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INTRODUCTION

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1.1 PROLOGUE

This chapter provides an overview of the origin and the developments of magnetism, electricity, and light theories. The chronology is traced up to the time of Maxwell who was the first to link all three together in a formal way even though many conjectured about their interrelations before him. First, an overview of magnetism is provided, followed by that of electricity, and then that of light. The material presented in this chapter is collected from the various references given at the end of the chapter. In addition, the various scientific works done by Maxwell and his legacy are described. Finally, an overview of the theory of electromagnetic waves first developed by Maxwell and how it was subsequently modified by Hertz and Heaviside and later on by Larmor is presented. This is a unique theory in physics where the basic fundamental equations did not change, while their physical interpretations underwent at least two major modifications.

1.2 DEVELOPMENT OF MAGNETISM

The development of magnetism is traced through the last 5000 years.

2637 BC:
- Emperor Huang-ti of China used the compass in a battle to find the direction along which he should pursue his enemies.

1110 BC:
- Taheon-Koung, the Chinese minister of state, gave his crew a compass to sail from Cochin, China, to Tonquin.

1068 BC:
- Chinese vessels routinely navigated the Indian Ocean by compass.

1022 BC:
- Some Chinese chariots had a floating magnetic needle, the motion of which was communicated to the figure of a spirit whose outstretched hands always indicated the south.

1000 BC:

- Homer of Greece wrote that loadstones were used by the Greeks to direct navigation at the time of the siege of Troy.

950 BC:

- King Solomon (970–928 BC) of Israel knew how to use the compass.

900 BC:

- Magnes, a Greek shepherd, walked across a field of black stones which pulled the iron nails out of his sandals and the iron tip from his shepherd's staff, as suggested by the Italian natural philosopher Giambattista della Porta (1540–1615). The same story had also been told by Gaius Plinius Secundus, better known as Pliny the Elder (23–79AD). This region became known as *Magnesia* in Asia Minor. Probably, the word magnet evolved from this and the iron oxide ore was named as magnetite. Pliny in *Naturalis Historia* also wrote of a hill near the river Indus that was made entirely of a stone that attracted iron.

600 BC:

- First recorded information by Greek philosophers, particularly by Thales of Miletus (624–546 BC), about the magnetic properties of natural ferric oxide (Fe_3O_4) stones. It was also known to the Indians. For example Susruta, a physician in the sixth century BC in India, used them for surgical purposes.

121 AD:

- The Chinese dictionary *Choue Wen* contained an explicit recorded reference of the magnet.

1186:

- Alexander Neckam (1157–1217), a monk and man of science of St. Albans, England, described the working of a compass in the western literature for the first time and he did not refer to it as something new, indicating that it had been in use for some time.

1254:

- Roger Bacon, a philosopher also called Friar Bacon and surnamed Doctor Mirabilis (1214–1294), a Franciscan monk of Ilchester, England, dealt with the magnet and its properties in *Opus Minus*.

1269:

- Petrus Peregrinus or Pierre de Maricourt, a Crusader from Picardy, France, who was a mathematician, aligned needles with lines of longitude pointing between two pole positions of the stone and established the concept of two poles of the magnet. He wrote it in *Epistola de Magnete*.

1400:

- Jean de Jaudun of France wrote about magnets and the problem of action-at-a-distance.

1492:

- Christopher Columbus (1451–1506), from Italy (navigating under the Spanish flag) was the first to determine astronomically the position of a line of no magnetic variation. He observed the compass changes direction as the longitude changes.

1497:

- Portuguese navigator Vasco da Gama (1469–1524) used the compass for his trip to the Indies. He said that he found pilots in the Indian Ocean who made ready use of the compass.

1530:

- Spanish cartographer Alonzo de Santa Cruz produced the first map of magnetic variations from the true north.

1544:

- German technician and physicist Georg Hartmann (1489–1564) also discovered the magnetic dip of the compass.

1558:

- Giambattista della Porta (1540–1615), an Italian natural philosopher, performed experiments with the magnet for the purpose of communicating intelligence at a distance.

1576:

- Robert Norman, a manufacturer of compass needles at Wapping, England, rediscovered the dip or inclination to the Earth of the magnetic needle in London and was the first to measure them.

1590:

- Giulio Moderati Caesare, an Italian surgeon, observed the conversion of iron into a magnet by geographical position alone.

