

A Brief Outline of the History of Electromagnetism

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The primary sources for this outline were *From Falling Bodies to Radio Waves*, Emilio Segrè, Freeman, New York, 1984, *A History of Electricity and Magnetism*, Herbert W. Meyer, MIT Press, Cambridge, MA, 1971, *Physics*, 3rd ed. David Halliday and Robert Resnick, Wiley, New York, 1978, and *Encyclopedia Britannica*.

1. **Ancient** Electrical, magnetic, and optical effects have been known since antiquity. – the ability of some materials, notably amber, when rubbed to attract bits of cloth or paper and the *lodestone* or natural magnet.
2. **Early** Systematic investigation did not occur until the middle ages. Magnetic phenomena were first explored. The magnetic compass was known in 12th century England and not considered a novelty. In the 13th century, **Petrus Peregrinus** de Maricourt (France) found that when a magnetized needle was placed on a spherical magnet it would align itself longitudinally. Tracing the lines, he showed that they intersected in two points on opposite sides of the sphere. He called these, “magnetic poles”. He also showed that the orientation of a magnetic needle near the sphere depended on its proximity to a pole.
3. **William Gilbert**, (1540-1603). Physician to QEI, time of Shakespeare, the Spanish Armada. Published *De Magnete* in 1600. He confirmed Peregrinus’s result and speculated that the Earth is giant magnet. Showed that friction caused the attractive phenomenon to appear in many materials. He called the property “electric” from the Latin word, *electrum*, for amber.

Gilbert attributed the electrification of a body by friction to the removal of a fluid or “humor” which then left an “effluvium” or atmosphere, around the body. Replace humor with charge and effluvium with electric field to see that he was on the right track.
4. **Otto Von Guericke**, (1602-1688), Burgermeister of Magdeburg, Germany; he was trained as an engineer. Invented the vacuum pump – astounded people with a demonstration that 2 opposing teams of 8 horses

each could not separate two evacuated hemispheres. He was interested in the behavior of phenomena in a vacuum; tried to understand forces, such as gravity, that would act at a distance. He built the first electrostatic generator (based on friction).

5. **Stephen Gray**, (1666-1736). the son of a dyer from Canterbury, England. He discovered that the charge on an electrified body could be extended from that body. He found the effect worked using some materials and didn't work with others. He was able to distinguish conductors from insulators But for static charges. Currents were as yet unknown. Of course, the term "static" was not in use until many years later when currents were discovered to be moving charges.
6. **Charles Dufay**, (1698-1739). the gardener to the King of France. (A position more like the Secretary of the Interior, than a weed puller.) He found that there were two and only two kinds of electricity, *vitreous* and *resinous* because they were elicited by rubbing glass or rosin, respectively. These are now known as positive and negative (static) charges. Dufay found that similar electricities repel each other and that dissimilar ones attract.
7. **The electrical condenser**. It was found that by charging a liquid in a bottle and holding the bottle in the hand, one could obtain powerful discharges. Observed by **E. G. von Kleist** (1700-1748). Publicized by **Petrus van Musschenbroek** (1692-1761) of Leyden, Netherlands. Hence, capacitors were first known as *Leyden jars*. It was soon found that the liquid could be replaced by a metal foil covering the inside of the bottle.
8. **Public demonstrations**. "By the middle of the 18th c., electrical experiments had become very fashionable. It was common to electrify people by insulating them and connecting them to an electrostatic machine. These demonstrations were performed in social gatherings and in elegant salons, as well as to a larger paying public; they even reached colonial America." Sergrè, p109.
9. **Benjamin Franklin**, (1706-1790). "One of those demonstrations had the momentous consequence of arousing the interest of an American spectator, Benjamin Franklin He had a strong penchant for practical invention." [Sergrè, p109.] – A natural engineer. He performed a number of experiments, published these in 1751, and was elected a fellow of the Royal Society of London. He exploited the principle of the conservation of charge, first perceived by several independent investigators including **William Watson**, (1715-1787). Franklin postulated that a body contains equal amounts of positive and negative electricity, which under normal circumstances, exactly neutralize each other. Electrification is the separation of the two electricities, which he called "positive" and "negative", with the implication that their sum is constant and remains zero.

