A Brief History of The Development of Classical Electrodynamics

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900 BC: Magnus, a **Greek** shepherd, walks across a field of black stones which pull the iron nails out of his sandals and the iron tip from his shepherd's staff (authenticity not guaranteed). This region becomes known as Magnesia.

600 BC: Thales of **Miletos (Greece)** discovered that by rubbing an 'elektron' (a hard, fossilized resin that today is known as amber) against a fur cloth, it would attract particles of straw and feathers. This strange effect remained a mystery for over 2000 years.

1269 AD: Petrus Peregrinus of Picardy, Italy, discovers that natural spherical magnets (lodestones) align needles with lines of longitude pointing between two pole positions on the stone.

ca. 1600: Dr. William Gilbert (court physician to **Queen Elizabeth**) discovers that the earth is a giant magnet just like one of the stones of Peregrinus, explaining how compasses work. He also investigates static electricity and invents an electric fluid which is liberated by rubbing, and is credited with the first recorded use of the word 'Electric' in a report on the theory of magnetism. Gilbert's experiments subsequently led to a number of investigations by many pioneers in the development of electricity technology over the next 350 years.

ca. 1620: Niccolo Cabeo discovers that electricity can be **repulsive** as well as **attractive**.

1630: Vincenzo Cascariolo, a **Bolognese** shoemaker, discovers **fluorescence**.

1638: Rene Descartes theorizes that light is a pressure wave through the second of his three types of matter of which the universe is made. He invents properties of this fluid that make it possible to calculate the reflection and refraction of light. The ``modern'' notion of the aether is born.

1638: Galileo attempts to measure the speed of light by a lantern relay between distant hilltops. He gets a very large answer.

1644: Rene Descartes theorizes that the magnetic poles are on the central axis of a spinning vortex of one of his fluids. This vortex theory remains popular for a long time, enabling **Leonhard Euler** and two of the **Bernoullis** to share a prize of the French Academy as late as **1743**.

1657: Pierre de Fermat shows that the **principle of least time** (using ***variational calculus***) is capable of explaining refraction and reflection of light. Fighting with the Cartesians begins. (n.b. This principle for reflected light had been anticipated anciently by **Hero of Alexandria**.)

1665: Francesco Maria Grimaldi, in a posthumous report, discovers and gives the name of diffraction to the bending of light around opaque bodies.

1667: Robert Hooke reports in his ***Micrographia*** the discovery of the rings of light formed by a layer of air between two glass plates. These were actually first observed by **Robert Boyle**, which explains why they are now called **Newton's rings**. In the same work he gives the matching-wave-front derivation of reflection and refraction that is still found in most introductory physics texts. These waves travel through the aether. He also develops a theory of color in which white light is a simple disturbance and colors are complex distortions of the basic simple white form.

1671: Isaac Newton destroys **Hooke's** theory of color by experimenting with prisms to show that white light is a mixture of all the colors and that once a pure color is obtained it can never be changed into another color. Newton argues against light being a vibration ***of*** the ether, preferring that it be something else that is capable of traveling ***through*** the aether. He doesn't insist that this something else consist of particles, but allows that it may be some other kind of emanation or impulse. In Newton's own words, ``...let every man here take his fancy."

1675: Olaf Roemer repeats **Galileo's** experiment using the moons of Jupiter as the distant hilltop. He measures $c = 2.3\text{x}10^8$ m/s.

1678: Christiaan Huygens introduces his famous construction and principle, thinks about translating his manuscript into Latin, then publishes it in the original French in 1690. He uses his theory to discuss the double refraction of Iceland Spar. His is a theory of pulses, however, not of periodic waves.

1717: Isaac Newton shows that the ``two-ness" of double refraction clearly rules out light being aether waves. (All aether wave theories were sound-like, so Newton was correct: longitudinal waves <u>cannot</u> be polarized.)

1728: James Bradley shows that the orbital motion of the earth changes the apparent motions of the stars in a way that is consistent with light having a finite speed of travel.

1729: Stephen Gray shows that electricity doesn't have to be made in place by rubbing, but can also be transferred from place to place with conducting wires. He also shows that the charge on electrified objects resides on their surfaces.

1733: Charles Francois du Fay discovers that electricity comes in two kinds, which he called *resinous* (–) and *vitreous* (+).

1742: Thomas Le Seur and **Francis Jacquier**, in a note to the edition of Newton's ***Principia*** that they publish, show that the force law between two magnets varies as the inverse cube of their separation.

1745: Pieter van Musschenbroek invents the **Leyden jar**, or capacitor, and nearly kills his friend **Cunaeus**.

1747: Benjamin Franklin invents the ***one-fluid theory of electricity***, in which one of **Nollet's** fluids exists and the other is just the absence of the first. Franklin also proposes the **<u>principle of conservation of charge</u>** and calls the fluid that exists and flows ``positive". {This educated guess ensures that undergraduates will always be confused about the direction of current flow.} He also discovers that electricity can act at a distance in situations where fluid flow makes no sense.

1748 : Sir William Watson uses an electrostatic machine and a vacuum pump to make the first glow discharge. His glass vessel is three feet long and three inches in diameter: the first fluorescent light bulb.

1749: Abbe Jean-Antoine Nollet invents the ***two-fluid theory electricity***.

1750: John Michell discovers that the two poles of a magnet are equal in strength and that the force law for individual poles is inverse square.

1752: Johann Sulzer puts lead and silver together in his mouth, performing the first recorded ``tongue test" of a battery.

