

Magnetism In the Nineteenth Century

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Introduction

We enter the history of magnetism during the nineteenth century with a different viewpoint or scientific fashion. The success of the Newtonian scientific philosophy as a theory of planetary motions led to its extension into all of the fields of scientific inquiry. This extension into the field of magnetism was successfully accomplished during the eighteenth century with the demonstration by Coulomb that magnetism obeyed the force law of the inverse square. This allowed the action at a distance forces: gravitation, electricity, and magnetism, to be united under the Newtonian scientific program. But, these forces were not viewed as unified in the modern sense. Certainly, the similarity of the force action law for electricity and magnetism did not imply a closer connection than the unity of forces under the Newtonian system. This system conceived all forces as being united in their mode of action, but this did not imply a more fundamental connection.

The history of magnetism in the nineteenth century begins with an attempt to unify forces under the Newtonian action-at-a -distance paradigm, and then separates into two distinct sciences. To make this clear, we will differentiate the two branches. The first we will call the science of electromagnetism, and the second will be termed magnetism in the classical mode. Electromagnetism is the science which results from the unification of electricity and magnetism, leading to the Maxwell equations and electromagnetic waves. Classical magnetism is the science which deals in the phenomena of magnetism which were studied during the era before unification with electricity. It deals with the phenomena of magnetic induction, terrestrial magnetism, magnetic materials, and the theory of magnets. This separation of magnetic science from electromagnetic science has not always been clear cut, but today the differences are clearly defined. An expert in magnetic materials, magnets, and magnetic phenomena, is not an expert in electromagnetic phenomena, because these are very different fields of study with completely different methods and theories. The objective of this chapter will be to trace the development of the classic magnetic science, with the electromagnetic science viewed as a secondary, but important development. Consequently the main story of development will focus upon the classical science of magnetism, and treat the electromagnetic unification with less emphasis.

The Metaphysical Background of The Newtonian Philosophy

Up until the triumph of the Newtonian philosophy in the eighteenth century, the metaphysical reality of magnetism was the primary problem. That reality could not be denied; magnetism existed, even though the metaphysical conditions of its existence were difficult to define. Magnetic influence could not be dismissed as unreal, or occult, or magical, or erroneous superstition. Hence the nature of this magnetic reality or “substance” was the primary focus of philosophy. The main question was, is magnetism material or immaterial. For Tales it was immaterial soul, Empedocles saw it as a corporeal substance, like air that could only be detected indirectly by its effects.

During the Christian Era, the idea that magnetism was immaterial became established and we see that Peregrinus, Gilbert, and Kepler take this view of it. Unfortunately, it is not clear whether magnetism is substance or quality. But in the seventeenth century there was a turn in fashion back to the corpuscular interpretation of magnetism. Here the metaphysical system required only void space and matter as the primary philosophical concepts. The Newtonian natural philosophy avoided the problem of magnetism by insisting that the metaphysical nature of magnetism was not necessary to scientific analysis. So action-at-a-distance became a satisfactory model. But this was not really an answer. Hence, we saw that Coulomb viewed magnetism as a kind of fluid. There were two of them, northern and southern, just as there were two different kinds of electricity.

The metaphysical assumptions of the Newtonian system consisted of three basic concepts; void space, matter, and force. These were essentially the same as for the systems of the ancient Greek materialists, with the addition of force as the active principle, where before this idea had been a soul or active intelligence. The force was envisioned as caused by matter located in empty space acting at a distance via the inverse square law of force. The Newtonian metaphysical system required matter as the source of the force, and hence numerous fluids were created to fulfil this function. Therefore, in the Newtonian interpretation, there were electric and magnetic fluids, the material cause, which set up forces in space which acted in accordance with the inverse square law of force. This metaphysics created a dilemma for science in the nineteenth. The question became, is the matter the cause of magnetism, or is the force the reality of it. When Faraday considered this problem he began to doubt the Newtonian metaphysical assumptions, and this led to field theory.