1600:

- Sir William Gilbert (1544–1603), court physician to Queen Elizabeth I, discovered that the Earth was a giant magnet and explained how compasses worked. He gave the first rational explanation to the mysterious ability of the compass needle to point north-south.

1644:

- René Descartes (1595–1650), the French physicist, physiologist, mathematician, and philosopher, in the *Principia Philosophiae*, theorized that the magnetic poles were on the central axis of a spinning vortex of fluids surrounding each magnet. The fluid entered by one pole and leaves through the other.

1687:

- English scientist and mathematician Sir Isaac Newton (1642–1727) estimated an inverse cubed law for the two poles of a magnet. He also published *Principia* that year whose costs and proofreading of the material were carried out by the English astronomer and mathematician Edmund Halley (1656–1742).

1699:

- Halley performed the first magnetic survey showing the variation of the compass.

1716:

- Halley proposed that the magnetic effluvia moving along the magnetic field of the Earth results in the aurora.

1730:

- English scientist Servigton Savery produced the first compound magnet by binding together a number of artificial magnets with a common pole piece at each end.

1740:

- Gowen Knight produced the first artificial magnets for sale to scientific investigators and terrestrial navigators.

1742:

- Thomas Le Seur and Francis Jacquier, of France, in a note to the edition of Newton's *Principia* that they published, showed that the force between two magnets was inversely proportional to the cube of the distance.

1750:

- English scientist John Mitchell (1724–1793) published the first book on making steel magnets. He also discovered that the two poles of a magnet were equal in strength and that the force between individual poles followed an inverse square law.

1759:

- German physicist Franz Maria Ulrich Theodor Hoch Aepinus (1724–1802) published *An Attempt at a Theory of Electricity and Magnetism*, the first book applying mathematical techniques to the subject.

1778:

- Sebald Justin Brugmans (1763–1819), a Dutch professor of natural history, demonstrated the diamagnetic properties of bismuth and antimony. A diamagnetic substance is one that has a permeability of less than one. A bar or a needle of such a substance, when free to move, will tend to be at right angles to the lines of force in a magnetic field.

1785:

- French physicist Charles-Augustin de Coulomb (1736–1806) independently verified Mitchell's law of force for magnets and extended the theory to the law of attraction of opposite electricity. He was the proponent of a two fluid theory proposed in 1759 by the English physicist Robert Symmer based on the ideas of the French physicist Charles François de Cisternay du Fay (1698–1739).

1820:

- French physicists Jean-Baptiste Biot (1774–1862) and Felix Savart (1792–1841) showed that the magnetic force exerted on a magnetic pole by a wire falls off as $1/r$ and is oriented perpendicular to the wire similar to what the Danish physicist Hans Christian Ørsted (1777–1851) had predicted. The English mathematician Edmund Taylor Whittaker (1873–1956) says that "This result was soon further analyzed, to obtain $d\boldsymbol{B} \propto (\boldsymbol{I}d\boldsymbol{s} \times \boldsymbol{r})/r^3$, where $\boldsymbol{B}$ stands for the magnetic flux vector, $\boldsymbol{I}$ for the current, $\boldsymbol{r}$ for the position vector, and ds for the elemental length of current."

1821:

- British scientist Michael Faraday (1791–1867) discovered that a conductor carrying a current would rotate around a magnetic pole and that a magnetized needle would rotate about a wire carrying a current.

- Self-educated British physicist William Sturgeon (1783–1850) made the first electromagnet.
- Physicist Prof. Joseph Henry (1797–1878) of Albany Academy, New York, made an electromagnet with superimposed layers of insulated wires.
- German physicists Johann Solomon Christoph Schweigger (1779–1857) and Johann Christian Poggendorf (1796–1877) constructed independently the first galvanometers.

