PHY3004W Project

The Development of the Theory of Electromagnetism

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Abstract

Contents

1 Introduction

Electromagnetism is arguably the best understood phenomenon in physics. This is meet since the Theory of Electromagnetism has been in development for more than 500 years.

Electromagnetism is a fairly large branch of physics. It is the study of the interaction between charged particles, the forces and fields associated with the interaction, (electric and magnetic forces, electric and magnetic fields).

Electromagnetism is a very fundamental phenomenon in the universe. The electromagnetic force is one of the four fundamental forces in the universe, which are the strong force, the weak force, gravity, and the electromagnetic force.

The purpose of this project is to look at how the theory of Electromagnetism developed and came together. To look at how various factors affected how the theory develped. Factors such as the times in which physiciscts lived, how various physicists influenced each other, how the times in which physicisits lived affected the type of physics they did, how the geolocation of the physiscsts affected their physics, and how communication sped up develppments.

Electromagnetism can be condensed to a few axioms and statements. There are two types of charges, positive and negative. Like charges attract, unlike charges repel, with forces proportional to the square of the distance between the charges. Each charge exhibits an electric field around it, which is how the forces are transmitted. Moving charges create magnetic fields, which result in the magnetic force, which acts perpendicular to velocities of particles. Changing electric fields create magnetics fields, changing, magnetic fields create electric fields. This coupling of electric and magnetic fields results in waves composed of electric and magnetic fields, called electromagnetic waves, that move at a set speed through a vacuum. Accelerating charges create electromagnetic fields.

Because Electromagnetism is such a fundamental part of the universe, it is responsible for most of our everyday experiences. Friction, light, the normal force and heat are all manifestations of the electromagnetic force. This is not to mention the various applications of electromagnetism. Almost all our technology is founded on electromagnetism. Tvs, cellphones, computers, electrical appliances, communications equipment and various other pieces of technology.

2 Early Development

Magnetism dates back to earlier than 600 B.C. Magnetism was first observed in the form of lodestone, a mineral magnetite which consists of iron oxide. The Ancient Greeks were the first known to use lodestone. They named it magnet, because of its ability to attract other metals. Aristotle (385 BC - 322 BC) was the first who attributed what could be regarded as the first scientifc discussion of magnetism to the philosopher Thales of Miletus (625 BC - 545 BC).

Lodestone is also mentioned in the ancient medical text *Sushruta Samhita*, which describes how to use lodetsone to remove arrows embedded in a person's body.

Magnetism is also recorded in ancient China. The earliest literrary reference to magnetism was in a 4th century BC book *The Sage of Ghost Valley. Lushi*

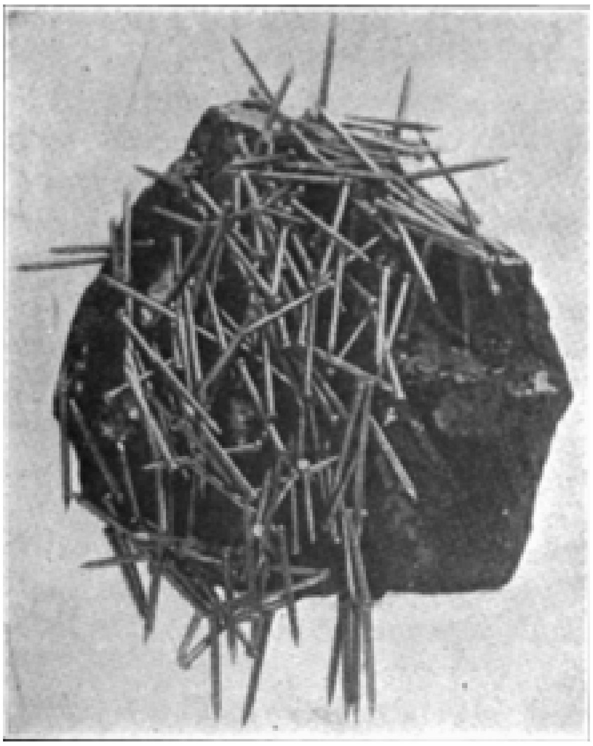

Figure 1: Figure showing natural Lodestone attracting nails.

3 Beginning of the Science

As has been mentioned above, electromagnetism had been discovered in ancient history, mainly in the form of magnetism.