The most important metaphysical change was the introduction of the Newtonian notion of force. This idea didn't exist for Gilbert and Kepler, but it was the primary metaphysical notion of the Newtonian philosophy. For the modern reader, the notion of a magnetic force is a natural concept. But, for Gilbert, the idea of the force was merely a descriptive adjective attached to the primary metaphysical reality which was the magnetic substance or soul. Gilbert might say that this was a kind of magnetic force or vigor, but his did not mean what it did in the nineteenth century after the Newtonian mathematical method gave it a specific meaning.

In the nineteenth century, the term "force" came to be used in the same way that the idea of magnetic species had been used in the Aristotelian theories. It was the force that pervaded the sphere of influence. Hence, for Faraday it is the "force" that is the primary metaphysical entity. Therefore, we see Faraday seeking the "unity of forces". The electric force, the magnetic force, and the gravitational force. Here force is the new metaphysical concept that identifies the underlying reality; what an Aristotelian would have identified with a kind of substance. The reader will surely have perceived that this identification is itself vague and unclear. This is correct. However, the metaphysical concept was useful, and it still exists, when we talk about the "forces of nature" in modern physics.

The Metaphysical Assumptions Of the Cartesian System

In the Cartesian system the metaphysical entities were an aether, instead of a void space, and matter. So for Cartesians space was a substance (it wasn't a void). It contained a material called the aether which was responsible for the transmission of forces, such as gravity. In the eighteenth century, there was a struggle between the Newtonian and Cartesian metaphysical systems in which the Newtonian view triumphed. This victory was not complete, because the Cartesian concept of an aether continued to prove useful. The reason was simple. Although the Newtonian view which assumed a void space for the propagation of the gravitational and other forces had proved entirely successful in the sciences of astronomy, electricity, and magnetism, there was a big difficulty that remained. This was the problem of light. The Newtonians were forced to advocate a corpuscular theory of light, similar to the modern idea of a photon, because in their metaphysical system space was empty of all matter, or completely void of substance. But, demonstrations of the wave nature of light presented severe difficulties for the idea of a Newtonian void space. The Cartesian idea of an aether filled space which provided a mechanically physical means to propagate light as a wave was therefore superior to the Newtonian interpretation of light. In the nineteenth century, the ultimate interpretation of light as an electromagnetic wave, would bring back the aether as the medium for its propagation within the context of field theory.

Most science history books fail to make it clear how the idea of the aether arose during the nineteenth century. Its source was the Cartesian system, combined with the doubts about the Newtonian metaphysical idea of action-at-a-distance through a void space that arose with the new discoveries of Faraday and others.

The Gilbertian Tradition In Terrestrial Magnetism

At the opening of the nineteenth century, the Gilbertian magnetic philosophy was almost entirely forgotten. This was certainly the case among the natural philosophers. Natural philosophy was Newtonian mathematical philosophy, based on mathematical principles, inferred from experiments and made general, and then made precise through deduction via Newtonian mathematical principles. The main ideas being action- at-a-distance, and the inverse square law of force. The system was mechanical because the central metaphysical idea, force, was a mechanically defined concept.

The Gilbertian tradition continued to survive in the very limited, highly practical, disciplines of maritime navigation and terrestrial magnetism. These practical arts, were largely outside the realm of the natural philosophers, and were concerned with the practical applications of magnetism to ship's navigation. Here the idea of field mapping continued to be used. In 1821, Christian Hansteen published a detailed worldwide chart of the magnetic variation and dip. The chart was a contour or "field map" of the variations of the compass for almost the entire navigable world.

In 1820, Peter Barlow, published "An Essay on Magnetic Attractions". Barlow's book addressed the practical problem of assessing the variations on a ship's compass caused by the iron contained within the ship; ie, iron cannons, cannon balls and other iron implements. This subject, known as ship's magnetism, became more important in the second half of the nineteenth century, when wooden ships were replaced by steel ships. Barlow studied the effects of an iron cannon

ball on terrestrial magnetism by mapping the field in a region of space with and without the presence of the cannon ball. The technique was based on the methods of Gilbert, who had clearly shown how the magnetic field could be mapped in a crude way using a compass needle as a probe of the magnetic field.