1752: Benjamin Franklin proved that lightning and the spark from amber were one and the same thing. The story of this famous milestone is a familiar one, in which Franklin fastened an iron spike to a silken kite, which he flew during a thunderstorm, while holding the end of the kite string by an iron key. When lightning flashed, a tiny spark jumped from the key to his wrist. The experiment proved Franklin's theory, but was extremely dangerous - he could easily have been killed.

1759: Francis Ulrich Theodore Aepinus shows that electrical effects are a combination of fluid flow confined to matter and action at a distance. He also discovers **charging by induction**.

1762: Canton reports that a red hot poker placed close to a small electrified body destroys its electrification.

1764: Joseph Louis Lagrange discovers the **divergence theorem** in connection with the study of gravitation. It later becomes known as **Gauss's law**. (See **1813**).

1766: Joseph Priestly, acting on a suggestion in a letter from **Benjamin Franklin**, shows that hollow charged vessels contain no charge on the inside and based on his knowledge that hollow shells of mass have no gravity inside correctly deduces that the electric force law is inverse square.

ca. 1775: Henry Cavendish invents the idea of ***capacitance*** and ***resistance*** (the latter without any way of measuring current other than the level of personal discomfort). But being indifferent to fame he is content to wait for his work to be published by **Lord Kelvin** in **1879**.

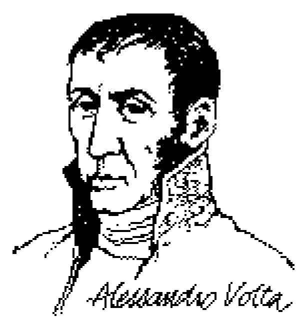
1777: Joseph Louis Lagrange invents the concept of the **scalar potential** for gravitational fields.

1780: Luigi Galvani (an Italian professor of medicine) discovered that when leg of a dead frog was touched with a metal knife, it twitched violently. Galvani deduced that the muscles of a frog must contain electricity. The phenomenon of **galvanism** is thus named in honor of Galvani. His followers invent another invisible fluid, that of ``animal electricity'', to describe this effect.

1782: Pierre Simon Laplace shows that Lagrange's potential satisfies $\nabla^2 V = 0$.

1785: Charles Augustin Coulomb uses a torsion balance to verify that the electric force law is inverse square. He also proposes a combined fluid/action-at-a-distance theory like that of **Aepinus** but with two conducting fluids instead of one. Fighting breaks out between single and double fluid partisans. He also discovers that the electric force near a conductor is proportional to its surface charge density and makes contributions to the two-fluid theory of magnetism.

1792: Alessandro Volta, disagreed with Galvani's claims: Volta realized that the main factors in Galvani's discovery were the two different metals - the steel knife and the tin plate - upon which the frog was lying. Volta showed that when moisture comes between two different/dissimilar metals, electricity is created. By **1800** this new understanding had enabled him to invent the first electric battery, the ***voltaic pile***, which he made from thin sheets of copper and zinc separated by moist pasteboard.



In this way, a new kind of electricity was discovered, electricity that ***flowed*** steadily like a current of water instead of discharging itself in a single spark or shock. Volta showed that electricity could be made to travel from one place to another by wire, thereby making an important contribution to the science of electricity. The unit of electrical potential, the **Volt**, is named after Volta.

1800: William Nicholson and **Anthony Carlisle** discover that water may be separated into hydrogen and oxygen by the action of ***Volta's pile***.

1801: Thomas Young gives a theory of ***Newton's rings*** based on constructive and destructive interference of waves. He explains the dark spot in the middle by proposing that there is a phase shift on reflection between a less dense and more dense medium, then uses essence of sassafras (whose index of refraction is intermediate between those of crown and flint glass) to get a light spot at the center.

1803: Thomas Young explains the fringes at the edges of shadows by means of the wave theory of light. The wave theory begins its ascendance, but has one important difficulty: light is thought of as a longitudinal wave, which makes it difficult to explain double refraction effects in certain crystals.

1807: Humphrey Davy shows that the essential element of **Volta's pile** is chemical action since pure water gives no effect. He argues that chemical effects are electrical in nature.

1808: Laplace gives an explanation of double refraction using the particle theory, which Young attacks as improbable.

1808: Etienne Louis Malus, a military engineer, enters a prize competition sponsored by the French Academy ``To furnish a mathematical theory of double refraction, and to confirm it by experiment." He discovers that light reflected at certain angles from transparent substances as well as the separate rays from a double-refracting crystal have the same property of *polarization*. In 1810 he receives the prize and emboldens the proponents of the particle theory of light because no one sees how a wave theory can make waves of different polarizations.

1811: Francois Arago shows that some crystals alter the polarization of light passing through them.

1812: Jean-Baptiste Biot shows that **Arago's** crystals rotate the plane of polarization of light about the propagation direction.

1812: Simeon Denis Poisson further develops the ***two-fluid theory of electricity***, showing that the charge on conductors must reside on their surfaces and be so distributed that the electric force within the conductor vanishes. This surface charge density calculation is carried out in detail for ellipsoids. He also shows that the potential within a distribution of electricity satisfies the equation: $\nabla^2 V = -\rho/\epsilon_0$

1812: Michael Faraday, a bookbinder's apprentice, writes to **Sir Humphrey Davy** asking for a job as a scientific assistant. Davy interviews Faraday and finds that he has educated himself by reading the books he was supposed to be binding. He gets the job.

ca. 1813: Laplace shows that at the surface of a conductor the electric force is perpendicular to the surface and that $E = \sigma/\epsilon_0$.

1813: Karl Friedrich Gauss rediscovers the ***divergence theorem*** of **Lagrange**. It will later become known as ***Gauss's law***.