“Franklin demonstrated these ideas by experiments in which two people, standing on insulated platforms took the electricity from a glass tube rubbed with a cloth. One took it from the glass, the other from the cloth. When their fingers came near each other, a spark flew from one to the other, and both were neutralized. . . . Franklin surmised that lightning was a gigantic electric spark,” [Sergère, pp. 112-113] an idea he later supported with an experiment using a kite. He successfully charged a Leyden jar with the kite string. [Note: although Franklin emerged unscathed from his lightning experiment, a similar one killed the German-Russian scientist **Georg Wilhelm Richmann** (1711-1753) in St. Petersburg.] Noticing that a pointed object will easily lose its charge, Franklin invented the lightning rod. For his many achievements in electrical science, Franklin was awarded the Copley Medal, England’s greatest scientific award, by the Royal Society of London in 1753.

10. **Joseph Priestly** (1733-1804), who emigrated to America from England, was the chemist who discovered oxygen. On a suggestion of Franklin’s, he showed that when a hollow metal vessel is electrified, no electric force acts on objects in its interior and there is no charge on the interior. Priestly was very familiar with the work of **Isaac Newton** (1642-1727) and inferred that this experiment could be explained by assuming that electric charges of equal sign repel each other with a force proportional to the inverse square of their distance apart. This inference was correct but not pursued for awhile by anyone. Direct experimental proof of the inverse-square law for electricity was obtained by **John Robison** (1739-1805) (Scotland). But he neglected to publish the result and has been largely forgotten.
11. **State-of-the-art: 1770.** It was known:
 - There are two types of electricity (or maybe one that can be added to some materials and taken away from others)
 - Electricity is conserved.
 - There are insulators in which charge cannot move.
 - There are conductors in which it can move freely.
 - Equal charges repel each other.
 - Opposite charges attract.

The time was ripe for the establishment of a quantitative theory of (static) electricity. Newton’s theory of gravitation must have been on the minds of many experimenters.

12. **Charles Augustin Coulomb** (1736-1806) studied engineering at the military school in Mézières, France. He invented the torsion balance and used this to demonstrate the inverse square law. He published the results in 1788. The fact is now known as Coulomb’s Law. The unit of charge is now called the *coulomb*.

13. **Henry Cavendish** (1731-1810) a wealthy and eccentric Englishman independently verified the inverse-square law but did not publish the results. He was best known as a chemist since he published little of his electrical work. Most of his results came to light later through the efforts of Maxwell. In his unpublished work, he defined the capacity of a conductor noting that conductors charged “in the same degree” (to the same potential) contain charge in amounts proportional to their capacities. He also found that two condensers having the same geometry have a capacity that depends on the dielectric. He was the first person to measure the resistance of various materials.
14. **Mathematical Theories of Electrostatics ca. 1800.** By 1790, both the phenomenology of electrostatics, knowledge of the inverse-square law, and the Newtonian idea of action at a distance were widespread. Several great mathematician physicists of the time formalized the mathematical description of the phenomena.
- **Joseph Louis Lagrange** (1736-1813) (Fr) (Lagrange multipliers). Gravitational potential.
 - **Pierre-Simon Laplace** (1749-1827) (Fr) (Laplacian). Potential in a vacuum.
 - **Simèon-Denis Poisson** (1781-1840) (Fr) (Poisson Distribution). Potential due to electrical charges.
 - **George Green** (1793-1841) (Br) (Green’s functions). Global effects computed by summation of point effects – convolution.
 - **Carl Friedrich Gauss** (1777-1855) (Gr) (Gauss’s Law for you-name-it). Forces due to groups of charges; something in virtually everything else imaginable. He is considered by many to be the most intelligent human being who ever lived. He developed a system of magnetic units. The unit of magnetic induction is now called the *gauss*.