In May 1824, George Birbeck presented an ingenious device, which demonstrated the identity of electromagnetism with terrestrial magnetism. Birbeck exhibited a wooden globe with electrical wires wound around it. The current carrying wires produced a magnetic field whose magnetic effects on a compass needle were comparable to those of the earth. The objective of the demonstration was to illustrate experimentally that Ampere's hypothesis that all magnetism is due to electrical currents could be used to explain the source of the earth's magnetic field. The demonstration had another motivation. It demonstrated that classical magnetism produced by lodestones, was no different from the electromagnetism discovered by Oersted. This demonstration is Gilbertian in the sense that while Gilbert used spherical lodestones as his magnetic model of the earth, Birbeck used a wooden globe with electrical wires wound around it.

In 1824, Barlow prepared an article on magnetism for the *Encyclopaedia Metropolitana* in which he presented illustrations of magnetic field lines obtained from iron filing patterns. This technique was so old, that it can not be determined who was the first to use it. The lines formed by the iron filings were suggestive of the physical character of magnetism, and more than any other demonstration provided convincing evidence of its reality. Here was a way that magnetism, normally invisible, could be seen. From this it is natural to conceive of magnetism in terms of lines of force, as long as we characterize magnetism using the Newtonian concept of force. During the nineteenth century this method of visualizing magnetism gained importance and certainly contributed to the acceptance of the field concept.

The evidence is clear that although the main focus of natural philosophers was Newtonian, there remained the traditional practical men, who continued to use the magnetic techniques in the old tradition of William Gilbert. They were imbued with the ideas of classical magnetism, and continued to work with them into the nineteenth century.

Classical Magnetism in The Nineteenth Century

Helmholtz's remark that "Our ignorance concerning magnetism is the disgrace of the nineteenth century" reflects the slow progress of classical magnetic studies during this period. When we survey the results of progress, we discover that Helmholtz is indeed correct. But this is deceiving. Viewed in terms of scientific theory regarding the true nature of magnetism, there is nothing new until Faraday's introduction of the field concept circa 1845. But, this does not lead to a really new theory of magnetism, only a different interpretation of its mode of action. In the area of technical and practical applications of magnetism, there are significant and rapid advances as the science of magnetism is applied to the development of the electromagnetic telegraph, electromagnetic machines, and improvements in the ship's compass. Scientific study of magnetic phenomena are overshadowed by the advances in electromagnetic science. What is really significant is that modern histories of magnetic science really only begin towards the end of the nineteenth century. The prevailing modern approach is that magnetic science begins with the discovery of the electron and the development of the electron theory by Lorentz, followed

closely by the advent of the modern quantum theory. This places emphasis on the modern approach to magnetic materials, which is primarily based on the quantum theory of electronic orbitals of electrons in atoms. This is not addressed here.

Prior to the nineteenth century, the concepts of electricity and magnetism are used within the context of the classical viewpoint that views these subjects as the study of the electric and magnetic attractions and the materials associated with these effects. The eighteenth century changed the context of these studies particularly in the science of electricity which advanced extremely rapidly outracing the study of magnetism and leaving it behind. But, there was a conceptual unification which interpreted both of these phenomena under the paradigm of the Newtonian action-at-a-distance theory. This was completed towards the end of the eighteenth century by Coulomb's proof that electric and magnetic attractions were subject to the same inverse square law of force. At the opening of the nineteenth century, the French mathematical school headed by Laplace was putting the finishing touches upon the mathematical methods which would bring the science to its mathematical perfection uniting it with the great science of planetary motions founded on the same law of force. The approach was to extend the mathematical methods proved for astronomical use to explain electric and magnetic attractions. We will see in the next section how this effort was effected by the discovery of totally new and unexpected phenomena. But, here we will try to keep to the classical line of development regarding the study of the attractive and repulsive forces.