1815: David Brewster establishes his law of complete polarization upon reflection at a special angle now known as Brewster's angle. He also discovers that in addition of uniaxial cystals there are also biaxial ones. For uniaxial crystals there is the faint possibility of a wave theory of longitudinal-type, but this appears to be impossible for biaxial ones.

1816: David Brewster invents the ***kaleidoscope***.

1816: Francois Arago, an associate of **Augustin Fresnel**, visits **Thomas Young** and describes to him a series of experiments performed by Fresnel and himself, which shows that light of differing polarizations <u>*cannot*</u> interfere. Reflecting later on this curious effect Young sees that it can be explained if light is a transverse, instead of longitudinal wave. This idea is communicated to Fresnel in 1818 and he immediately sees how it clears up many of the remaining difficulties of the wave theory. Six years later the particle theory is dead.

1817: Augustin Fresnel annoys the French Academy. The Academy, hoping to destroy the wave theory once and for all, proposes ***diffraction*** as the prize subject for **1818**. To the chagrin of the particle-theory partisans in the Academy, the winning memoir in **1818** is that of **Augustin Fresnel**, who explains diffraction as the mutual interference of the secondary waves emitted by the unblocked portions of the incident wave, in the style of Huygens. One of the judges from the particle camp of the Academy is **Poisson**, who points out that if **Fresnel's** theory were to be indeed correct, then there should be a bright spot at the center of the shadow of a circular disc. This, he suggests to **Fresnel**, must be tested experimentally. The experiment doesn't go as Poisson hopes, however, and the spot becomes known as **``Poisson's spot.''**

1820: Hans Christian Oersted discovers that electric current in a wire causes a compass needle to orient itself perpendicular to the wire.

1820: Andre Marie Ampere, a French mathematician, one week after hearing of **Oersted's** discovery, shows that parallel currents attract each other and that opposite currents attract. He was the first to explain the electro-dynamic theory. A permanent memorial to Ampere is the use of his name for the unit of electric current.

1820: Jean-Baptiste Biot and **Felix Savart** show that the magnetic force exerted on a magnetic pole by a wire falls off like 1/*r* and is oriented perpendicular to the wire. **Whittaker** then says that ``This result was soon further analyzed," to obtain:

$$d\mathbf{B} \propto \frac{I d\mathbf{l} \times \mathbf{r}}{r^3}$$

1820: John Herschel shows that quartz samples that rotate the plane of polarization of light in opposite directions have different crystalline forms. This difference is helical in nature.

1821: Michael Faraday begins electrical work by repeating **Oersted's** experiments.

1821: Humphrey Davy shows that direct current is carried throughout the volume of a conductor and establishes that:

$$R \propto \frac{l}{A}$$

for long wires. He also discovers that resistance is increased as the temperature rises.

1822: Thomas Johann Seebeck discovers the ***thermoelectric effect*** by showing that a current will flow in a circuit made of ***dissimilar metals*** if there is a ***temperature difference*** between the metals.

1824: Poisson invents the concept of the ***magnetic scalar potential*** and of ***surface*** and ***volume pole densities*** described by the formulas:

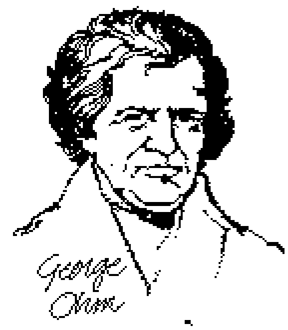
$$V = -\int \mathbf{M} \cdot \frac{\mathbf{r} - \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3} dV' \quad = \quad \int \frac{\nabla' \cdot \mathbf{M}}{|\mathbf{r} - \mathbf{r}'|} dV' - \int \frac{\mathbf{M} \cdot \mathbf{n}'}{|\mathbf{r} - \mathbf{r}'|} dA'$$

He also finds the magnetic field inside a spherical cavity within magnetized material.

1825: Ampere publishes his collected results on magnetism. His expression for the magnetic field produced by a small segment of current is different from that which follows naturally from the ***Biot-Savart law*** by an additive term which integrates to zero around closed circuit. It is unfortunate that electrodynamics and relativity decide in favor of Biot and Savart rather than for the much more sophisticated **Ampere**, whose memoir contains both mathematical analysis and experimentation, artfully blended together. In this memoir are given some special instances of the result we now call ***Stokes theorem*** or as we usually write it $\oint \mathbf{B} \cdot d\mathbf{l} = \mu_0 I$. **Maxwell** describes this work as ``one of the most brilliant achievements in science. The whole, theory and experiment, seems as if it had leaped, full-grown and full-armed, from the brain of the `Newton of electricity'. It is perfect in form and unassailable in accuracy; and it is summed up in a formula from which all the phenomena may be deduced, and which must always remain the cardinal formula of electrodynamics."

1825: Fresnel shows that combinations of waves of opposite circular polarization traveling at different speeds can account for the rotation of the plane of polarization.

1826: Georg Simon Ohm, a German mathematician and physicist, was a college teacher in Cologne. He established the result now known as **Ohm's law.** ***V=IR*** seems a pretty simple law to name after someone, but the importance of Ohm's work does not lie in this simple proportionality. What Ohm did was develop the idea of voltage as the driver of electric current. He reasoned by making an analogy between **Fourier's** theory of heat flow and electricity. In his scheme temperature and voltage correspond as do heat flow and electrical current. It was not until some years later that Ohm's electroscopic force (*V* in his law) and Poisson's electrostatic potential were shown to be identical. In **1827** he published, "The Galvanic Circuit Investigated Mathematically". His theories were coldly received by German scientists, however his research was recognized in Britain and he was awarded the Copley Medal in 1841. His name has been given to the unit of electrical resistance.