Magnetism closely followed the developments in electricity since the phenomenology of the two are so similar. Except, it was well known that there is no magnetic monopole. Except for the similar mathematical descriptions, there was no clear idea how these phenomena were related.

15. **Luis Galvani** (1737-1798). Anatomist and biologist from Bologna. For many years numerous electricians had purported physiological effects of electricity. Most of these were incorrect or outright fraudulent of the medicine show variety. The subject did not elicit much respect from the scientists of the day.

Galvani was dissecting a frog in a room with some sort of electrical machine. He had a scalpel in contact with a nerve running to the leg of the frog. The electrical machine happened to spark; this apparently caused the frog’s leg to contract. He found:

- Sparks in the air, including lightning, caused the response.
- Metallic foil covering the muscles increased the effect.
- A large response was obtained by touching both the nerves and the muscles with a metallic arc. A larger effect was obtained if the arcs were composed of two different metals

With this set of experiments, Galvani initiated electrophysiology and the study of electric currents. He was unable to disentangle the two problems and his obsession with finding the “animal spirits” led many other scientists to not take his work seriously. Yet the term “galvanism” and its many derivatives came to mean electric current.

16. **Alessandro Volta** (1745-1827). From Como, Italy. Studied languages, liberal arts. He “played” with electricity and became quite knowledgeable in the phenomenology. He invented a novel way to charge a Leyden jar. He tried to devise a means of measuring electric charge in a reproducible way and devised the first “volt” meter (although he didn’t call it that). He read Galvani’s work and although skeptical, tried to reproduce the results, which he did. He decided the frog was acting chiefly as a detector rather than a source of electricity. Following this idea and using Galvani’s bi-metal arc, he found that two metals in contact acquire different potentials. He concluded that the frog was no more than a sensitive electrometer. Galvani countered that the effect worked with a one-metal arc as well. Volta declared that inhomogeneities in the metal must cause the current.

Using the discovery of contact potential differences, Volta invented *Voltaic pile* or battery. He found that in a stack of metal plates of alternating types the potential differences sum. The first and last plates on the stack have a potential difference equal to the sum of the potential differences of each pair in the stack. The “pile” was a pile of disks of zinc, copper, and cloth soaked with an acid repeated many times. “The pile generated a continuous electric current of an intensity greater by orders of magnitude from that obtainable by orders of magnitude from that obtainable by electrostatic machines and thus started a true revolution in science.” [Sergre, p. 122] **Dominique Arago** (1786-1853) called the voltaic pile “the most marvelous instrument ever invented by mankind.” It is perhaps ironic that the name of the man who discovered the electric current is applied to the unit of measure of electrostatic potential.

17. **Another type of electricity.** Voltaic piles were constructed that delivered currents of 10 amps at 1000 volts. The effects of these 10kW currents were so different from the 1W sparks produced by electrostatic machines that most scientists thought that this so-called “galvanic” electricity was a different thing than static electricity. A number of chemists and Physicists almost immediately started using this device and made seminal discoveries (e.g. **William Nicholson**’s (1753-1815) discovery that water is made up of hydrogen and oxygen).

18. **Hans Christian Oersted** (1777-1851), was philosophically convinced of the unification of the forces in nature. He therefore set out to show that electricity and magnetism were related. It had long been known that lightning would cause compasses to deflect. As soon as Oersted heard of Volta's discovery he tried to get a galvanic current to deflect a magnet. In 1820 he published his results. They were immediately recognized as important and widely demonstrated. The unit of magnetic intensity is now called an *oersted*.
19. **André Marie Ampère** (1775-1836), heard Oersted's results presented at the French Académie de Sciences on 11 Sept, 1820 by Arago. Within one week Ampère developed a complete quantitative theory of Oersted's observation and succeeded in laying the foundation of a mathematical theory of electromagnetism. He refined and perfected his theory in the following years and published it in 1827. This treatise had at its foundation four experiments. In effect, he showed that two parallel conductors carrying electricity in the same direction attract each other, whereas if the currents are in opposite directions, the conductors repel one another. From the experiments he claimed:
- Outside its body, a permanent magnet is exactly equivalent in its magnetic action to a coil of wire carrying a current. (He called the coil a "solenoid".)
 - Each molecule in permanent magnet has a closed current loop.
 - Magnetization is the alignment of the molecules with an external magnetic field (he didn't call it a "field").

