquid condensation. To be precise, the system was significantly more compressible in the vicinity of the phase transition. This led Ørsted to conclude that

> "the compression of atmospheric air and gases is proportional to the compressing forces, however great these may be, presuming that the gases remain in their aëriform state. . . . Thence it appears that our investigations have done no more than confirm the opinions of the most distinguished men of science of our time with respect to this subject. . . . The compression of liquids is subject to the same law as far as our experience goes. Here, too, the compression and the compressing force seem to be in a direct proportion. We may therefore assume that gases converted into liquids begin anew to follow the same law to which they answered as gases. It is also quite likely that liquids converted into solids are subject to the same law. If this should be confirmed by

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[33] JJK, p. 453.

[34] As he readily acknowledged, Ørsted had been unaware that a similar apparatus had been built by the American inventor Jacob Perkins (1766–1849) in 1820.

> further experiments, it may be said that the compression of a body ceases to conform to this law only at the moment of its transition from one state to another."[35]

It is striking that there is no mention of the possible significance of these results in connection with the question of the existence of atoms.

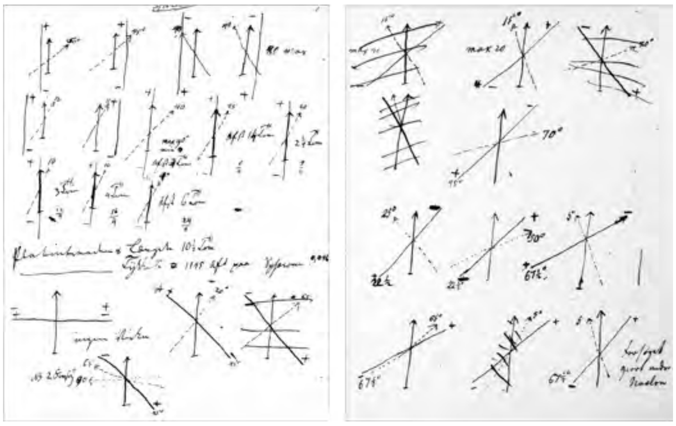

Figure 9: Two pages from the notes and sketches made by Ørsted in July 1820.

Discovery

We have now reached the spring of 1820. Ørsted understood that the "feeble" disturbance of the compass needle seen in his lecture demonstration was a genuinely important discovery. Other duties prevented a more detailed and quantitative investigation of this effect until the beginning of July 1820. Ørsted had new laboratory facilities and a more powerful galvanic apparatus that facilitated his measurements. Confident that his experiments would have a successful outcome, he gathered a group of six distinguished observers who would serve as witnesses of his experiments. (Their names and credentials were duly noted in the written description of his investigations.) He set about an exhaustive series of measurements aimed at documenting how the distance and orientation of a current-carrying wire affected the deflection of a compass needle. He made copious notes and drawings, many of which can be seen in Det Kongelige Bibliotek in Copenhagen. The results of his investigations were quickly written in a privately printed manuscript in Latin entitled *Experimenta circa effectum conflictus electrici in acum magneticam*[36] and sent to learned societies and scholars throughout Europe on 21 July 1820.

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[35] *Experiments Proving That Mariotte's Law Is Applicable to All Kinds of Gases; and at All Degrees of Pressure under Which the Gases Retain Their Aëriform State*, KM II, pp. 285–97 and JJK, pp. 481-91. JJK, p. 490.

[36] Experiments on the Effect of the Electric Conflict on the Magnetic Needle.

Figure 10: Portrait of Hans Christian Ørsted by C. W. Eckersberg (1823)

There should be no doubt that Ørsted knew precisely what he had discovered. As he wrote[37] soon after his discovery:

> “A long time ago the author himself adopted a system according to which all internal effects in bodies, such as electricity, heat, light, as well as chemical combinations and dissociations are due to the same fundamental forces. This system, which he has advanced in a few earlier treatises, has been developed more completely in his *Ansichten* [sic] *der chemischen Naturgesetze*, which was published in 1812, and even then he arrived at the result that magnetism must be produced by electrical forces in their most bound form. For a long time he imagined that it would be far more difficult to confirm this idea experimentally than the outcome later showed it to be.”[38]

In general if not specific terms, these were the results he had been expecting

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[37] KM II, pp. 12–21 and JJK, pp. 425–29.

[38] JJK, p. 425.

for almost two decades. And Ørsted was not alone in understanding their context. Consider, for example, Eckersberg's famous portrait of Ørsted from 1823[39]. The compass needle is clearly seen (lower right) as is the massive galvanic apparatus (upper left). Even greater prominence is given to the acoustic figure held in Ørsted's left hand and the violin bow used to excite it, and his piezometer dominates the right background. The fact that all of the tools required for Ørsted to confirm his deeply held Kantian convictions are present in the portrait cannot be a mere accident.