1827: Augustin Fresnel publishes a decade of research in the wave theory of light. Included in these collected papers are explanations of diffraction effects, polarization effects, double refraction, and **Fresnel's** sine and tangent laws for reflection at the interface between two transparent media.

1827: Claude Louis Marie Henri Navier publishes the correct equations for vibratory motions in one type of elastic solid. This begins the quest for a detailed mathematical theory of the aether based on the equations of continuum mechanics.

1827: F. Savery, after noticing that the current from a ***Leyden jar*** magnetizes needles in alternating layers, conjectures that the electric motion during the discharge consists of a series of oscillations.

1828: George Green generalizes and extends the work of **Lagrange**, **Laplace**, and **Poisson** and attaches the name ***potential*** to their ***scalar function***. ***Green's theorems*** are given, as well as the ***divergence theorem*** (***Gauss's law***), but **Green** doesn't know of the work of **Lagrange** and **Gauss** and only references **Priestly's** deduction of the inverse square law from **Franklin's** experimental work on the charging of hollow vessels.

1828: Augustine Louis Cauchy presents a theory similar to **Navier's**, but based on a direct study of elastic properties rather than using a molecular hypothesis. These equations are more general than **Navier's**. In **Cauchy's** theory, and in much of what follows, the aether is supposed to have the same inertia in each medium, but different elastic properties.

1828: Poisson shows that the equations of **Navier** and **Cauchy** have ***wave solutions*** of ***two*** types: ***transverse*** and ***longitudinal***. Mathematical physicists spend the next 50 years trying to invent an elastic aether for which the longitudinal waves are ***absent***.

1831: Michael Faraday reasoned: If electricity could produce magnetism, then why couldn't magnetism produce electricity? Faraday found the solution. Electricity could be produced through magnetism by ***motion***. He discovered that when a magnet was moved inside a coil of copper wire, a tiny electric current flowed through the wire. Of course, by today's standards, Faraday's electric dynamo/electric generator was crude, and provided only a small electric current,

however he discovered the first method of generating electricity by means of motion in a magnetic field. Faraday convincingly showed the world that changing currents in one circuit ***induce*** currents in a neighboring circuit. Over the next several years he performed hundreds of experiments and showed that his results could all be explained by the idea of ***changing magnetic flux***. No mathematics was involved, just picture-thinking using his concept of magnetic field-lines.

Faraday also investigated many other aspects of electromagnetism, the unit of capacitance (Farad) is named in honor of him.

1831: Ostrogradsky rediscovers the divergence theorem of Lagrange, Gauss, and Green.

1832 :Joseph Henry independently discovers induced currents.

1833: Faraday begins work on the relation of electricity to chemistry. In one of his notebooks he concludes after a series of experiments, ``...there is a certain absolute quantity of the electric power associated with each atom of matter."

1834: Faraday discovers self inductance.

1834: Jean Charles Peltier discovers the flip side of **Seebeck's *thermoelectric effect***. He finds that current driven in a circuit made of dissimilar metals causes the different metals to be at different temperatures.

1834: Emil Lenz formulates his rule for determining the direction of Faraday's induced currents. In its original form it was a force law rather than an induced emf law: ``Induced currents flow in such a direction as to produce magnetic forces that try to keep the magnetic flux the same." So Lenz would predict that if you try to push a conductor into a strong magnetic field, it will be repelled. He would also predict that if you try to pull a conductor out of a strong magnetic field that the magnetic forces on the induced currents will oppose the pull.

1835: James MacCullagh and **Franz Neumann** extend **Cauchy's theory** to crystalline media

1837: Faraday discovers the idea of the ***dielectric constant***.

1837: George Green attacks the elastic aether problem from a new angle. Instead of deriving boundary conditions between different media by finding which ones give agreement with the experimental laws of optics, he derives the correct boundary conditions from general dynamical principles. This advance makes the elastic theories not quite fit with light.

1838: Faraday shows that the effects of induced electricity in insulators are analogous to induced magnetism in magnetic materials. Those more mathematically inclined immediately appropriate Poisson's theory of induced magnetism, inventing $\mathbf{P}$, $\mathbf{D}$, and ϵ.

1838: Faraday discovers ***Faraday's dark space***, a dark region in a glow discharge near the negative electrode.

1839: James MacCullagh invents an elastic aether in which there are ***no*** longitudinal waves. In this aether the potential energy of deformation depends only on the rotation of the volume elements and not on their compression or general distortion. This theory gives the same wave equation as that satisfied by $\mathbf{E}$ and $\mathbf{B}$ in Maxwell's theory.

1839: William Thomson (**Lord Kelvin**) removes some of the objections to **MacCullagh's** rotation theory by inventing a mechanical model which satisfies **MacCullagh's** energy of rotation hypothesis. It has spheres, rigid bars, sliding contacts, and flywheels.

1839: Cauchy and **Green** present more refined elastic aether theories, **Cauchy's** removing the longitudinal waves by postulating a negative compressibility, and **Green's** using an involved description of crystalline solids.

1841: Michael Faraday is completely exhausted by his efforts of the previous 2 decades, so he rests for 4 years.

1841: James Prescott Joule shows that energy is conserved in electrical circuits involving current flow, thermal heating, and chemical transformations.

1842: F. Neumann and **Matthew O'Brien** suggest that optical properties in materials arise from differences in the amount of force that the particles of matter exert on the aether as it flows around and between them.

1842: Julius Robert Mayer asserts that heat and work are equivalent. His paper is rejected by *Annalen der Physik*.