But the first systematic investigation of electromagnetism using the scienctifc method was by the Physicist Petrus Peregrinus (1240-1280), who experimented on magnetism and published the ”Epistola and Sigeam de Foucaucourt moletom de magnete” in 1269.

The Epistola was divided into two parts. In the first part, he discussed the physical properties of the lodestone, and gave an account of the polarity of magnets. He provide methods of determining the north and south poles of magnets, and describes how like poles repel each other and unlike poles attract each other. He also described the attraction of iron by lodestones, how lodestones can magnetize iron, and how to reverse the polarity of magnetized iron. In the second part he discusses the applications of magnets.

4 Time Frames of Development

Time period	Important results
28th cebtury BC	Ancient Egyptian texts describe electric fish. They refer to them as the ”Thunderer of the Nile”, and c
6th century BC	Greek philosopher Thales of Miletus observes that rubbing fur on various substances, such as amber, w
424 BC	Aristophanes’ ”lens” is a glass globe filled with water.(Seneca says that it can be used to read letters n
4th century BC	Mo Di first mentions the camera obscura, a pin-hole camera
3rd century BC	Euclid is the first to write about reflection and refraction and notes that light travels in straight lines[
1st century AD	Pliny in his Natural History records the story of a shepherd Magnes who discovered the magnetic prop
8th century AD	Electric fish are reported by Arabic naturalists and physicians
130 AD	Claudius Ptolemy (in his work Optics) wrote about the properties of light including: reflection, refract
1021	Ibn al-Haytham (Alhazen) writes the Book of Optics, studying vision
1088	Shen Kuo first recognizes magnetic declination
1187	Alexander Neckham is first in Europe to describe the magnetic compass and its use in navigation.
1269	Pierre de Maricourt describes magnetic poles and remarks on the nonexistence of isolated magnetic po
1305	Dietrich von Freiberg uses crystalline spheres and flasks filled with water to study the reflection and re
14th century AD	Possibly the earliest and nearest approach to the discovery of the identity of lightning, and electricity f
1550	Gerolamo Cardano writes about electricity in De Subtilitate distinguishing, perhaps for the first time,
1600	William Gilbert publishes De Magnete, Magneticisque Corporibus, et de Magno Magnete Tellure (”On
1604	Johannes Kepler describes how the eye focuses light. Johannes Kepler specifies the laws of the rectiline
1608	first telescopes appear in the Netherlands
1611	Marko Dominis discusses the rainbow in De Radiis Visus et Lucis. Johannes Kepler discovers total inte
1620	the first compound microscopes appear in Europe
1621	Willebrord van Roijen Snell states his Snell’s law of refraction
1630	Cabaeus finds that there are two types of electric charges
1637	René Descartes quantitatively derives the angles at which primary and secondary rainbows are seen wi
1646	Sir Thomas Browne first uses the word electricity is in his work Pseudodoxia Epidemica.
1657	Pierre de Fermat introduces the principle of least time into optics
1660	Otto von Guericke invents an early electrostatic generator.
1663	Otto von Guericke (brewer and engineer who applied the barometer to weather prediction and invente
1665	Francesco Maria Grimaldi highlights the phenomenon of diffraction
1673	Ignace Pardies provides a wave explanation for refraction of light
1675	Robert Boyle discovers that electric attraction and repulsion can act across a vacuum and do not depe
1676	Olaus Roemer measures the speed of light by observing Jupiter’s moons
1678	Christiaan Huygens states his principle of wavefront sources and demonstrates the refraction and diffra
1704	Isaac Newton publishes Opticks, a corpuscular theory of light and colour
1705	Francis Hauksbee improves von Guericke’s electrostatic generator by using a glass globe and generates
1728	James Bradley discovers the aberration of starlight and uses it to determine that the speed of light is a
1729	Stephen Gray and the Reverend Granville Wheler experiment to discover that electrical ”virtue”, prod
1732	C. F. du Fay Shows that all objects, except metals, animals, and liquids, can be electrified by rubbing
1734	Charles François de Cisternay DuFay (inspired by Gray’s work to perform electrical experiments) disp

