ARTICLE

Electromagnetic Unification

150th Anniversary of Maxwell's Equations

Written by Augusto Beléndez

By kind permission of the Master and Fellows of Peterhouse (Cambridge, UK)
Picture of James Clerk Maxwell (1831-1879), who, together with Newton and Einstein, is considered one of the greats in the history of physics. His theory of the electromagnetic field was fundamental for the comprehension of natural phenomena and for the development of technology, specially for telecommunications.

When we use mobile phones, listen to the radio, use the remote control, watch TV or heat up food in the microwave, we may not know James Clerk Maxwell is the one to thank for making these technologies possible. In 1865, Maxwell published an article titled «A Dynamical Theory of the Electromagnetic Field», where he stated: «it seems we have strong reason to conclude that light itself (including radiant heat, and other radiations if any) is an electromagnetic disturbance in the form of waves propagated through the electromagnetic field according to electromagnetic laws» (Maxwell, 1865). Now, in 2015, we celebrate the 150th anniversary of Maxwell's equations and the electromagnetic theory of light, events commemorating the «International Year of Light and Light-Based Technologies», declared by the UN.

«At the beginning of the nineteenth century, electricity, magnetism and optics were three independent disciplines»

At the beginning of the nineteenth century, electricity, magnetism and optics were three independent disciplines. However, the situation changed thanks to one invention and two discoveries. The invention was the electrical battery, a continuous source of electrical current created by Alessandro Volta towards 1800. The two discoveries were, on the one hand, the demonstration of magnetic effects caused by electrical currents by Hans Christian Oersted and André-Marie Ampére in 1820; on the other, Michael Faraday's discovery, in 1831, of the generation of electrical currents with magnetic fields: electromagnetic induction. These contributions set the pillars of modern electromagnetism, which peaked in the last

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third of the nineteenth century with Maxwell's synthesis of electricity, magnetism and optics. Such a synthesis represents, probably, the most profound transformation of the fundamentals of physics since Newton and is one of the greatest scientific achievements, unifying electrical and magnetic phenomena and enabling the development of the theory of electromagnetic waves, including light (Udías, 2004).

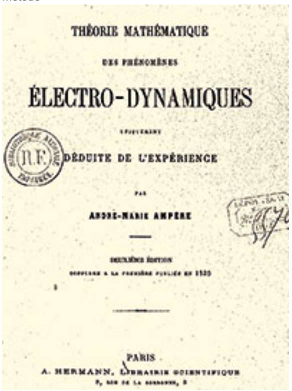
THE ORIGINS OF MODERN ELECTROMAGNETISM

Hans Christian Oersted (1777-1851) studied natural philosophy in the University of Copenhagen, where he was Full Professor of Physics and Chemistry (Pérez and Varela, 2003). The invention of the electrical battery had been a revolution among scientists, who were able to work with permanent sources of «electrical fluid». Oersted started making experiments with a voltaic battery and proved, in April 1820, that an electrical current altered a nearby magnetised needle. He discovered that an electrical current produced magnetic effects and that electricity and magnetism were not independent phenomena. Oersted published his results in a brief article written in Latin, *Experimenta circa effectum conflictus electrici in acum magneticam*, dated 21 July 1820, and coined the term *electromagnetism* to designate the part of physics that would comprehend both phenomena as of then.

André-Marie Ampère (1775-1836) was a contemporary of Oersted. His first years were marked by the French Revolution and the execution of his father in the guillotine (Pérez and Varela, 2003). After being a physics and chemistry teacher in high schools for a long time, in 1804, he obtained a position as Professor in the École polytechnique in Paris, and he was admitted, in 1814, in the French Academy of Sciences. Although Ampère showed great mathematical, optics and chemistry skills, his most important contributions were in the field of electromagnetism. In 1820, he received news of Oersted's discovery, the *conflictus electrici* that altered the behaviour of a magnetised needle. The summer of that year, he carried out several experiments. If an electrical current produced magnetic effects in a magnet, why would it not produce magnetic effects in another current?

In September 1820, he presented his results in the Academy of Sciences: mutual action between currents without the intervention of any magnet. That is, two parallel electrical currents attract or repel each other depending on their polarity – the same or the opposite, respectively. In 1826, he published his book *Theory of Electrodynamic Phenomena, Uniquely Deduced from Experience*, whereby he claimed that «magnetism is merely electricity in motion» and that magnetic phenomena depend only on the existence and motion of electrical charges.

Mètode



THÉORIE MATHÉMATIQUE

DES PHÉNOMÈNES

ÉLECTRO-DYNAMIQUES

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The demonstration of magnetic effects caused by electrical currents by Hans Christian Oersted and André-Marie Ampére in 1820 contributed to the foundations of modern electromagnetism. Top picture: Oersted. Bottom picture: cover of Ampère's *Theory of Electrodynamic Phenomena*.