1842: Joseph Henry rediscovers the result of **F. Savery** about the oscillation of the electric current in a capacitive discharge and states, ``The phenomena require us to admit the existence of a principal discharge in one direction, and then several reflex actions backward and forward, each more feeble than the preceding, until equilibrium is restored."

1842: Christian Doppler gives the theory of the ***Doppler effect***.

1845: Faraday quits resting and discovers that the plane of polarization of light is rotated when it travels in glass along the direction of the magnetic lines of force produced by an electromagnet (***Faraday rotation***).

1845: Franz Neumann uses (i) ***Lenz's law***, (ii) the assumption that the induced *emf* is proportional to the magnetic force on a current element, and (iii) **Ampere's** analysis to deduce ***Faraday's law***. In the process he finds a potential function from which the induced electric field can be obtained, namely the vector potential $\mathbf{A}$(in the Coulomb gauge), thus discovering the result which **Maxwell** wrote as $\mathbf{E} = -\nabla\phi - \partial\mathbf{A}/\partial t$.

1846: George Airy modifies **MacCullagh's** elastic aether theory to account for ***Faraday rotation***.

1846: Faraday, inspired by his discovery of the magnetic rotation of light, writes a short paper speculating that light might electro-magnetic in nature. He thinks it might be transverse vibrations of his beloved field lines.

1846: Faraday discovers ***diamagnetism***. He sees the effect in heavy glass, bismuth, and other materials.

1846: Wilhelm Weber combines **Ampere's** analysis, **Faraday's** experiments, and the assumption of Fechner that currents consist of equal amounts of positive and negative electricity moving opposite to each other at the same speed to derive an electromagnetic theory based on forces between moving charged particles. This theory has a velocity-dependent potential energy and is wrong, but it stimulates much work on electromagnetic theory which eventually leads to the work of **Maxwell** and **Lorenz**. It also inspires a new look at gravitation by **William Thomson** to see if a velocity-dependent correction to the gravitational energy could account for the precession of Mercury's perihelion.

1846: William Thomson shows that **Neumann's** electromagnetic potential $\mathbf{A}$is in fact the vector potential from which $\mathbf{B}$ may be obtained via . $\mathbf{B} = \nabla \times \mathbf{A}$

1847: Weber proposes that diamagnetism is just ***Faraday's law*** acting on molecular circuits. In answering the objection that this would mean that everything should be diamagnetic he correctly guesses that diamagnetism is masked in paramagnetic and ferromagnetic materials because they have relatively strong permanent molecular currents. This work rids the world of magnetic fluids.

1847: Hermann von Helmholtz writes a memoir ***``On the Conservation of Force''*** which emphatically states the ***principle of conservation of energy***: ``Conservation of energy is a universal principle of nature. Kinetic and potential energy of dynamical systems may be converted into heat according to definite quantitative laws as taught by Rumford, Mayer, and Joule. Any of these forms of energy may be converted into chemical, electrostatic, voltaic, and magnetic forms." He reads it before the Physical Society of Berlin whose older members regard it as too speculative and reject it for publication in *Annalen der Physik*.

1848-9: Gustav Kirchoff extends **Ohm's** work to conduction in three dimensions, gives his laws for circuit networks, and finally shows that Ohm's ``electroscopic force" which drives current through resistors and the old electrostatic potential of **Lagrange**, **Laplace**, and **Poisson** are the same. He also shows that in steady state electrical currents distribute themselves so as to minimize the amount of Joule heating.

1849: A. Fizeau repeats **Galileo's** hilltop experiment (9 km separation distance) with a rapidly rotating toothed wheel and measures $c = 3.15 \times 10^8$ m/s.

1849: George Gabriel Stokes studies diffraction around opaque bodies both theoretically and experimentally and shows that the vibration of aether particles are executed at right angles to the plane of polarization. Three years later he comes to the same conclusion by applying aether theory to light scattered from the sky. This result is, however, inconsistent with optics in crystals.

ca. 1850: Stokes overcomes some of the difficulties with crystals by turning Cauchy's hypothesis around and letting the elastic properties of the aether be the same in all materials, but allowing the inertia to differ. This gives rise to the conceptual difficulty of having the inertia be different in different directions (in anisotropic crystals).

ca. 1850: Jean Foucault improves on **Fizeau's** measurement and uses his apparatus to show that the speed of light is less in water than in air.

1850: Stokes law is stated without proof by **Lord Kelvin** (**William Thomson**). Later **Stokes** assigns the proof of this theorem as part of the examination for the Smith's Prize. Presumably, he knows how to do the problem. **Maxwell**, who was a candidate for this prize, later remembers this problem, traces it back to **Stokes** and calls it ***Stokes theorem.***

1850: William Thomson (**Lord Kelvin**) invents the idea of magnetic permeability and susceptibility, along with the separate concepts of $\mathbf{B}$, $\mathbf{M}$, and $\mathbf{H}$.

1851: Thomson gives a ***general theory of thermoelectric phenomena***, describing the effects seen by **Seebeck** and **Peltier**.

1853: Thomson uses **Poisson's** magnetic theory to derive the correct formula for magnetic energy: . He $U = \int \mu \mathbf{H}^2 dV/2$ also gives the formula $U = LI^2/2$ and gives the world the powerful, but confusing, analysis where the forces on circuits are obtained by taking either the positive or negative gradient of the magnetic energy. Knowing which sign to use is, of course, the confusing part.

1853: Thomson gives the theory of the RLC circuit providing a mathematical description for the observations of **Henry** and **Savery**.

1854: Faraday clears up the problem of disagreements in the measured speeds of signals along transmission lines by showing that it is crucial to include the effect of capacitance.