The change in scientific fashion, engineered by Newton, had by the beginning of the nineteenth century displaced qualitative experiment and inductive reasoning, replacing it with emphasis upon mathematical quantitative explanation and reasoning. The new science was explicitly based on mathematical reasoning. The mathematical development continued apace during the first decades of the century within the capable hands of the French mathematicians Laplace, Biot, and Poisson. But, magnetism was only one of the many phenomena that demanded the attention of the mathematical physicists. Heat, light, mechanics and other topics were just as important. The mathematical development proceeded apace. It culminated in 1824 with Poisson's publication of a work devoted to magnetism. This was based upon the two fluid theory of Coulomb. The main accomplishment was to bring the mathematical methods to a new level. The work is important because it establishes the foundation for the modern theory of magnetic and dielectric materials. It establishes the mathematical methods for the analysis of materials which consist of individual particles which are subject to external magnetic forces and become polarized.

Returning to the work of Coulomb, we recall that his proof was based upon the disquieting assumption that the magnetic fluid was totally concentrated at the ends of long thin iron wires. This approach allowed the proof of the inverse square law of action, which had eluded previous investigators including Newton. But, this proof was certainly not secure and beyond doubt. Clearly, the mathematicians of the French academy believed that it was certainly true, but the proof was insecure. Hence, one goal was to develop the mathematical methods and perfect the proof by extending the methods to be universally applicable. This effort certainly received impetus from Hans Christian Oersted's discovery of the magnetic attraction of an electric current upon a compass needle. Oersted discovered that the magnetic force acted in circles. This did not appear to conform to the inverse square law. Attempts by Biot with the assistance of his student Savart to establish the inverse square law of magnetic force for magnetic currents faced the same

problem as Newton's experiments over a hundred years before. By measuring the oscillating period of a compass needle, Biot and Savart claimed to establish an inverse square law for the magnetic force, but Andre Marie Ampere showed that this method was flawed. Ampere eventually established the new science of electrodynamic force in the 1830's as a result of his theory of magnetic action. This story will be described in detail in the next section. The result of the electromagnetic revolution initiated by Oersted was the establishment of several new lines of scientific inquiry. Each leading in a different direction away from the mainstream of classical magnetic science. The effect was to demonstrate that the classical approach needed refinement. Poisson made a good attempt at this in his 1824 book. This work can be seen as the starting point for the development of the classical theory of magnetic action into its modern form in the hands of George Green, Michael Faraday, Karl Fredrich Gauss, William Thomson, James Clerk Maxwell, and others.

From a strictly scientific viewpoint, Poisson's accomplishments are mainly in terms of mathematical technique. He is important because he extended the solution of the potential functions for the force to include regions which included the magnetic and electric fluids. Laplace's name is associated with the solution of the potential function for regions without these fluids. We see this today in the names associated with the solutions of electrostatic and magnetostatic field problems. But these developments were only a start. In 1832, the English mathematician George Green published an Essay on Electricity and Magnetism. He developed the methods for the solution of the potential functions, which he is responsible for naming. We see his efforts memorialized today in the method of Green's functions, which is an important method for solving electromagnetic problems.

Poisson's other major contribution was the method for the analysis of the polarization of magnetic materials. The main assumption was that the magnetic fluids were isolated in magnetic particles distributed throughout the magnetic body.

When we contrast the classical Aristotelian theory, or the theory of William Gilbert, with the magnetic theory of Poisson, there are some significant and important differences. In the first place, the mathematical rationalism of the Newtonian approach had no role for the propagation of the magnetic action throughout space. This was accomplished by the use of action-at-a-distance via the mathematical rule of the inverse square law. The concept of a field didn't exist. This was a hindrance but not a decisive difficulty. However, there were problems.