Michael Faraday's (1791-1867) case is not common in the history of physics. A man of humble abode, he abandoned school when he was thirteen and started working in a bookbinding workshop. His passion for science was triggered there, after reading the description of *electricity* in the *Encyclopædia Britannica* when he was binding a copy, after which he started experimenting in an improvised laboratory. He was hired in 1813 as Humphry Davy's laboratory assistant in the Royal Institution, in London, where he was elected a member in 1824 and where he worked until his passing away in 1867. Faraday made such an impression on Davy that when he was asked about his biggest scientific discovery, he answered: «My greatest discovery was Michael Faraday» (Díaz, 2001).

In 1821, Faraday repeated Oersted's experiment placing a small magnet around a wire with current and checked that the force exerted by the current on the magnet was circular. As he expressed years later, the wire was surrounded by an infinite series of circular and concentric «lines of force»: the magnetic field of the current, a term coined by Faraday. In 1831, he managed to produce an electrical current from a magnetic action, a phenomenon known as electromagnetic induction. He found that sending an electrical current through a coil, another current – a very short one – was generated in a nearby coil. The discovery set a decisive milestone in the progress not only of science, but also of society, and is used today in order to generate electricity on a large scale in power stations.

Faraday abandoned fluid theory to explain electricity and magnetism and introduced the concepts of *field* and *field lines*, moving away from the mechanicist description of natural phenomena, like Newton's *actions at a distance*.

JAMES CLERK MAXWELL

James Clerk Maxwell (1831-1879) was one of the most important scientists of all time. He gave us the theory of the electromagnetic field, fundamental not only for the comprehension of natural phenomena, but also for its technical application, in particular in the today ever-present field of telecommunications. Maxwell is one of the greats in the history of physics, along with Newton and Einstein (Sánchez Ron, 2006).

Maxwell was born in Edinburgh to a wealthy family. After receiving private education in the family estate of Glenlair, he was sent to Edinburgh Academy, where he spent five years and learned French, German, Logic, Philosophy, Chemistry and Mathematics. In 1847, he entered the University of Edinburgh and, three years later, the University of Cambridge, the most influential school of physics at the time. He was also admitted in the Trinity College. Upon finishing his studies, Maxwell got the Chair of Natural Philosophy at the Marischal College in Aberdeen, where he spent four years. There he investigated on colour theory and married Katherine Mary Dewar, daughter of the College Principal. In 1860, he left Aberdeen to occupy another chair in London's King's College, and he was appointed a member of the Royal Society a year later. In February 1865, halfway through the academic year, he resigned from the chair voluntarily and went back to his Scottish estate in Glenlair (Reid, 2014). He wrote his *magnus opus* there, *A Treatise on Electricity and Magnetism*, published in 1873, two volumes of more than 500 pages each, peak of nineteenth century physics and comparable to Newton's *Principia*, published almost two centuries before. In this work, Maxwell manages to unify all known phenomena at the moment regarding electricity and magnetism.

In 1871, Maxwell was appointed to take up the newly created Chair of Experimental Physics at the University of Cambridge, and in 1874 he became the first director of a new research centre, the Cavendish Laboratory. In early 1879, Maxwell's health started to deteriorate. He passed away due to an abdominal cancer on 5 November that same year. He was 48.

«Faraday coined the term 'magnetic field' and in 1831, he managed to produce an electrical current from a magnetic action»

Lucía Sapiña

Michael Faraday introduced the concept of *lines of force* to represent the electrical and magnetic fields and, in 1831, he managed to produce an electrical current from a magnetic action. In the picture, Faraday statue at the entrance of the Royal Institution in London.

MAXWELL'S EQUATIONS

Maxwell left us contributions to colour theory, knowledge of the structure of Saturn's rings and statistical physics. However, his most important contributions were to electromagnetism. In 1856, he published *On Faraday's lines of force*; in 1861, *On physical lines of force*. In these two articles he provided a mathematical explanation for Faraday's ideas on electrical and magnetic phenomena depending on the distribution of lines of force in space, definitively abandoning the classical doctrine of electrical and magnetic forces as actions at a distance. His mathematical theory included the aether, that «most subtle spirit», as Newton described it. He studied electromagnetic interactions quite naturally in the context of an omnipresent aether. Maxwell stood firm that the aether was not a hypothetical entity, but a real one and, in fact, for physicists in the nineteenth century, aether was as real as the rocks supporting the Cavendish Laboratory.

James Clerk Foundation
In 1871, Maxwell was appointed to take up the newly created Chair of Experimental Physics at the University of Cambridge, and in 1874 he became the first director a new research centre, the Cavendish Laboratory (in the picture).