1854: Thomson, in a letter to **Stokes**, gives the equation of telegraphy $\partial^2 V/\partial x^2 = RC\,\partial V/\partial t$ ignoring the inductance: , where *R* is the cable resistance and where *C* is the capacitance per unit length. Since this is the diffusion equation, the signal does not travel at a definite speed.

1855: Faraday retires, living quietly in a house provided by the Queen until his death in **1867**.

1855: James Clerk Maxwell writes a memoir in which he attempts to marry **Faraday's** intuitive field line ideas with **Thomson's** mathematical analogies. In this memoir the physical importance of the divergence and curl operators for electromagnetism first become evident. The following equations appear in this memoir: $\nabla \cdot (\epsilon \mathbf{E}) = 4\pi\rho$ $\nabla \times \mathbf{A} = \mathbf{B}$ $\nabla \times \mathbf{H} = 4\pi \mathbf{J}$

1857: Gustav Kirchoff derives the equation of telegraphy for an aerial coaxial cable where the $\partial^2 V/\partial x^2 = LC\partial^2 V/\partial t^2 + RC\,\partial V/\partial t$ inductance is important and derives the full telegraphy equation: : , where *L* and *C* are the inductance per unit length and the capacitance per unit length. He recognizes that when $v = \sqrt{LC}$ the resistance is small, this is the wave equation with propagation speed , which for a coaxial cable turns out to be very close to the speed of light. Kirchoff notices the coincidence, and is thus the first to discover that electromagnetic signals can travel at the speed of light.

1861: Bernhard Riemann develops a variant of **Weber's** electromagnetic theory, which is also wrong.

1861: Maxwell publishes a mechanical model of the electromagnetic field. Magnetic fields correspond to rotating vortices with idle wheels between them and electric fields correspond to elastic displacements, hence displacement currents.

The equation for **H** now becomes $\nabla \times \mathbf{H} = 4\pi \mathbf{J}_{tot}$, where $\mathbf{J}_{tot}$ is the total current, conduction plus displacement, and is conserved: . $\nabla \cdot \mathbf{J}_{tot} = 0$ This addition completes Maxwell's equations and it is now easy for him to derive the wave equation exactly as done in our textbooks on electromagnetism and to note that the speed of wave propagation was close to the measured speed of light. Maxwell writes, ``We can scarcely avoid the inference that light in the transverse undulations of the same medium which is the cause of electric and magnetic phenomena." Thomson, on the other hand, says of the displacement current, ``(it is a) curious and ingenious, but not wholly tenable hypothesis."

1864: Maxwell reads a memoir before the Royal Society in which the mechanical model is stripped away and just the equations remain. He also discusses the vector and scalar potentials, using the Coulomb gauge. He attributes physical significance to both of these potentials. He wants to present the predictions of his theory on the subjects of reflection and refraction, but the requirements of his mechanical model keep him from finding the correct boundary conditions, so he never does this calculation.

1867: Stokes performs experiments that kill his own anisotropic inertia theory.

1867: Joseph Boussinesq suggests that instead of aether being different in different media, perhaps the aether is the same everywhere, but it interacts differently with different materials, similar to the modern electromagnetic wave theory.

1867: Riemann proposes a simple electric theory of light in which ***Poisson's equation*** is replaced by .

$$\nabla^2 V - (1/c^2)\partial^2 V/\partial t^2 = -4\pi\rho$$

1867: Ludwig Lorenz develops an electromagnetic theory of light in which the scalar and vector potentials, in retarded form, are the starting point. He shows that these retarded potentials each satisfy the wave equation and that Maxwell's equations for the fields **E** and **H** can be derived from his potentials. His vector potential does not obey the Coulomb gauge, however, but another relation now known as the Lorenz gauge. Although he is able to derive Maxwell's equations from his retarded potentials, he does not subscribe to Maxwell's view that light involves electromagnetic waves in the aether. He feels, rather, that the fundamental basis of all luminous vibrations is electric currents, arguing that space has enough matter in it to support the necessary currents.

1868: Maxwell decides that giving physical significance to the scalar and vector potentials is a bad idea and bases his further work on light on **E** and **H**.

1869: Maxwell presents the first calculation in which a dispersive medium is made up of atoms with natural frequencies. This makes possible detailed modeling of dispersion with refractive indices having resonant denominators.

1869: Hittorf finds that cathode rays can cast a shadow.

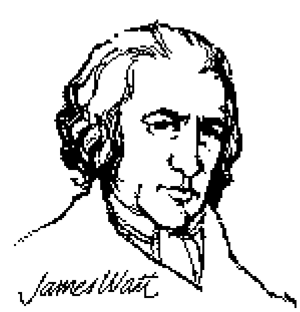
1870: Helmholtz derives the correct laws of reflection and refraction from ***Maxwell's equations*** by using the following boundary conditions: , $\mathbf{D}_n$ $\mathbf{E}_t$, and **B** are continuous. Once these boundary conditions are taken, ***Maxwell's theory*** is just a repeat of ***MacCullagh's theory***. The details were not given by **Helmholtz** himself, but appear rather in the inaugural dissertation of **H. A. Lorentz**.