The Eckersberg portrait gives rise to an interesting question. Note the size of the galvanic apparatus. As described in the Latin paper,

> "The galvanic apparatus which we employed consists of 20 copper troughs, the length and height of each of which was 12 inches; but the breadth scarcely exceeded 2 $^1/_2$ inches. Every trough is supplied with two plates of copper, so bent that they could carry a copper rod, which supports the zinc plate in the water of the next trough. The water of the troughs contained $^1/_{60}$th of its weight of sulphuric acid, and an equal quantity of nitric acid. The portion of each zinc plate sunk in the water is a square whose side is about 10 inches in length. A smaller apparatus will answer provided it be strong enough to heat a metallic wire red hot."[40]

The question is simple: Given the strength of his galvanic apparatus, how could the effect on a compass needle have been "feeble" when even a crude experiment with a single AA battery as current source is sufficient to produce a dramatic effect? It seems likely that Ørsted had intuitively assumed an incorrect symmetry argument when he performed his lecture demonstration. For example, if the current-carrying wire was perpendicular to the compass needle, it might seem obvious that the needle would attempt to turn in a direction that was either parallel or anti-parallel to the direction of the current. If, on the other hand, the wire was parallel to the compass needle, it would appear that there was no reason to expect the needle to rotate clockwise rather than anti-clockwise. When Ørsted finally had the time to perform detailed experiments, he soon discovered the circular nature of the magnetic field produced by the current. A parallel orientation led to the largest effect; a perpendicular orientation gave no effect at all.

Confirmation

One of the copies of Ørsted's Latin article was sent to Sir Humphry Davy (1778–1829). With the aid of his assistant Michael Faraday (1791–1867), he soon succeeded in verifying Ørsted's results. Davy, who had been elected

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[39] Ørsted's wife, Inger Birgitte, did not approve of Eckersberg's efforts. This might have been because Ørsted's receding hair is not covered by his customary peruke.

[40] JJK, p. 417.

President of the Royal Society in 1820, immediately proposed Ørsted for membership and succeeded in securing the Copley Medal for him in the same year. Faraday was equally active in defending Ørsted against claims that he was lucky, or that others had made the discovery first. (See below.) The Prussian Academy of Sciences in Berlin worked almost as quickly as the English and awarded Ørsted membership in December 1820.

The list of French recipients of Ørsted's article was perhaps the most impressive and included André-Marie Ampère (1775–1836), François Arago (1786–1853), Jean-Baptiste Biot (1774–1862), Augustin Fresnel (1788–1827), Pierre-Simon Laplace (1749–1827), and Félix Savart (1791–1841) among others. Events proceeded rapidly. Arago quickly verified Ørsted's results experimentally and demonstrated them convincingly to a sceptical audience in Paris at a meeting of the *Académie Royale des Sciences* on September 11. Two weeks later Ampère demonstrated the interaction between two current-carrying wires[41]. In November, Arago performed a simple but compelling demonstration in which he used iron filings to reveal the circular magnetic field associated with the current-carrying wire. Finally, Biot and Savart showed how to describe the direction and magnitude of the magnetic field produced by a long current-carrying wire. This result was soon generalised by Laplace into the form now commonly known as the Biot-Savart Law[42]. This entire outburst of French scientific creativity, triggered by Ørsted's discovery, took only a few months. In spite of this, Ørsted was not offered membership in the *Académie Royale* until 1823.

It is interesting to note that Ørsted did not get along well with Ampère. In a letter to his wife in 1823[43] he wrote, "I had a long debate with Ampère about magnetism. He is a very inept debater and understands neither how to grasp properly the reasons of others nor to present his own; nevertheless, he has a profound mind." He was somewhat more formal but no milder in print: "The ingenuity with which this clever French mathematician has gradually changed and developed his theory in such a way that it is consistent with a variety of contradictory facts is very remarkable."[44]

Given the demonstrated scientific abilities of French physicists and the excellent technical facilities available to them, one might well ask why they did not discover electromagnetism themselves. Fortunately, Jacques Roux-

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[41] This discovery is sometimes known as "Ampère's force law" and is distinct from the more familiar law bearing his name. "Ampère's circuital law" (1823) states that the integrated magnetic field around a closed loop is proportional to the electric current passing through the loop.

[42] If your familiarity with either Ampère's laws or with the Biot-Savart law needs refreshing, consult the Wikipedia.