1824:

- French mathematician Siméon–Denis Poisson (1781–1840) invented the concept of the magnetic scalar potential and of surface and volume pole densities described by the formula

$$\boldsymbol{F} = -\int \boldsymbol{M} \bullet \frac{\boldsymbol{r}-\boldsymbol{r}'}{|\boldsymbol{r}-\boldsymbol{r}'|^3} dV' = \int \frac{\nabla' \bullet \boldsymbol{M}}{|\boldsymbol{r}-\boldsymbol{r}'|} dV' - \int \frac{\boldsymbol{M} \bullet \boldsymbol{n}'}{|\boldsymbol{r}-\boldsymbol{r}'|} dS' .$$

  where $\boldsymbol{F}$ is the electric vector potential, $\boldsymbol{M}$ is the magnetic current, $\boldsymbol{r}$ and $\boldsymbol{r}'$ are the field and the source coordinates, respectively, $\boldsymbol{n}'$ is the direction of the outward normal to the surface, dS' and dV' are the elemental surface and volume elements, respectively. He also provided the formula for the magnetic field inside a spherical cavity within magnetized material.

- French physicist Dominique François Jean Arago (1786–1853) demonstrated that a copper disk can be made to rotate by revolving a magnet near it.

1825:

- French mathematician and physicist André-Marie Ampère (1775–1836) published his collected results on magnetism. His expression for the magnetic field produced by a small segment of current was different from that which followed naturally from the Biot-Savart law by an additive term which integrated to zero around a closed circuit. In his memoir one found the result known as *Stoke's theorem* written as $\oint \boldsymbol{B} \bullet d\boldsymbol{s} = \mu_0 I$, where μ_0 is the permeability of vacuum. James Clerk Maxwell described this work as *one of the most brilliant achievements in science.*
- Italian physicist Leopoldo Nobili (1784–1835), invented a static needle pair, which produced a galvanometer independent of the magnetic field of the Earth.

1831:

- Henry discovered that a change in magnetism can make currents flow, but he failed to publish this. In 1832 he described self-inductance as the basic property of an inductor. In recognition of his work, inductance is measured in henries. He improved upon Sturgeon's electromagnet, substantially increasing the electromagnetic force. He also developed the principle of self-induction.

1832:

- Karl Friedrich Gauss (1777–1855), the mathematician, astronomer, and physicist from Germany, independently stated Green's theorem (named after the British mathematician George Green, 1793–1841) without proof. He also reformulated Coulomb's law without proof. He formulated separate electrostatic and electrodynamic laws including Gauss's law. All of it remained unpublished till 1867.

1838:

- Wilhelm Eduard Weber (1804–1891), a physicist from Germany, together with Gauss applied potential theory to the magnetism of Earth.

1850:

- Irish-Scottish physicist William Thomson (Lord Kelvin, 1824–1907) invented the idea of magnetic permeability and susceptibility, along with the separate concepts of **B**, **M** and **H**, where **H** stands for the magnetic field intensity.

1853:

- William Thomson used Poisson's magnetic theory to derive the correct formula for magnetic energy: $U = 0.5 \int \mu H^2\, dV$. He also gave the formula $U = 0.5LI^2$, where U is the magnetic energy, μ is the permeability, and L is the self induction parameter.

1864:

- James Clerk Maxwell (1831–1879), the physicist and mathematician from Scotland, published a mechanical model of the electromagnetic field. Magnetic fields corresponded to rotating vortices with idle wheels between them and electric fields corresponded to elastic displacements, hence displacement currents. The equation for **H** now became $\nabla \times \boldsymbol{H} = 4\pi \boldsymbol{J}_{tot}$, where $\boldsymbol{J}_{tot}$ is the total current, conduction plus displacement, and is conserved, i.e., $\nabla \bullet \boldsymbol{J}_{tot} = 0$. They were all available in scalar form in his paper *On Physical Lines of Force*. This addition completed Maxwell's equations and it now became easy for him to derive the wave equation exactly, and to note that the speed of wave propagation was close to the measured speed of light. Maxwell wrote:

> *We can scarcely avoid the inference that light is 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.*

Maxwell read a memoir before the Royal Society in which the mechanical model was stripped away and just the equations remained. He also discussed the vector and scalar potentials, using the Coulomb gauge. He attributed physical significance to both of these potentials. He wanted to present the predictions of his theory on the subjects of reflection and refraction of electromagnetic waves, but the requirements of his mechanical model kept him from finding the correct boundary conditions, so he never did this calculation. He published his paper *A Dynamical Theory of the Electromagnetic Field* [*Philosophical Trans.*, Vol. 166, pp. 459–512, 1865] – the first to make use of a mathematical theory for Faradays' concept of fields.

1.3 DEVELOPMENT OF ELECTRICITY

Next, the development of electricity is traced back to prehistoric times.