The unit of electrical current is now called the *ampere*.

20. **Dominique François Jean Arago** (1786-1853) was the secretary of the Académie de Sciences. He discovered in 1820 that a wire carrying a current of electricity would attract iron filings. Both he and Ampère demonstrated independently that a wire helix carrying an electric current was capable of magnetizing a soft iron bar around which it was wound.
21. **Georg Simon Ohm** (1787-1854) began his study of electric currents, flowing through conductors, in 1825. He published the results of his studies in 1827, and in his paper, the law, which now bears his name, was presented for the first time. This is probably the best known of the laws of electricity.
22. **Jean-Baptiste Biot** (1744-1862) and **Félix Savart** (1791-1841) discovered the law governing the force between a long, straight conductor and a magnetic pole. They showed that the magnetic effect (field strength) is proportional to the current in the wire and inversely proportional to the perpendicular distance from the point of measurement to the conductor.

23. **Michael Faraday** (1791-1876) introduced the concept of a *field* and thereby greatly simplified the mathematics that describe the phenomena. As a young man, Faraday was employed as a bookbinder in London. He had an avocation for science and was quite likable. Some of his customers gave him tickets to hear lectures at the Royal Institution. (People used to go to hear scientific lectures at the Royal Institution for entertainment. It was a popular pastime, the tickets were in demand and expensive.) He took notes on the lectures of **Humphrey Davy** (1778-1829), wrote them up nicely, bound them and presented them to Davy while asking him for a job. Davy hired him. Davy soon became aware that Faraday was likely to be one of the greatest physicists (“natural philosophers”) of all time. “By the end of his career, around 1860, Faraday’s laboratory notes contained more than 16,000 entries carefully numbered in sequence and bound in volumes where the author delighted in showing his old proficiency as a bookbinder.” [Sergère, p. 138]

Faraday described the force initiated by electric charges or magnetism as a disturbance in space which he called a field. The action of the field occurred along “lines of force”. He showed the magnetic field by sprinkling iron filings on a piece of paper covering a magnet. Faraday was much impressed by Oersted’s discovery and he made a great point that the magnetic action was at right angles to the direction of the current that produced it. He became convinced that if an electric current could produce a magnetic field then a magnetic field must be able to produce a current. He brooded over this for about ten years. In the summer of 1831 he built an iron ring around which he wrapped two coils of copper wire. He sent a current through one and connected the other to a galvanometer. He found that the galvanometer did not respond when there was a current flowing steadily in the other wire. But, much to his amazement, it responded briefly when the current was switched on or off.

It had never occurred to anyone that one type of force could be induced by the change over time of another type of force. This was a totally unexpected result, and one with enormous ramifications. By September of 1831 he developed a clear understanding and experimental demonstration of electromagnetic induction. From this (using the fact that the motion of a conductor near a magnet effectively increases or decreases the field as a function of time) Faraday was able to design and build a generator. A politician asked him what good his discoveries were. He replied, “At present, I don’t know, but one day you will be able to tax them.” He also built the first electric motor and the first transformer.

By this time, no one had yet been able to show one way or the other if static charges, galvanic current, and currents produced by induction were indeed manifestations of the same phenomenon. He used electrochemical studies to show that the carriers of electricity all had the same charges proportional to their atomic weight and that, therefore, all three types of electricity must be the same. (The concept of the atom was just forming

and being hotly debated).

Faraday was interested in the effects of matter on fields. He found that he could alter the capacity of a condenser by the type of material he put in it. (Capacitance, C , is now measured in farads, the unit's name being taken from Faraday.) Cavendish figured this out first, but never published it. Faraday attributed the effect to the polarization of the matter through the rotation of dipolar atoms. He did not consider the relative movement of free charge within the material; the discrete charge, the electron, had not yet been discovered.