1737	C. F. du Fay and Francis Hauksbee the younger[citation needed] independently discover two kinds of fr
1740	Jean le Rond d'Alembert, in Mémoire sur la réfraction des corps solides, explains the process of refract
1745	Pieter van Musschenbroek of Leiden (Leyden) independently discovers the Leyden (Leiden) jar, a prim
1746	Leonhard Euler develops the wave theory of light refraction and dispersion
1747	William Watson, while experimenting with a Leyden jar, observes that a discharge of static electricity
1752	Benjamin Franklin establishes the link between lightning and electricity by the flying a kite into a thun
1753	C. M. (of Scotland, possibly Charles Morrison, of Greenock or Charles Marshall, of Aberdeen) propose
1767	Joseph Priestley proposes an electrical inverse-square law
1774	Georges-Louis LeSage builds an electrostatic telegraph system with 26 insulated wires conducting Leyo
1784	Henry Cavendish defines the inductive capacity of dielectrics (insulators) and measures the specific ind
1785	Charles Coulomb introduces the inverse-square law of electrostatics
1786	Luigi Galvani discovers "animal electricity" and postulates that animal bodies are storehouses of electr
1791	Luigi Galvani discovers galvanic electricity and bioelectricity through experiments following an observa
1799	Alessandro Volta, following Galvani's discovery of galvanic electricity, creates a voltaic cell producing a
1800	William Herschel discovers infrared radiation from the Sun. William Nicholson, Anthony Carlisle and .
1801	Johann Ritter discovers ultraviolet radiation from the Sun. Thomas Young demonstrates the wave nat
1802	Gian Domenico Romagnosi, Italian legal scholar, discovers that electricity and magnetism are related b
1803	Thomas Young develops the Double-slit experiment and demonstrates the effect of interference.[
1806	Alessandro Volta employs a voltaic pile to decompose potash and soda, showing that they are the oxid
1808	Étienne-Louis Malus discovers polarization by reflection
1809	Étienne-Louis Malus publishes the law of Malus which predicts the light intensity transmitted by two p
1811	François Jean Dominique Arago discovers that some quartz crystals continuously rotate the electric ve
1814	Joseph von Fraunhofer discovered and studied the dark absorption lines in the spectrum of the sun no
1816	David Brewster discovers stress birefringence
1818	Siméon Poisson predicts the Poisson-Arago bright spot at the center of the shadow of a circular opaqu
1820	Hans Christian Ørsted, Danish physicist and chemist, develops an experiment in which he notices a co
1821	André-Marie Ampère announces his theory of electrodynamics, predicting the force that one current ex
1824	
1825	Augustin Fresnel phenomenologically explains optical activity by introducing circular birefringence. W
1826	Georg Simon Ohm states his Ohm's law of electrical resistance in the journals of Schweigger and Pogg
1829-1830	Francesco Zantedeschi publishes papers on the production of electric currents in closed circuits by the
1831	Michael Faraday began experiments leading to his discovery of the law of electromagnetic induction, th
1832	Baron Pavel L'vovitch Schilling (Paul Schilling) creates the first electromagnetic telegraph, consisting o
1833	Heinrich Lenz states Lenz's law: if an increasing (or decreasing) magnetic flux induces an electromotive
1834	Heinrich Lenz determines the direction of the induced electromotive force (emf) and current resulting f
1835	Joseph Henry invents the electric relay, which is an electrical switch by which the change of a weak cu
1836	William Fothergill Cooke invents a mechanical telegraph. 1837 with Charles Wheatstone invents the C
1837	Samuel Morse develops an alternative electrical telegraph design capable of transmitting long distance
1838	Michael Faraday uses Volta's battery to discover cathode rays.
1839	Alexandre Edmond Becquerel observes the photoelectric effect with an electrode in a conductive soluti
1840	James Prescott Joule formulates Joule's Law (sometimes called the Joule-Lenz law) quantifying the an
1845	Michael Faraday discovers that light propagation in a material can be influenced by external magnetic
1849	Hippolyte Fizeau and Jean-Bernard Foucault measure the speed of light to be about 298,000 km/s
1852	George Gabriel Stokes defines the Stokes parameters of polarization. Edward Frankland develops the t
1854	Gustav Robert Kirchhoff, physicist and one of the founders of spectroscopy, publishes Kirchhoff's Laws
1855	James Clerk Maxwell submits On Faraday's Lines of Force for publication containing a mathematical s
1861	the first transcontinental telegraph system spans North America by connecting an existing network in
1864	James Clerk Maxwell publishes his papers on a dynamical theory of the electromagnetic field
1865	James Clerk Maxwell publishes his landmark paper A Dynamical Theory of the Electromagnetic Field
1866	the first successful transatlantic telegraph system was completed. Earlier submarine cable transatlantic
1869	William Crookes invents the Crookes tube.
1871	Lord Rayleigh discusses the blue sky law and sunsets (Rayleigh scattering)
1873	Willoughby Smith discovers the photoelectric effect in metals not in solution (i.e., selenium). J. C. Ma
1874	German scientist Karl Ferdinand Braun discovers the "unilateral conduction" of crystals.[18][19] Braun
1875	John Kerr discovers the electrically induced birefringence of some liquids