Today field theory is identified with action at a distance through the agency of the

Poisson's Analysis Of Magnetism In Materials

Poisson's analysis of the magnetism of materials is really an application of the basic ideas of the Aristotelian theory of magnetism restricted to the region of the magnetic material. In the Aristotelian theory, and Gilbert's, the basic idea was that the lodestone or magnet contained within it a soul, or active principle, which gave to it power or vigor. Today we use the term "magnetic force" to describe this concept. Surrounding the magnet as the source of this energy or vigor, was the sphere of virtue, or realm of magnetic action. Today called the magnetic field. When a magnetic material was brought within this sphere, it was excited by the presence of the vigor within the magnet and this excitation caused it to become a magnet in response. Hence the

presence of a nearby magnet awakened within the iron its own magnetic power in response. This theory had its roots in the observation by Plato described in his dialog Ion. The phenomenon is known today as magnetic induction.

In Poisson's analysis of magnetic materials, when a magnetic field existed in a magnetically active material such as iron, the magnetic fluids within the material which were more or less randomly dispersed, became activated in response to the applied magnetism and the result was a multiplication of the strength of the magnetic action by focussing the magnetic power within the material. This effect resulted from the action of the magnetic domains within the material upon each other, bringing them all into alignment and focussing their power.

The Discovery Of Electro-Magnetism

At the end of the eighteenth century the very important discovery of the electrochemical current was made by Alessandro Volta. This discovery was the culmination resulting from the study of animal electricity. A science which sought to determine the nature of electrical action and its effects upon animals. Volta constructed the first chemical source of electricity in an attempt to demonstrate that the electrical effects of animal electricity did not arise within organisms but from the effects of external sources of electricity. His invention of the chemical battery constituted his proof of this viewpoint.

The study of current electricity or galvanism, as the electrical effects of Volta's pile were described, developed slowly at first. The discovery remained a subject of scientific inquiry until the 1840s, when the invention of Morse's electromagnetic telegraph sparked the first technological application of the new science. During the first two decades of the nineteenth century, there was no significant exploitation, but behind the scenes a revolution was brewing, nurtured by the Kantian philosophy. The first real breakthrough occurred twenty years later when Oersted discovered that an electrical current produced a magnetic action upon a compass needle.

Hans Christian Oersted initiated a wide reaching revolution which has not been fully explored and documented. If we examine his discovery in the traditional manner, it appears as the discovery that an electrical or galvanic current creates a magnetic force. This is easily said but comprehended with difficulty. Transporting ourselves into the context of nineteenth century science is easier said than done. Today the discovery seems important, but not as revolutionary as it actually was. The effects were far reaching. Here the main lines will be summarized as an introduction.

Putting ourselves in the place of the French academy mathematicians, the discovery comes as a shock. Oersted announces the discovery in a manner which casts doubt on its conformity with Newtonian scientific principles. This causes an immediate flurry of activity, among both proponents and critics of the European physics establishment. It is surprising how rapidly and fast the new discovery is exploited. This is curious in relation to the fact that Oersted did not actually make the crucial discovery associated with his name. The magnetic effect of the electrical current should have been known to the physics community. It was well documented

that in 1802 shortly after Volta's invention of the galvanic battery an Italian savant Gian Domenico Romagnosi from Trent discovered "the directive influence of a galvanic conductor on a magnetic needle." The discovery was well documented in the reference books of the time, and is beyond dispute. The mystery is why Oersted's rediscovery should have caused the resulting revolution in electromagnetic science.

Many attempts were made to discover the magnetic action. Oersted had tried and constantly failed since his first attempts began in 1812. The important point is that the announced discovery occurred in a manner that aroused a maximum of publicity and as a consequence a lot of activity followed at a rapid pace. But, this does not really explain the flurry of activity. There is more here than is immediately obvious. The reason is that Oersted's announcement describes the results of a series of experiments which if interpreted in the manner which Oersted desired could topple the entire basis of the Newtonian action at a distance paradigm. This was faced squarely by the French school. They proceeded to quickly show that the new discovery was consistent with the Newtonian theory. But there were flaws in the proofs. The attempts to prove and disprove the Newtonian action of an electric current led to the foundation of new fields of inquiry and technological advance.