1870-1900: The hunt is on for physical models of the aether which are natural and from which Maxwell's equations can be derived. The physicists who work on this problem include **Maxwell**, **Thomson**, **Kirchoff**, **Bjerknes**, **Leahy**, **Fitz Gerald**, **Helmholtz**, and **Hicks**.

ca.1870: Thomas Alva Edison builds the first ***practical*** DC (Direct Current) generator**,** setting the stage for future commercial power generation (and consumption).Edison's many inventions included the phonograph and an improved printing telegraph. In **1878 Joseph Swan**, a British scientist, invented the incandescent filament lamp and within twelve months **Edison** made a similar discovery in America. Swan and Edison later set up a joint company to produce the first practical filament lamp. Prior to this, electric lighting had been my crude arc lamps. Edison used his DC generator to provide electricity to light his laboratory and later to illuminate the first New York street to be lit by electric lamps, in September **1882**. Edison's successes were not without controversy, however - although he was convinced of the merits of DC for generating electricity, other scientists in Europe and America recognized that DC brought major disadvantages.

George Westinghouse was a famous American inventor and industrialist who purchased and developed **Nikola Tesla's** patented motor for generating ***alternating current***. The work of Westinghouse, Tesla and others gradually persuaded American society that the future lay with AC rather than DC (The adoption of AC generation enabled the transmission of large amounts of electrical, power using higher voltages via transformers, which would have been impossible otherwise). Today the unit of measurement for magnetic fields commemorates Tesla's name.

When Edison's generator was coupled with **James Watt's** steam engine, large-scale electricity generation became a practical proposition. James Watt, the Scottish inventor of the steam-condensing engine, was born in 1736. His improvements to steam engines were patented over a period of 15 years, starting in 1769 and his name was given to the electric unit of power, the **Watt**. Watt's steam engines used the reciprocating piston, however, today's thermal power stations use steam turbines, following the Rankine cycle,



worked out by another famous Scottish engineer, William J.M Rankine, in **1859**.

1872: E. Mascart looks for the motion of the earth through the aether by measuring the rotation of the plane of polarization of light propagated along the axis of a quartz crystal. No motion is found with a sensitivity of . $v/c \approx 10x^{-5}$

1873: Maxwell publishes his ***Treatise on Electricity and Magnetism***, which discusses everything known at the time about electromagnetism from the viewpoint of **Faraday**. His own theory is not very thoroughly discussed, but he does introduce his electromagnetic stress tensor in this work, including the accompanying idea of electromagnetic momentum.

1875: John Kerr shows that ordinary dielectrics subjected to strong electric fields become double refracting, showing directly that electric fields and light are closely related.

1876: Henry Rowland performs an experiment inspired by Helmholtz which shows for the first time that moving electric charge is the same thing as an electric current.

1876: A. Bartoli infers the necessity of light pressure from thermal arguments, thus beginnning the exploration of the connection between electromagnetism and thermodynamics.

1879: J. Stefan discovers the ***Stefan-Boltzmann law***, i.e., that radiant emission is proportional to T^4.

1879: Edwin Hall performs an experiment that had been suggested by Henry Rowland and discovers the Hall effect, including its theoretical description by means of the Hall term in Ohm's law.

1879: Sir William Crookes invents the radiometer and studies the interaction of beams of cathode ray particles in vacuum tubes.

1879: Ludwig Boltzmann uses **Hall's** result to estimate the speed of charge carriers (assuming that charge carriers are only of one sign.)

1880: Rowland shows that ***Faraday rotation*** can be obtained by combining Maxwell's equations and the Hall term in Ohm's law, assuming that displacement currents are affected in the same way as conduction currents.

1881: J. J. Thomson attempts to verify the existence of the displacement current by looking for magnetic effects produced by the changing electric field made by a moving charged sphere.

1881: George Fitz Gerald points out **that J. J. Thomson's** analysis is ***incorrect*** because he left out the effects of the conduction current of the moving sphere. Including both currents makes the separate effect of the displacement current disappear.

1881: Helmholtz, in a lecture in **London**, points out that the idea of charged particles in atoms can be consistent with **Maxwell's** and **Faraday's** ideas, helping to pave the way for our modern picture of particles and fields interacting instead of thinking about everything as a disturbance of the aether, as was popular after **Maxwell**.

1881: Albert Michelson and **Edwin Morley** attempt to measure the motion of the earth through the aether by using interferometry. They find no relative velocity. **Michelson** interprets this result as supporting **Stokes** hypothesis in which the aether in the neighborhood of the earth moves at the earth's velocity.

1883: Fitz Gerald proposes testing ***Maxwell's theory*** by using oscillating currents in what we would now call a magnetic dipole antenna (loop of wire). He performs the analysis and discovers that very high frequencies are required to make the test. Later that year he proposes obtaining the required high frequencies by discharging a capacitor into a circuit.

1883-5: Horace Lamb and **Oliver Heaviside** analyze the interaction of oscillating electromagnetic fields with conductors and discover the effect of ***skin depth***.

1884: John Poynting shows that ***Maxwell's equations*** predict that energy flows through empty space with the energy flux given $\mathbf{E} \times \mathbf{B}/4\pi$ by . He also investigates energy flow in Faraday fashion by assigning energy to moving tubes of electric and magnetic flux.

1884: Heinrich Hertz asserts that $\mathbf{E}$ made by charges and $\mathbf{E}$ made by a changing magnetic field are identical. Working from dynamical ideas based on this assumption and some of Maxwell's equations, **Hertz** is able to derive the rest of them.

1887: Svante Arrhenius deduces that in dilute solutions electrolytes are completely dissociated into positive and negative ions.

1887: Hertz finds that ultraviolet light falling on the negative electrode in a spark gap facilitates conduction by the gas in the gap.

1888: R. T. Glazebrook revives one of **Cauchy's** ***wave theories*** and combines it with **Stokes** *anisotropic aether inertia theory* to get agreement with the experiments of **Stokes** in **1867**.