[43] JJ, pp. 288.

[44] JJK, p. 539.

Figure 11: François Arago, Pierre-Simon Laplace, and Jean-Baptiste Biot

Bordier[45] posed precisely this question in a letter to his friend Ampère. Ampère replied on 21 February 1821:

> “You are right in saying that it is inconceivable that twenty years ago, the action of the voltaic pile on the magnet was not tested. However, I believe we can determine the reason which was Coulomb’s hypothesis as to the nature of the magnetic action; we believed that this hypothesis was a fact; it absolutely excluded any idea of interaction between electricity and the so-called magnetic wire; the prohibition was so great that when M. Arago spoke of this new phenomenon at the Institute, it was rejected, just as was the idea of stones falling from the sky when M. Pictet, then only 20, read a memoir about it. They all decided it was impossible.”

There are morals to this story. Science is about “understanding” and not about “belief”. So, if you don’t understand it, don’t believe it! This obvious fact lies at the heart of any number of great discoveries. In June 1956, T. D. Lee and C. N. Yang raised the possibility that the weak interaction did not respect parity conservation (i.e. mirror symmetry). For years, everyone had simply assumed that it did. When Lee and Yang looked for evidence, they discovered that “for the weak interactions parity conservation is so far only an extrapolated hypothesis unsupported by experimental evidence”[46]. They suggested a simple experiment to see. Within a few months the exper-

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[45] Jacques Roux-Bordier (1771–1822) was a wealthy amateur botanist and a close friend of Ampère. Born in Geneva, he knew a great deal about German philosophy and had read Kant’s *Naturphilosophie*.

[46] T. D. Lee and C. N. Yang, Physical Review **104** (1956) 254.

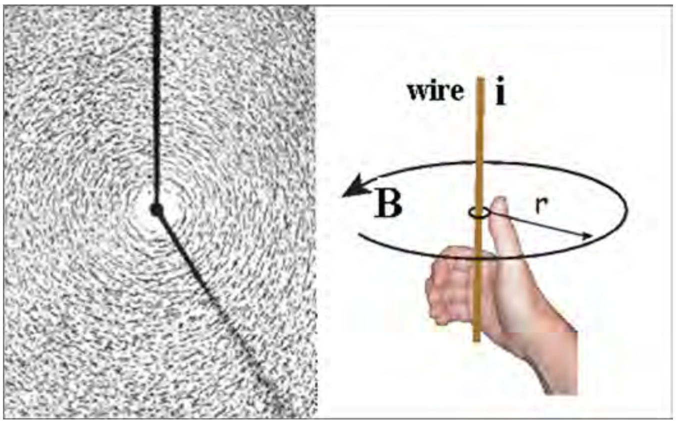

Figure 12: Arago's 1820 demonstration with iron filings of the direction of the magnetic field (B) from a wire carrying a current (i) and the right-hand rule.

iment was performed, and parity was found to be violated. Lee and Yang were awarded the 1957 Nobel Prize for physics.

A significant part of contemporary experimental research is performed in large collaborations with billion dollar budgets. It is simply too expensive for others to reproduce its results, and it is difficult at best to check the validity of experimental techniques and methods of data analysis. Even worse, the desire to protect large budgets and keep the money flowing, can introduce a "confirmation bias" that will tend towards the verification of a priori expectations. Science must learn how to deal with such problems if it is to maintain its credibility.

Conflict

Unfortunately, there were also negative reactions to the discovery of electromagnetism. These ranged from claims that Ørsted had been "lucky" to the more serious charge that the discovery had been made before Ørsted. Indeed, there were even claims of plagiarism. Some said that the initial discovery had been made in 1802 by Gian Domenico Romagnosi, an Italian jurist and amateur scientist, and that Ørsted had been informed of this in 1804 by Giovanni Aldini, an Italian physicist, who happened to be the nephew of the famous Galvani. Such claims persisted well into the twentieth century[47]. Ørsted's first published reaction to such charges appeared in