1878	Thomas Edison, following work on a "multiplex telegraph" system and the phonograph, invents an im
1879	Jožef Stefan discovers the Stefan–Boltzmann radiation law of a black body and uses it to calculate the
1880	Edison discovers thermionic emission or the Edison effect
1882	Edison switches on the world's first electrical power distribution system, providing 110 volts direct cu
1884	Oliver Heaviside reformulates Maxwell's original mathematical treatment of electromagnetic theory fro
1886	Oliver Heaviside coins the term inductance.
1887	Heinrich Hertz invents a device for the production and reception of electromagnetic (EM) radio waves.
1888	Introduction of the induction motor, an electric motor that harnesses a rotating magnetic field produc
1893	Victor Schumann discovers the vacuum ultraviolet spectrum.
1895	Wilhelm Conrad Röntgen discovers X-rays. Jagadis Chandra Bose gives his first public demonstration
1896	Arnold Sommerfeld solves the half-plane diffraction problem
1897	J. J. Thomson discovers the electron.
1899	Pyotr Lebedev measures the pressure of light on a solid body.
1900	The Liénard–Wiechert potentials are introduced as time-dependent (retarded) electrodynamic potentia
1904	John Ambrose Fleming invents the thermionic diode, the first electronic vacuum tube, which had prac
1905	Albert Einstein proposes the Theory of Special Relativity, in which he rejects the existence of the aeth
1911	Superconductivity is discovered by Heike Kamerlingh Onnes, who was studying the resistivity of solid
1919	Albert A. Michelson makes the first interferometric measurements of stellar diameters at Mount Wilso
1924	Louis de Broglie postulates the wave nature of electrons and suggests that all matter has wave propert
1946	Martin Ryle and Vonberg build the first two-element astronomical radio interferometer (see history of
1953	Charles H. Townes, James P. Gordon, and Herbert J. Zeiger produce the first maser
1956	R. Hanbury-Brown and R.Q. Twiss complete the correlation interferometer
1960	Theodore Maiman produces the first working laser
1966	Jefimenko introduces time-dependent (retarded) generalizations of Coulomb's law and the Biot–Savart
1999	M. Henny and others demonstrate the Fermionic Hanbury Brown and Twiss Experiment

Figure 3 is the plot of the number of published works published in each year. We observe that most of the work between 1820 and 1870.