1888: Hertz discovers that oscillating sparks can be produced in an open secondary circuit if the frequency of the primary is resonant with the secondary. He uses this radiator to show that electrical signals are propagated along wires and through the air at about the same speed, both about the speed of light. He also shows that his electric radiations, when passed through a slit in a screen, exhibit diffraction effects. Polarization effects using a grating of parallel metal wires are also observed.

1888: Roentgen shows that when an uncharged dielectric is moved at right angles to $\mathbf{E}$ a magnetic field is produced.

1889: Hertz gives the theory of radiation from his oscillating spark gap.

1889: Oliver Heaviside finds the correct form for the electric and magnetic fields of a moving charged particle, valid for all speeds $v < c$.

1889: J. J. Thomson shows that ***Canton's effect*** (**1762**) in which a red hot poker can neutralize the electrification of a small charged body is due to (thermal/thermionic) electron emission causing the air between the poker and the body to become conducting.

1890: Fitz Gerald uses the retarded potentials of L. Lorenz to calculate electric dipole radiation from Hertz's radiator.

1892: Oliver Lodge performs experiments on the propagation of light near rapidly moving steel disks to test Stokes hypothesis that moving matter drags the aether with it. No such effect is observed.

1892: Hendrik Anton Lorentz presents his electron theory of electrified matter and the aether. This theory combines Maxwell's equations, with the source terms ρ and $\mathbf{J}$, with the Lorentz force law for the acceleration of charged particles:

$$m\mathbf{a} = q\mathbf{E} + q\mathbf{v} \times \mathbf{B}\ .$$

Lorentz's aether is simply space endowed with certain dynamical properties. Lorentz gives the modern theory of dielectrics involving $\mathbf{D}$ and $\mathbf{P}$, and also includes the effect of magnetized matter. He also gives what we now call the Drude-Lorentz harmonic oscillator model of the index of refraction. But Lorentz's theory has a ``stationary aether", which conflicts with the negative Michelson-Morley result.

1892: George Fitz Gerald proposes length contraction as a way to reconcile Lorentz's theory and the null results on the motion of the earth through the aether. At the end of this year Lorentz endorses this idea.

1894: J. J. Thomson measures the speed of cathode rays and shows that they travel much more slowly than the speed of light. The aether model of cathode rays begins to die.

1894: Philip Lenard studies the penetration of cathode rays through matter.

1895: Pierre Curie experimentally discovers ***Curie's law for paramagnetism*** and also shows that there is no temperature effect for diamagnetism.

1895: Lorentz, in his ``Search for a theory of electrical and optical effects in moving bodies'' gives the Lorentz transformation to first order in $v/c$. The transformed time variable he calls ``local time''.

1895: Wilhelm Roentgen discovers X-rays produced by bremsstrahlung in cathode ray tubes.

1896: Arthur Shuster, **Emil Wiechert**, and **George Stokes** propose that X-rays are aether waves of exceedingly small wavelength.

1896: J. J. Thomson discovers that materials through which X-rays pass are rendered conducting.

1896: Henri Becquerel discovers that some sort of natural radiation from uranium salts can expose a photographic plate wrapped in thick black paper.

1896: P. Zeeman discovers the splitting of atomic line spectra by a magnetic field.

1896: Lorentz gives an electron theory of the ***Zeeman effect***.

1897: J. J. Thomson argues that cathode rays must be charged particles smaller in size than atoms (Emil Wiechert made the same suggestion independently in this same year). In response Fitz Gerald suggests that ``we are dealing with free electrons in these cathode rays.''

1897: W. Wien discovers that positively-charged moving particles can also be made (the so-called *canal rays* of E. Goldstein) and that they have a much smaller q/m ratio than cathode rays.

1897: J. J. Thomson deflects cathode rays by crossed electric and magnetic fields and measures e/m.

1898: Marie and Pierre Curie separate from pitchblende two highly radioactive elements which they name polonium and radium.

1899: Ernest Rutherford discovers that the rays from uranium come in two types, which he calls alpha and beta radiation.

1900: Marie and Pierre Curie show that beta rays and cathode rays are identical.

1900: Emil Wiechert shows that simply replacing the distributed charge $\rho\,dx\,dy\,dz$ from Lorentz's theory with the charge of a moving point particle gives incorrect results. Instead the ***Lienard-Wiechert retarded potentials*** must be used.

1900: Joseph Larmor obtains the second order corrections to the ***Lorentz Transformation***.

1901: R. Blondlot performs experiments that show that Lorentz's theory in which there is no moving aether gives the correct result in cases where the hypothesis of a moving aether gives the wrong result.

1902: Lord Rayleigh performs experiments to test whether the Fitz Gerald contraction is capable of causing double refraction in moving transparent substances. No such effect is found.

1903: The Hagen-Rubens connections between the conductivity of metals and their optical properties are experimentally established.

1903: Lorentz gives the famous square root formulas for the ***Lorentz transformation*** giving the effect to all orders in v/c.

1904: Lorentz gives his electron-collision theory of electrical conduction

1905: H. A. Wilson performs experiments similar to those of **Blondlot**; again, ***Lorentz's theory*** is found to give the correct result.

1905: Albert Einstein completes **Lorentz's** work on space-time transformations and ***relativity*** is born.

If one plots the rate of the above-mentioned discoveries vs. time on semi-log graph (no weight as to absolute importance), one learns that the discovery rate associated with the physics of classical E&M is approximately ***exponential***, aside from the two earliest entries! Note also that a.) having a written language and b.) books ***greatly*** facilitated this discovery & learning process, as well as inter-communication & interactions amongst the ~ 100 or so human beings involved in this endeavor!