When he was 33, he published «A Dynamical Theory of the Electromagnetic Field». In this text, Maxwell includes twenty equations he called «General Equations of the Electromagnetic Field». He links them to twenty variables governing the behaviour of electromagnetic interaction. The article is 53 pages long, divided in seven parts. His twenty general equations of the electromagnetic field, which expressed and summarised the experimental laws of electromagnetism, provide a complete theoretical basis for the treatment of classical electromagnetic phenomena. With them, Maxwell proved that electricity and magnetism are only different manifestations of the same physical substrate, electromagnetism (Sánchez Ron, 2006).

«Maxwell's synthesis set a milestone in the history of the unification of forces»

In 1884, Oliver Heaviside – and later and independently, Heinrich Hertz – synthesised, using vector notation, the twenty equations of the electromagnetic field in the four Maxwell equations we know today: Gauss's law for electric fields, Gauss's law for magnetic fields, Faraday-Henry's law for electromagnetic induction and Ampère-Maxwell's law. From then on, electromagnetism equations were known as Hertz-Heaviside equations or Maxwell-Hertz equations, until Einstein popularised, in 1940, the wording «Maxwell equations» (Turnbull, 2013). The Austrian physicist Ludwig Boltzmann considered them such beautiful equations in their simplicity and elegance that, with a quote from Goethe's *Faust*, he asked: «Was it a god who wrote these signs?» (Darrigolp, 2002).

James Clerk Foundation
In 1865, Maxwell resigned from his chair in King's College and went back to his Scottish estate in Glenlair. He wrote his *magnus opus* there, *A Treatise on Electricity and Magnetism*, peak of nineteenth century physics and comparable to Newton's *Principia*, published almost two centuries before. In the picture, James Clerk Maxwell with his wife, Katherine Mary Dewar, in 1869.

In the sixth part of his 1865 paper «Electromagnetic Theory of Light», Maxwell concludes: «we can hardly avoid the inference that light is nothing more than transverse undulations of the same medium that causes electric and magnetic phenomena». Maxwell proved that the equations of the electromagnetic field could combine into a wave equation and suggested the existence of electromagnetic waves. Calculating the speed of propagation of these waves, he obtained the value of the speed of light, and concluded that it was an electromagnetic wave.

Einstein referred to that crucial moment of Maxwell by pointing out: «Imagine [Maxwell's] feelings when the differential equations he had formulated proved to him that electromagnetic fields spread in the form of polarised waves, and at the speed of light! To few men in the world has such an experience been vouchsafed» (Einstein, 1940). Before Maxwell, the speed of light was only one among many other. After him, the speed of light became exceptional, pointing the way for Einstein and relativity.

Electromagnetic waves were produced by Heinrich Hertz in a laboratory in 1888, thus confirming Maxwell's theory. In 1901, the Italian engineer Guillermo Marconi transmitted across the Atlantic ocean, from Cornwall (England) to St. John's, in Newfoundland (Canada), using electromagnetic waves. Marconi was awarded a Nobel Prize for Physics in 1909, due to his contributions to the development of wireless telegraphy.

Gamma rays, X rays, ultraviolet radiation, visible light, infrared radiation, microwaves and radio and television waves constitute the spectrum of electromagnetic waves, whose existence was predicted by Maxwell 150 years ago. Maxwell's synthesis set a milestone in the history of the unification of forces that were so powerful that many nineteenth-century physicists thought the physical laws were already sufficiently comprehended. This led the American physicist Albert Michelson to write: «the more important fundamental laws and facts of

Albert Michelson to write: «the more important fundamental laws and facts of physical science have all been discovered, and these are so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote. Our future discoveries must be looked for in the sixth place of decimals» (Michelson, 1903). Nothing further from the truth. In the first years of the twentieth century there were two momentous changes in physics: Planck's quantum theory (1900) and Einstein's theory of special relativity (1905), both consequences of Maxwell's electromagnetic theory, which laid the groundwork for these two revolutionary ideas. It is clear that Maxwell opened the doors for twentieth century physics (Gabàs, 2012).

MAXWELL'S LEGACY

Although Maxwell's work on electromagnetism was essential, there were limitations, like trying to reconcile Netonian mechanics and Maxwell's electromagnetism. The problem was solved by Einstein in 1905 with his theory of special relativity. After Einstein's works, the luminiferous aether – the focus of nineteenth century physics – was dead and buried. Even Einstein recognised his theory of special relativity owed a lot to Maxwell's equations. In a 1931 article, on the occasion of the centenary of Maxwell's birth, he claimed that «one scientific epoch ended and another began with James Clerk Maxwell» and that «Maxwell changed the world forever» (Einstein, 1931).

Richard Feynman, Nobel Prize for Physics in 1965, pointed out: «from a long view of the history of mankind – seen from, say, ten thousand years from now – there can be little doubt that the most significant event of the nineteenth century will be judged as Maxwell's discovery of the laws of electrodynamics» (Feynman *et al.*, 1987).

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