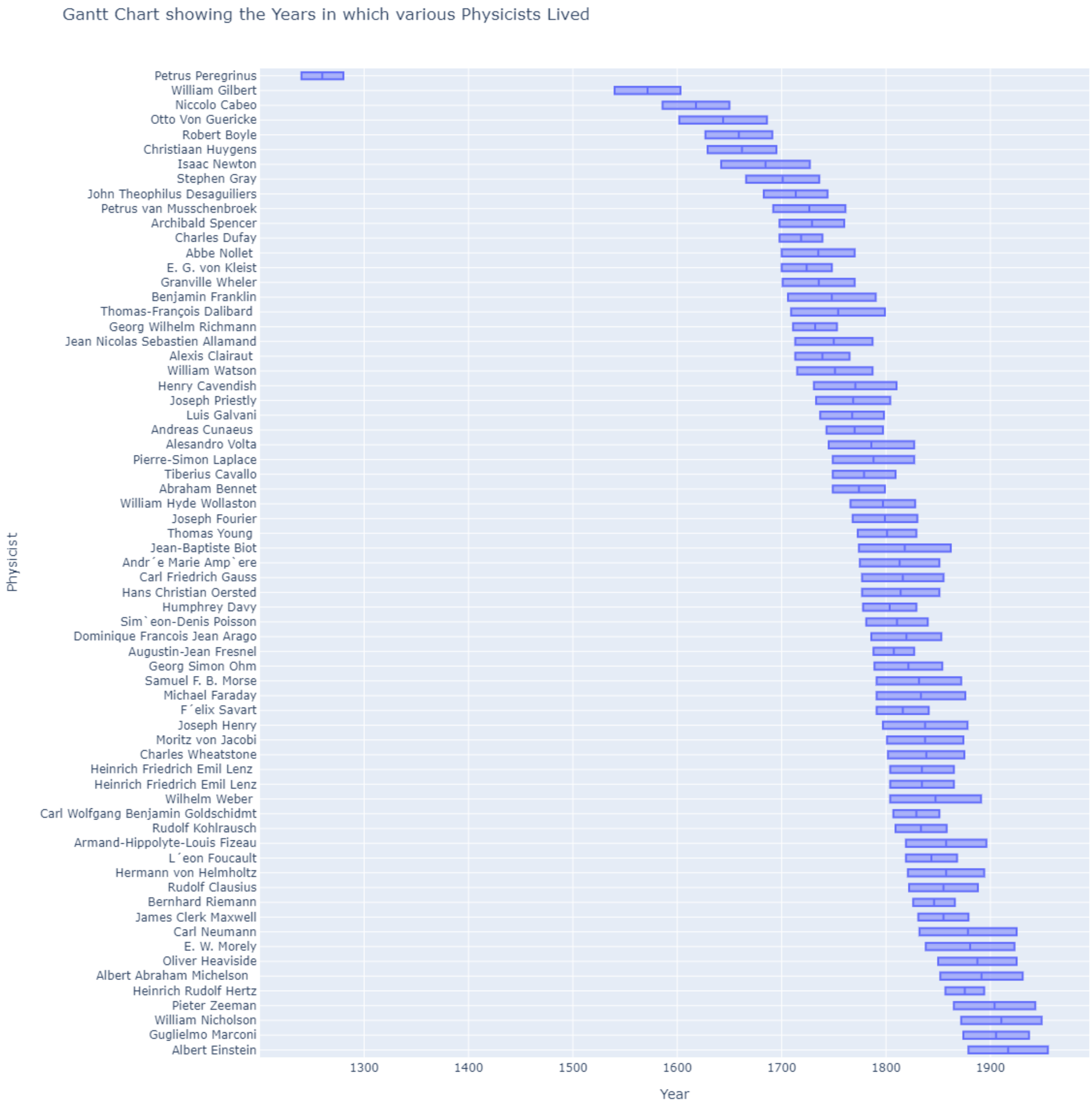

Figure 2: Gantt chart showing years in which various physicists lived.