Faraday like Oersted, was philosophically convinced of the unification of the forces in nature. He thought that surely, light and electromagnetism must be related. He set up experiments and was able to demonstrate a dependency by rotating the polarization of a plane of light with a magnetic field. He speculated that light might be a wavelike manifestation of electromagnetism. He also tried to find a connection between electricity and gravity (a search that still continues).

24. **Joseph Henry** (1797-1878) was born in Albany, New York. While a professor (ca. 1830) at the Albany Academy, he discovered electromagnetic self-induction. That is the property of an electrical circuit that causes an opposing voltage when a circuit is made or broken. This is the basic property, designated L , of an inductor. It is now measured in units of Henries. He also discovered the oscillatory nature of an LC circuit. Henry was the first director of the Smithsonian Institution in Washington, D. C.
25. **Gustav Robert Kirchhoff** (1824-1887), studied at Königsberg, Germany. At the age of 20, he solved the problem of calculating the distribution of currents in an arbitrary network. The solutions are now called "Kirchhoff's Laws."
26. **Wilhelm Weber** (1804-1891) and **Rudolf Kohlrausch** (1809-1858), determined a universal constant that appeared in various formulas and represented the velocity of propagation of electrical action. Kirchhoff noted that it virtually coincided with the (known) velocity of light. But this was taken to be a curiosity; no further connections between light and electromagnetism were made until Maxwell.
27. **Heinrich Friedrich Emil Lenz** (1804-1865), an Estonian physicist, observed that the voltage induced in a circuit by a changing magnetic flux is oriented so that the resulting current generates a magnetic field opposed to the original. That is, the current is induced to *resist* the changing magnetic flux. This is called "Lenz's Law."
28. **James Clerk Maxwell** (1831-1879). Probably the greatest theoretical physicist of the 19th century. The founder of modern electrical theory and one of the founders of thermodynamics and statistical mechanics. Maxwell started his research with work on color vision and made some significant

contributions. In 1861, he made the first color photograph. He studied Saturn's rings and concluded that their stability implied that they must be made of loose materials. Solid or fluid rings would be unstable.

Maxwell's first work in electromagnetic theory concerned Faraday's lines of force. He noted the mathematical similarity between the potential equation (Laplace's equation) and the equation of stationary heat propagation (i.e. without convection; equation due to Fourier). He then proceeded with analogies with hydrodynamics to conceive of four vectors – \mathbf{E} , the electric field intensity, \mathbf{H} , the magnetic field intensity, \mathbf{B} , the magnetic flux density, and \mathbf{I} the electric current density. \mathbf{E} and \mathbf{H} are forces and \mathbf{B} and \mathbf{I} are fluxes (lines of force) produced by the forces. He established their interdependencies with equations. He defined the *magnetic vector potential*, \mathbf{A} , a very convenient way to formulate a number of difficult problems.

With all the previous discoveries, Maxwell's and other's, the stage was set for developing the modern theory of electromagnetism. However, Maxwell's discovery of the electromagnetic nature of light and postulation of radio waves was not the result of his simply compiling the results. The discoveries also required a great flash of genius couched in the idea that nature is symmetric. Faraday had shown that the voltage induced in a circuit was proportional to the time rate of change of magnetic flux through the circuit. Lenz demonstrated that this was a negative relationship. The result is Faraday's Law:

$$\nabla \times \mathbf{E} = -\partial\mathbf{B}/\partial t$$

Ampère had shown that the magnetic field in a closed loop around a current was, in fact, equal to the current through the loop. This is known as Ampère's law:

$$\nabla \times \mathbf{H} = \mathbf{I}$$

Maxwell saw an incomplete symmetry in these equations. Faraday's law says that if you change a magnetic field, you induce an electric field. The equations would be symmetric in one sense if you could also say "If you change an electric field you induce a magnetic field." That is, if the equations were written as