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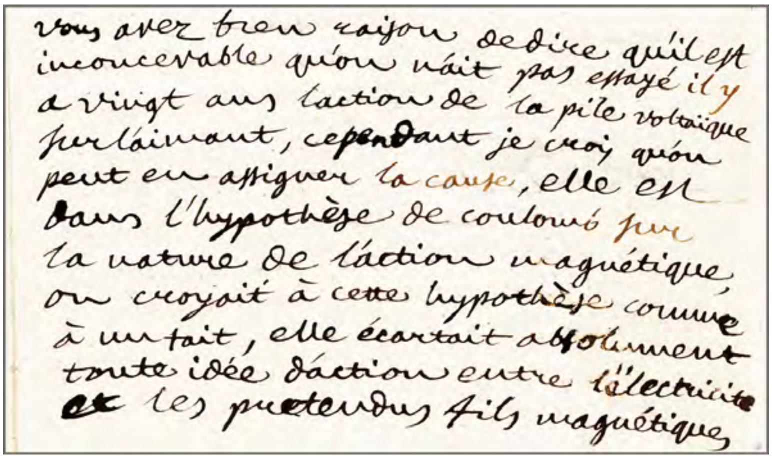
[47] For a balanced discussion of this criticism see, e.g. R. Martins (2001), "Romagnosi and Volta's pile: early difficulties in the interpretation of Voltaic electricity", in Fabio Bevilacqua, Lucio Fregonese (eds), Nuova Voltiana: Studies on Volta and his Times (2001) vol. 3, pp. 81–102. This article is available online.



vous avez bien raiſon de dire quil eſt
inconcevable quón náit pas eſſayé il y
a vingt ans laction de la pile voltaïque
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peut en aſſigner la cauſe, elle eſt
dans l'hypothèſe de coulomb ſur
la nature de láction magnétique,
on croyait à cette hypothèſe comme
à un fait, elle écartait abſolument
toute idée dáction entre lélectricite
et les pretendus fils magnétiques

Figure 13: A portion of the letter from Ampère to Jacques Roux-Bordier (21 February 1821).

Figure 14: Gian Domenico Romagnosi (1765–1831).

Thomson's *Annals of Philosophy* in 1821 and is quoted above. Ørsted published a more comprehensive response to the serious charges of priority and plagiarism in an article published in *The Edinburgh Encyclopaedia* in 1830. Ørsted became acquainted with the editor David Brewster during his first trip to England in 1823. Brewster convinced Ørsted to contribute an article on electromagnetism. Unfortunately, the encyclopaedia was alphabetically arranged and was published in instalments between 1808 and 1830. Thus, Ørsted's article was entitled *Thermo-Electricity* and dealt nominally with work that he had performed with Joseph Fourier (1768–1830). Writing in the third person, Ørsted availed himself of the opportunity to describe his own role in the discovery of electromagnetism and to reject the claims of others. His defense sounds familiar.

> "Throughout his literary career, he adhered to the opinion, that the magnetical effects are produced by the same powers as the electrical. He was not so much led to this, by the reasons commonly alleged for

> this opinion, as by the philosophical principle, that all phenomena are produced by the same original power."[48]

More recent investigations have made it clear that Romagnosi's experiments involved static electricity and were completely unrelated to Ørsted's.

From a more modern perspective, the question of "luck" is irrelevant. As Pasteur put it, "Chance favours the prepared mind". There can be absolutely no doubt that Ørsted's mind was prepared. However feeble the motion of the compass needle may have been, Ørsted knew precisely what it meant as soon as he saw it. His mind was prepared. Fortunately, he was also capable of communicating this understanding to the scientific world so effectively that no one else could ever claim to have made the discovery first. In other words, it does not matter who is the *first* to discover a new phenomenon. What matters is who is *last*.

1800	Alessandro Volta makes the electric first battery.
1820	H. C. Ørsted discovers EM.
1828	Ányos Jedlik makes EM a "self rotor"— a primitive electric motor.
1831	Faraday discovers EM induction.
1832	Hippolyte Pixii builds first alternating current generator.
1837	Charles Wheatstone introduces a commercial telegraph.
1855	Jedlik builds the first modern electric motor.
1865	James Clerk Maxwell provides a complete theory of electromagnetism.
1879	Thomas Edison invents light bulb.
1887	Michelson and Morley disprove the existence of "aether".
1895	Gugielmo Marconi and Nikola Tesla develop radio.
1905	Albert Einstein discovers special relativity.
1922	First radio station (Hilversum).
1936	The BBC begins regular television broadcasts.

Table 1: Some highlights from the first century of electromagnetism[49].

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[48] See KM II, pp. 351-98 and JJK pp. 546.

[49] In the case of technical discoveries, there are often several independent discoverers. For example, the telegraph could also be credited to Wilhelm Weber and Carl Gauss or to Samuel Morse.

Conclusion

The speed with which Ørsted's discovery affected physics would have been remarkable at any time. It was nothing short of a sensation in 1820 when the fastest means of communication was by coach and horses. As we known, electromagnetism soon changed that. As shown in the Table, the following years saw a steady stream of contributions to electromagnetism — both fundamental and technical — that have literally changed the world we live in. Athough Ørsted contributed to the further development of electromagnetism in the form of ten additional scientific manuscripts, none of them merit inclusion in this list. From ca. 1825 until his death in 1851, Ørsted's primary efforts were increasingly directed towards education and public service in a variety of forms.