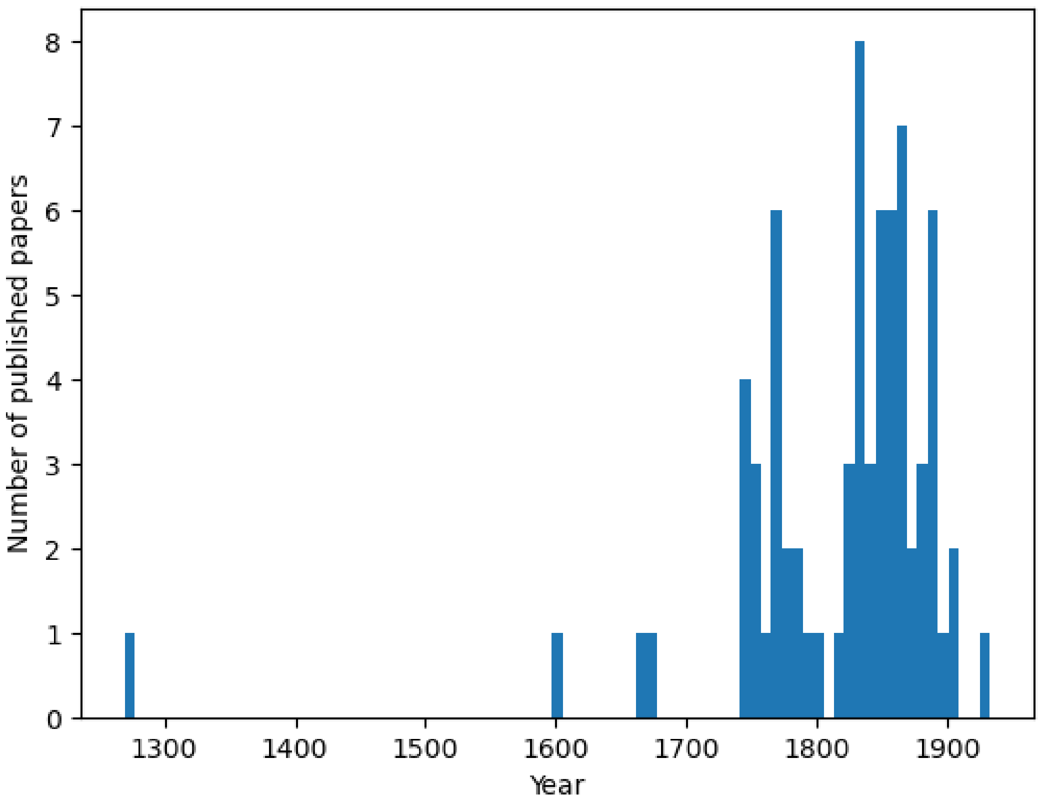

Figure 3: Histogram showing the number of published works in each year.

5 Influence Among Physicists

In the development of electromagnetism, physicists influenced each other and built on each others work.

Figure 2 is a digraph showing the connections and influences between the various physicists.

From the color coding, we observe that the development of the different fields seems to be clustered. Meaning that physicists tend to work on fields that the people who influenced them also worked on.

Influence includes physicists listening to talks given by other physicists, physicits working together in collaboration, and physicists mentoring other phycists.

There are 74 physicists in the above diagram. 45 phisicists only have 1 type colored arrow attached to them, 29 have different colored arrows connecting them. This suggests further that physicists tend to work on the same branch of physics that their influencers worked on.

So then we can conclude that a physicist will tend to work on the same field of physicist that his/influencer worked on.

It is worth mentioning that physicists sometimes develop exactly the same physics or come up with exactly the same invention independently, without any input from each other. An example of this

5.1 Impact of Communication

5.2 Collaboration

5.3 Disconnect Development of the same Physics

5.4 Influence of Geolocation

Maxwell, impressed by Faraday's work on magnetic lines, furthered the theory while at the university of Cambridge in the 1850s. He later moved to King's College London, where he came into regular contact with Faraday, and between 1861 and 1862 published 4 papers on magnetic field lines that built upon Faraday's work.

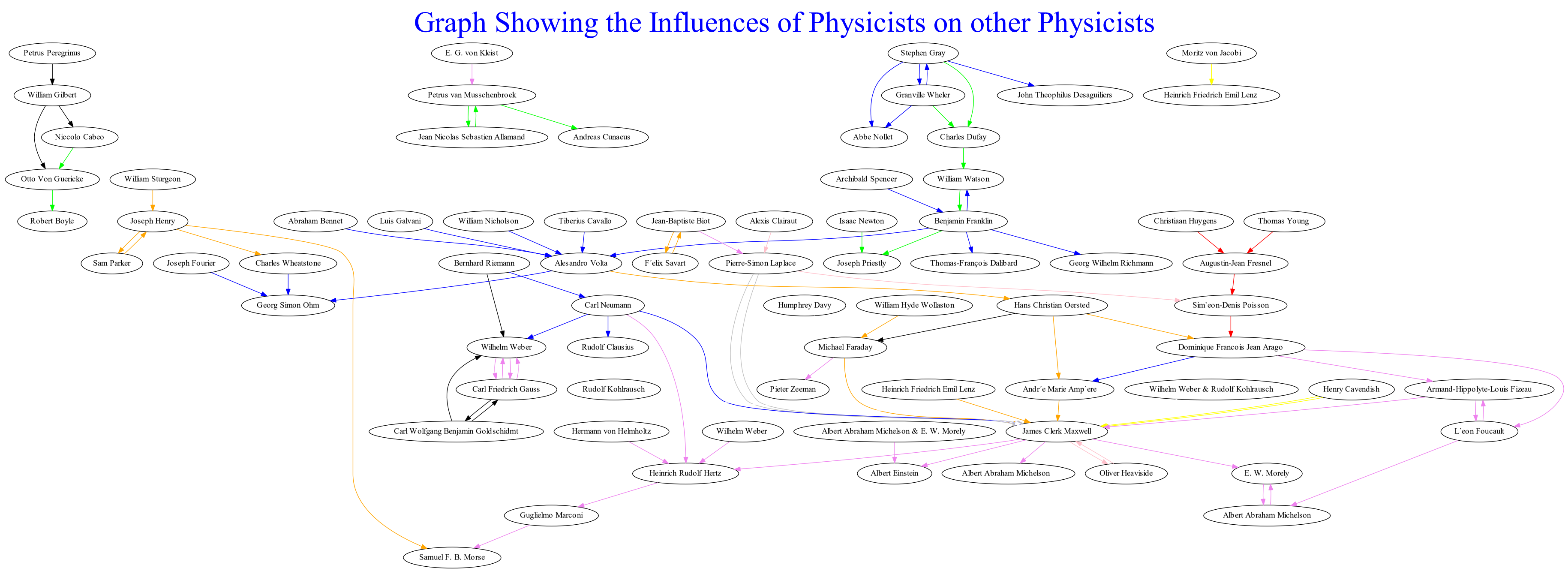

Figure 4: Figure showing the influences that various phycisists had on each other.

