A Ridiculously Brief History of Electricity and Magnetism

Note: I found this at maxwell.byu.edu/~spencerr/phys442/node4.html , brought it up in Word and highlighted various things in bold and underline. I later found a PDF at the same site. I then did some cut and pastes from the PDF into this Word doc for equations and various other symbols. If something is unreadable, see the PDF.

Mostly from E. T. Whittaker's *A History of the Theories of Aether and Electricity...*

Prehistory

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 rubs amber (**elektron** in Greek) with cat fur and picks up bits of feathers.

1269 - 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.

The 17th Century

1600 - 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 discusses static electricity and invents an electric fluid which is liberated by rubbing.

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 is capable of explaining refraction and reflection of light. Fighting with the Cartesians begins. (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 $c = 2.3 \times 10^8$ 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.

The 18th Century

1717 - **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 right; longitudinal waves can't be polarized.) [The pressure-sound wave theory through a fluid can only support longitudinal compression and does not support transverse polarization. Since light was showing two polarization states in this spar, that ruled out simple pressure wave in aether idea.]

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. (speed of light)

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. [Still in the static world only.]

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 is inverse cube.

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

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

1747 - Benjamin **Franklin** invents the theory of one-fluid electricity in which one of Nollet's fluids exists and the other is just the absence of the first. He proposes the principle of conservation of charge 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.

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.

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** causes dead frog legs to twitch with static electricity, then also discovers that the same twitching can be caused by contact with dissimilar metals. His followers invent another invisible fluid, that of ``animal electricity'', to describe this effect. [He really thinks animals are creating the electricity somehow, not just responding to it.]

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.

1793 - Alessandro **Volta** makes the first batteries and argues that animal electricity is just ordinary electricity flowing through the frog legs under the impetus of the force produced by the contact of dissimilar metals. He discovers the importance of ``completing the circuit.''

The period 1800-1825 -- things heat up after Volta invents the battery so currents may be produced and studied

1800 - In 1800 **Volta** discovers the Voltaic pile (dissimilar metals separated by wet cardboard) which greatly increases the magnitude of the effect.

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. [diffraction]

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. [scalar theory bypasses polarization question]

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 - **Arago** shows that some crystals alter the polarization of light passing through them. [rotation!]

1812 - **Biot** shows that Arago's crystals rotate the plane of polarization 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 $\nabla^2 \phi = -\rho/\varepsilon_0$.

1812 - Michael **Faraday**, a bookbinders 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 $E = \sigma/\varepsilon_0$.

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 to 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 cannot interfere. Reflecting later on this curious effect Young sees that it can be explained if light is transverse instead of longitudinal. 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**, one week after hearing of Oersted's discovery, shows that parallel currents attract each other and that opposite currents attract.

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

$$d\mathbf{B} \propto \frac{Id\mathbf{s} \times \mathbf{r}}{r^3}$$

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 - **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

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

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 [was this the time term in the curlB equation?] 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.

$$\oint \mathbf{B} \cdot d\mathbf{s} = \mu_0 I.$$

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."

The period 1825-1850

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** establishes 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. [again, the new world of DC currents from batteries is not quite linked to the static electricity world]

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. [By this time, it was known that solids can support transverse polarizations, so it probably seemed only a matter of time until the nature of the aether as some kind of solid was elucidated. But why then did the ether not support longitudinal polarization, as all solids do?]

1831 - **Faraday** shows that [the transformer] changing currents in one circuit induce currents in a neighboring circuit. Over the next several years he performs hundreds of experiments and shows that they can all be explained by the idea of changing magnetic flux. No mathematics is involved, just picture thinking using his field-lines. [

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 P, 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 E and B in Maxwell's theory. [interesting...]

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. [It derives its name from the title, Baron Kelvin of Largs, that Thomson received from the British government in 1892, and named after Thomson because of his proposal in this 1848 paper. Sir William was later named Lord Kelvin when he was made a Baron and a member of the House of Lords. He adopted **the name Kelvin** from the river Kelvin in Scotland with due regard to the association he had with Glasgow University and the area.]

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 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 be electro-magnetic in nature. He thinks it might be transverse vibrations of his beloved field lines. [as opposed to a wave traveling in an ether?]

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 is in fact the vector potential from which B may be obtained via $B = \nabla \times A$.

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** [misspelled] 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. [speed of light] and measures c = 3.15 x 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.

The period 1850-1875

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 B, M, and 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:

$$U = \int \mu \mathbf{H}^2 dV/2.$$

He 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 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. [transmission line theory]

1855 - **Faraday retires**, living quietly in a house provided by the Queen until his death in 1867. [good work!]

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 equations $\nabla \cdot (\epsilon \mathbf{E}) = 4\pi\rho$, $\nabla \times \mathbf{A} = \mathbf{B}$, and $\nabla \times \mathbf{H} = 4\pi\mathbf{J}$ appear in this memoir.

1857 - Gustav **Kirchoff** derives the equation of telegraphy for an aerial coaxial cable where the inductance is important and derives the full telegraphy equation.

$$\partial^2 V/\partial x^2 = LC\partial^2 V/\partial t^2 + RC\ \partial V/\partial t,$$

He recognizes that when the resistance is small, this is the wave equation with propagation speed v = sqrt(LC), 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 $\nabla \times H = 4\pi J_{tot}$, where J_{tot} is the total current, conduction plus displacement, and is conserved $\nabla \bullet J = 0$. This addition of a displacement current 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 Maxwell's equations for the fields and 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. [Aμ]

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: Dn, Et, 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.

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 $v/c = 10^{-5}$.

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.

The period 1875-1900

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. [Kerr effect, an electric Faraday rotation effect]

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 by $ExB/4\pi$. He also investigates energy flow in Faraday fashion by assigning energy to moving tubes of electric and magnetic flux.