The investigations created the discovery and technical development of the electromagnet. The technological revolutions of the telegraph, and electrical machines followed. Faraday and Henry discovered electromagnetic induction, the creation of electricity from magnetism. Henry continued on to discover self induction, and establish the transmission of electromagnetic forces through empty space. A prelude to the discovery of electromagnetic waves by Hertz fifty years later.

The main scientific advance was the development of field theory in the hands of Faraday, Thomson, and Maxwell. Shortly after Oersted's discovery Faraday was commissioned to write a summary of the discovery and the resulting developments. This induced Faraday to perform his own experiments. He performed a famous demonstration which refuted the interpretation of Andre Ampere. This began a long contentious struggle that led Faraday to his great discoveries in electricity and magnetism and to the concept of lines of force. An idea which Maxwell developed into field theory.

The Second Electromagnetic Revolution

In 1831, barely a decade after Oersted's discovery of the magnetic effect of current electricity, Michael Faraday and Joseph Henry announced the discovery that electricity could be produced from magnetism. This is really the decisive discovery that creates electromagnetism. While Oersted had shown that current electricity creates magnetism, the reciprocal effect, that magnetism creates electricity had resisted all efforts to demonstrate its existence. The long search ended with Faraday's discovery. While Faraday is usually given the credit and Henry is mentioned as a coincidental discoverer, in many ways it was Henry who really understood most deeply the implications of the new phenomenon.

This is not the traditional viewpoint, and to understand it more clearly, consider what Faraday did. Faraday had attempted to induce electricity in the following manner using a device known as

a torroid transformer. Wire was wound on the primary, and a secondary winding was connected to a galvanometer, or current detecting device. When Faraday connected the primary to the battery, he expected that a steady current would be observed in the secondary circuit. This type of experiment had been tried many times but had always failed. However, Faraday noticed that when the battery in the primary circuit was connected or disconnected, a transient electric current appeared in the secondary circuit, but only briefly.

This discovery that a changing electric current in the primary, creates an electric current in the secondary is called Faraday's law. But in truth, this does not really imply that electricity and magnetism are reciprocal, it means that current electricity creates current electricity in a reciprocal manner. In another view of it, we can say that a magnetic field created in the primary circuit, creates a magnetic field in the secondary circuit. Hence, it does not seem correct to say that Faraday's discovery proves that magnetism creates electricity and vice versa. The problem here is the identification of current electricity with electricity, when they are not really the same thing at all. The identification arises because current electricity was thought to be the result of electricity moving through the wires of the circuit from the poles of the battery, positive to negative. Hence, it was thought that electricity in motion caused magnetism.

Joseph Henry had a clearer idea as a result of his experiments. He saw clearly how the magnetism and electricity were related. In Henry's experiments, he noticed that when he disconnected the poles of the battery from the circuit of an electromagnet a spark occurred. Henry recognized that an electric spark was an indication of a high electric potential in the circuit, because an electric spark was one of the defining characteristics of static electricity. It is this observation that shows that electricity is produced by a changing magnetic field. Henry correctly deduced that a spark ensued because of a high electric potential, since when the circuit was closed with out connecting through the electromagnet there was no spark. In fact, the intensity of the spark increased when the length of the wire was increased, not by increasing the power of the battery. So Henry is correctly credited with the discovery of the law of inductance. What Henry demonstrated was that the electric force or voltage, which is a measure of the intensity of electricity, was increased far beyond the capability of the battery when a circuit carrying current electricity was disconnected. Hence, electricity was created by the change in magnetism in the circuit.

Faraday's Field Theory

Although the discovery of electromagnetic induction by Michael Faraday in 1831 falls into the category of electromagnetism, it is his field theory of magnetism that establishes the modern field theory.

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