6 Coming together of Maxwell's Equations

Alomost all of electromagnetism can be derived from Maxwell's equations:

$$\nabla . \mathbf{E} = \frac{1}{\epsilon_0} \rho \tag{1}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \tag{2}$$

$$\nabla . \mathbf{B} = 0 \tag{3}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} \tag{4}$$

Figure 5: James Clerk Maxwell.

Maxwell's equations are the culmination of many results found by many different physicists. Maxwell didn't come up with the physicics encoded in equations, what he did was put together and reconcile the different experimental results gotten by various physicists.

Before Maxwell, these experimental results and and discovered rules were not well organized and were sometimes confusing to scientists. A neat formulation of electrodynamic principles was in order.

Maxwell accomplished this through a series of papers he published between the 1850s and 1870s. In the 1850s, Maxwell was proccupied with Michael Faraday's work on 'Lines of Force' (now known as magnetic field lines), built on them published his first paper on electromagnetism 'On Faraday's Lines of Force' in 1856. In his paper, he introduced the idea of a field, he used the analogy that the lines of force behave like a flowing incmpressable fluid. He then came into regular contact with Michael Faraday and worked with him. Maxwell then published a series of 4 papers between 1861 and 1862, titled 'On Physical Lines of Force'. These papers introduced various models to to describe and model the observed electromagnetic phenomena. His models include using rotating vortex tubes to model some of the phenomena. They also inluded modeling a vacuum as an insulating elastic medium. Moreover, he also derived the speed of light from the wave equation.

In 1865, he published 'A Dynamical Theory of the Electromagnetic Field'. This paper had the theory of electromagnetism formulated in precise mathematical form, and also included all of Maxwell's equations. He further publishd 'A Dynamical Theory of the Electromagnetic Field' in 1873. This paper showed the unification of light with electromagnetism, and gave a summary of Maxwell's work on electromagnetism.

Oliver Heaviside later studied Maxwell's paper 'A Treatise on Electricity and Magnetism', and usd vector calculus to reduce Maxwell's 20 equations into just 4. In the 1890s Heinrich Hertz in a series of experiments provided experimental proof of Maxwell's equations, which then led to them being fully accepted by physicists worldwide.

6.1 Relation of light and electromagnetism

The relationship between light and electromagnetism was first discovered in 1855 by Wilhelm Weber and Rudolf Kohlrausch. They discovered that "the ratio of the absolute electromagnetic unit of charge to the absolute electrostatic unit of charge" has units of velocity. Moreover, they measured this ratio in an experiment that consisted of charging and discharging a Leyden jar, and measuring the magnetic force from the discharge current. They found a value of $3.107 \times 10^8 m.s^{-1}$, which was very close to the then known speed of light of $2.98 \times 10^8 m.s^{-1}$, which was measured by Leon Foucault in 1850. But Weber and Kohlrausch did not realize the relationship of light to electromagnetism.

While Maxwell was working on part III of his paper the 'On Physical Lines of Force' in 1861, he looked up Weber's and Kohlrausch's results, interpreted in terms of his theory of electromagnetism, made a connection between the speed of light and electromagnetism, and concluded that light was electromagnetic radiation.

6.2 "Maxwell's Equations"

As was mentioned, Maxwell's 1861 paper included 20 of Maxwell's equations. It was only in 1884 that they were reduced to just 4 equations using vector notation. This was done by Oliver Heaviside, concurrently with similar work by Josiah Gibbs and Heinrich Hertz. The 4 equations were first known as the Hertz-Heaviside equations and the Maxwell-Hertz equations.

Maxwell made a correction to Ampere's law in his 1861 paper 'On Physical Lines of Force', he added the displacement current

6.3 Gauss's Law

6.4 Faraday's Law

6.5 Ampere's Law

6.6 No Name Law

7 Conclusion

8 References