1884 - Heinrich **Hertz** asserts that E made by charges and 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. [in other words, radio waves do the same things that light waves do]

1888 - **Roentgen** shows that when an uncharged dielectric is moved at right angles to 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 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 J , with the Lorentz force law for the acceleration of charged particles: $ma = qE + q\ v \times B$. Lorentz's aether is simply space endowed with certain dynamical properties. Lorentz gives the modern theory of dielectrics involving D and 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. [so now we have light waves, radio waves, and X-rays all being the same thing]

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.

The period 1900-1925

1900 - Emil **Wiechert** shows that simply replacing the distributed charge 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. [there is no ether, so there is no special frame in which the ether is at rest, so all frames are equivalent and relative]

Index

Aepinus, Francis Ulrich Theodore - 1759
Airy, George - 1846
Ampere, Andre Marie - 1820, 1825
Arago, Francois - 1811, 1816
Arrhenius, Svante - 1887
Bartoli, A. - 1876
Becquerel, Henri - 1896
Biot, Jean-Baptiste - 1812, 1820
Blondlot, R. - 1901
Boltzmann, Ludwig - 1879
Boussinesq, Joseph - 1867
Bradley, James - 1728
Brewster, David - 1815, 1816
Cabeo, Niccolo - 1620
Canton - 1762
Carlisle, Anthony - 1800
Cascariolo, Vincenzo - 1630
Cauchy, Augustine Louis - 1828, 1839
Cavendish, Henry - 1775
Coulomb, Charles Augustin - 1785
Crookes, William - 1879
Curie, Marie - 1895, 1900
Curie, Pierre - 1895, 1898, 1900
Davy, Humphrey - 1807, 1821
Descartes, Rene - 1638, 1644
Doppler, Christian - 1842
du Fay, Charles Francois - 1733
Einstein, Albert - 1905
Faraday, Michael - 1812, 1821, 1831, 1833, 1834, 1837, 1838, 1841, 1845, 1846, 1854, 1855
Fermat, Pierre de - 1657
Fitz Gerald, George - 1881, 1883, 1890, 1892
Fizeau, A. - 1849
Foucault, Jean - 1850
Franklin, Benjamin - 1747
Fresnel, Augustin - 1817, 1825, 1827
Galileo - 1638
Galvani, Luigi - 1780
Gauss,Karl Friedrich - 1813
Gilbert, William - 1600
Glazebrook, R. T. - 1888
Gray, Stephen - 1729

Green, George - 1828, 1837, 1839
Grimaldi, Francesco Maria - 1665
Hagen - 1903
Hall, Edwin - 1879
Heaviside, Oliver - 1883, 1889
Helmholtz, Hermann von - 1847, 1870, 1881
Henry, Joseph - 1832, 1842
Herschel, John - 1820
Hertz, Heinrich - 1884, 1887, 1888, 1889
Hittorf - 1869
Hooke, Robert - 1667
Huygens, Christiaan - 1678
Jacquier, Francis - 1742
Joule, James Prescott - 1841
Kerr, John - 1875
Kirchoff, Gustav - 1848, 1857
Lagrange, Joseph Louis - 1764, 1777
Lamb, Horace - 1883
Laplace, Pierre Simon - 1782, 1808, 1813
Larmor, Joseph - 1900
Le Seur, Thomas - 1742
Lenard, Philip - 1894
Lenz,Emil - 1834
Lodge, Oliver - 1892
Lorentz, Hendrik Anton - 1892, 1895, 1896, 1903, 1904
Lorenz, Ludwig - 1867
MacCullagh, James - 1835, 1839
Magnus - 900 BC
Malus, Etienne Louis - 1808
Mascart, E. - 1872
Maxwell, James Clerk - 1855, 1861, 1864, 1868, 1869, 1873
Mayer, Julius Robert - 1842
Michell, John - 1750
Michelson, Albert - 1881
Morley, Edwin - 1881
Musschenbroek, Pieter van - 1745
Navier, Claude Louis Marie Henri - 1827
Neumann, Franz - 1835, 1842, 1845
Newton, Isaac - 1671, 1717
Nicholson, William - 1800
Nollet, Abbe Jean-Antoine - 1749
O'Brien, Matthew - 1842
Oersted, Hans Christian - 1820
Ohm,Georg Simon - 1826
Ostrogradsky - 1831
Peltier, Jean Charles - 1834
Peregrinus, Peytrus - 1269
Poisson, Simeon Denis - 1812, 1824, 1828
Poynting, John - 1884

Priestly, Joseph - 1766
Rayleigh, Lord - 1902
Riemann, Bernhard - 1861, 1867
Roemer, Olaf - 1675
Roentgen, Wilhelm - 1888, 1895
Rowland, Henry - 1876, 1880
Rubens - 1903
Rutherford, Ernest - 1899
Savart, Felix - 1820
Savery, F. - 1827
Seebeck,Thomas Johann - 1822
Shuster, Arthur - 1896
Stefan, J. - 1879
Stokes, George Gabriel - 1825, 1849, 1850, 1867, 1896
Sulzer, Johann - 1752
Thales of Miletos - 600 BC
Thomson, J. J. - 1881, 1889, 1894, 1896, 1897
Thomson, William (Lord Kelvin) - 1839, 1846, 1850, 1851, 1853, 1854
Volta, Alessandro - 1793
Watson, William - 1748
Weber, Wilhelm - 1846, 1847
Wiechert, Emil - 1896, 1900
Wien, W. - 1897
Wilson, H. A. - 1905
Young, Thomas - 1801, 1803
Zeeman, Pieter - 1896

Next: Review Sheet Up: No Title Previous: Homework Assignments
Ross Spencer
Tue Apr 13 10:47:17 MDT 1999