$$\nabla \times \mathbf{E} = \mathbf{M} - \partial\mathbf{B}/\partial t$$

and

$$\nabla \times \mathbf{H} = \mathbf{I} + \partial\mathbf{D}/\partial t$$

they would be mathematically symmetric. Now, \mathbf{M} is a magnetic current, which cannot exist because there are no magnetic monopoles. On the other hand, there was no physical reason to exclude the term, $\partial\mathbf{D}/\partial t$. Maxwell said it must exist and called it the "displacement current." He set up a purely hypothetical medium, an *æther* that would behave "elastically" in the presence of electromagnetic fields. If one of the modified

equations is substituted into the other, one can easily derive an equation that represents a wave traveling in space with transversal vibrations and with a velocity equal to that of light. (The velocity of light had been calculated in 1850 by **Armand-Hippolyte-Louis Fizeau** (1819-1896) and **Léon Foucault** (1819-1868) and subsequently verified by other researchers.)

In 1861, Maxwell published these results and noted: “The velocity of transverse undulations in our hypothetical medium calculated from the experiments of Kholrausch and Weber, agrees so exactly with the velocity of light calculated from the optical experiments of Fizeau that we can scarcely avoid the inference that light consists in the transverse undulations of the same medium which is the cause of electric and magnetic phenomenon.”

“The derivation of the speed of light from purely electromagnetic considerations was the crowning achievement of Maxwell’s electromagnetic theory. Maxwell made this prediction before radio waves were known and before it was realized that light was electromagnetic in nature.” [Halliday and Resnick, p. 909]

In 1864, Maxwell abandoned the idea that a medium was necessary for the propagation of electromagnetic waves. Three logical consequences of Maxwell’s theory seemed unbelievable to many physicists of the day. (1) Light can propagate in a vacuum without an ætherial medium. (2) The vibration is transverse to the direction of propagation, unlike acoustic waves which are longitudinal. (3) The speed of light appeared to be independent of any frame of reference. Of course, all three of these have since been verified countless times. The famous 1881 experiment of **Albert Abraham Michelson** (1852-1931) and **E. W. Morely** proved that there cannot be an æther. The second consequence was accepted since transverse undulations nicely explain the polarizability of light. The third consequence was seen as demonstrating the incompleteness of the equations. In fact, they are anything but incomplete. Convinced that Maxwell’s equations were accurate and complete, **Albert Einstein** (1879-1955) developed the special theory of relativity (1905). A fundamental premise of this theory is that the speed of light is constant in every inertial reference frame.

Maxwell’s electrical work was ultimately summed up in his *Treatise on Electricity and Magnetism* (1st ed. 1873, 2nd ed. 1881). Maxwell’s equations led not only to the development of radio and all of modern communications and electronics, but also spawned the modern theories of space-time and cosmology.

29. **Heinrich Rudolf Hertz** (1857-1894) studied under the great German physicist **Hermann von Helmholtz** (1821-1894). “Hertz’s scientific work is based on the combination of unusual analytical power with extraordinary experimental ability.” [Segrè, pp. 176-177] He tried to find proofs of Maxwell’s equations and to connect them to the electrody-

ical theories of **Wilhelm Weber** and **Carl Neumann**. These studies depended on the existence of electromagnetic waves. Hertz made an oscillating dipole circuit containing an inductor a wire loop and a spark gap. A short distance away, he had a similar circuit containing only a spark gap. A discharge from the induction coil across the first gap was accompanied by a weaker spark across the gap in the receiving circuit. With these tools, Hertz could reproduce many of the fundamental experiments of optics and demonstrate that his waves propagate with the velocity of light. He considered the experiments conclusive proofs of Maxwell's theory. Hertz never realized the practical potential of his discovery.

30. **Guglielmo Marconi** (1874-1937) of Bologna, Italy, began in 1894 to extend Hertz's work with the definite purpose of using electromagnetic waves for communication without wires. [**Samuel F. B. Morse** (1791-1872) invented the telegraph over the years 1829-1837]. In 1895 Marconi was able to transmit wireless messages a distance one mile. On 12 Dec 1901 Marconi received a wireless signal in St. John's Newfoundland which had originated at Poldu in Cornwall, England.