While this is not the place to consider all of the entries in this table in detail, a few comments should be made. Michael Faraday's discovery of electromagnetic introduction (1831) was directly inspired by his work in the same year on the acoustic figures formed by solids and on the surface of liquids. This work was, in turn, a direct consequence of Faraday's desire to understand some of Ørsted's own results from 1810.

Figure 15: Michael Faraday (1791–1867), James Clerk Maxwell (1831–79), and Oliver Heaviside (1850–1925).

Maxwell's equations represent both an end and a beginning. In Maxwell's original formulation, there were no less than twenty equations! In this form they provided a complete but clumsy statement of the laws that govern electromagnetism. The more familiar and transparent form of these equations involving only four equations was written by Oliver Heaviside, a self-taught engineer, mathematician, and physicist, who adopted modern vector notation. Their "beginning" is more interesting since Maxwell's equations predicted electromagnetic waves that would propagate (in vacuum) with a velocity, c. This prediction encouraged the work of Marconi and Tesla and led to the development of radio. According to Maxwell, this velocity should be independent of the motion of the source and the observer. This prediction and its experimental confirmation by Michelson and Morley in 1887, led directly to Einstein's discovery of special relativity in 1905.

The glorious mixture of fundamental and practical consequences that resulted from his discovery of electromagnetism would have pleased Ørsted. It would not have surprised him. So, let the last words be his:

> "*[I]nsight is good in itself*, and no external justification is needed for wanting to acquire it. Science, then, must be studied for its own sake, as the vital manifestation of our innermost being, as the acknowledgement of the Divine. The fact that this also produces the most glorious fruits in the lower sphere is a consequence of that rational harmony which inspires everything. . . . [T]he utility of natural science is twofold, in that it both increases our powers and multiplies the means for their exercise."[50]

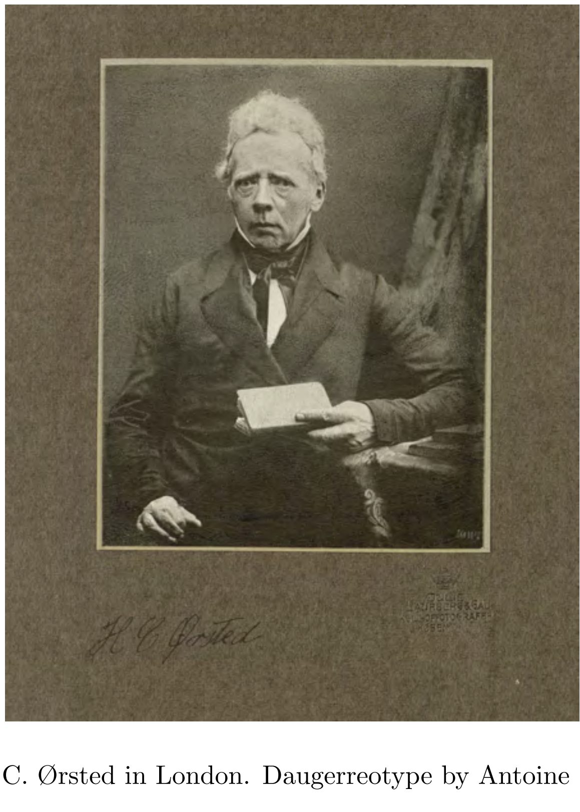

Figure 16: H. C. Ørsted in London. Daugerreotype by Antoine Claudet (1846).

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[50] KM III, p. 160 and JJK, p. 287.

Literature:

- Kirstine Meyer, ed., *H. C. Ørsteds Videnskabelige Værker*, vols. I–III, Copenhagen, 1920. (Abbreviated as KM.) Meyer's edition of Ørsted's scientific works, prepared in connection with the centenary of his discovery of electromagnetism, represents a complete edition of his scientific works in their original language (i.e. Danish, German, French, English and Latin). Volume I contains an introductory English essay entitled *The Scientific Life and Works of H. C. Ørsted*, and volume III contains a Danish description of his contributions to Danish society entitled *H. C. Ørsteds Arbejdsliv i det danske Samfund.* Both essays remain useful.

- K. Jelved, A. D. Jackson, and O. Knudsen, eds. and trans., *Selected Scientific Works of Hans Christian Ørsted*, Princeton, 1998. (Abbreviated as JJK.) This volume contains English translations of a broad selection of Ørsted's most important scientific works.

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