Prehistoric times:

- Early humans were aware of lightning, sting rays, electric eels, and static charges in a dry climate.

600 BC:

- The Greek philosopher Aristophanes was aware of the peculiar property of amber, which is a yellowish translucent resin. When rubbed with a piece of fur, amber developed the ability to attract small pieces of material such as feathers. For centuries this strange, inexplicable property was thought to be unique to amber.
- The Etruscans were known to have been devoted to the study of electricity. They were said to have attracted lightning by shooting metal arrows into clouds threatening thunder and lightning.
- Thales (640–546 BC) of Miletus rubbed amber (*elektron* in Greek) with cat fur and picked up bits of feathers. Unfortunately for posterity he left no writings, and all that we know was transmitted orally until Aristotle (384–322 BC), the great philosopher from Greece, recorded his teachings. So it was not clear whether he discovered the facts himself or learned from the Egyptian priests and others whom he visited on his extensive trips.

341 BC:

- Aristotle wrote about a fish called *torpedo* which gave electrical shocks and paralyzed muscles if touched.

250 BC:

- A Galvanic cell composed of copper and iron immersed in wine or vinegar called the *Baghdad Battery*, was excavated in Baghdad, Iraq, by the German archeologist Wilhelm König in 1938, and was dated back to 250 BC.

1600 AD:

- English physician Sir William Gilbert (1544–1603) proved that many other substances besides amber displayed electrical properties and that they have two electrical effects. When rubbed with fur, amber acquired *resinous* electricity; glass, however, when rubbed with silk, acquired *vitreos* electricity. Electricity of the same kind repels, and electricity of the opposite kind of attracts each other.

1629:

- Italian Jesuit priest Niccolò Cabeo (1585–1650) also observed electrical repulsion and attraction. Others who also did were the English diplomat and naval commander Sir Kenelm Digby (1603–1665) and the Irish natural philosopher and experimenter Sir Robert Boyle (1627–1691). However, there were some differences in opinion on exactly how it worked!

1646:

- Walter Charlton coined the term electricity. Others say it was coined by the English physician Robert Browne even though he contributed nothing else to science.

1663:

- Otto von Guericke (1602–1686), the German physicist, first published the phenomenon of static electricity and built a machine to produce it.

1665:

- French mathematician, physicist, and astronomer Honoré Fabri (1607-1688) demonstrated the reciprocity of the electric force.

1675:

- Jean Picard (1620–1682), a French astronomer, observed flashes of light from the vacuum space produced in a Torricellian barometer.

1705:

- English physicist Francis Hawksbee (1687–1763) further illustrated this phenomenon and generated light under different environmental conditions.

1729:

- Stephen Gray (1666–1736), a pensioner at the Charter House in London, England, showed that electricity did not have to be made in place by rubbing but can also be transferred from place to place with conducting wires. He also showed that the charge on electrified objects resided on their surfaces.

1733:

- Charles François de Cisternay du Fay (1698–1739), superintendent of gardens of the King of France, also came to the conclusion that electricity came in two kinds, which he called *resinous*(-) and *vitreous*(+).

1742:

- Jean-Théophile Desaguliers (1683–1744), a French-born scientist and Englishman by adoption, since he was brought to England after the revocation of the Edict of Nantes, became a protestant chaplain, continued the work of Gray, and used the names *non-electrics* or *conductors* for materials displaying the corresponding electrical properties.

1745:

- Pieter van Musschenbroek (1692–1761), physicist and professor at Leyden, The Netherlands, invented the Leiden jar, or capacitor, and nearly killed his assistant Andreas Cunaeus in demonstrating his experiment.
- Abbé Jean-Antoine Nollet (1700–1770), member of the court of Louis XV and a physics professor of the French Royal Children, expanded on

Fay's ideas and invented the two-fluid theory of electricity.

1746:

- Sir William Watson (1715–1787), a London apothecary, physicist, physician, and botanist, propounded the doctrine that electrical actions are due to the presence of electric aether and suggested conservation of charge.
- Johann Heinrich Winckler (1703–1770), a professor of philosophy and physics at the University of Leipzig, Germany, was the first to use electricity for telegraphic purposes using sparks.

1747:

- Benjamin Franklin (1706–1790), the American writer, statesman, and scientist, invented the theory of one-fluid electricity in which one of Nollet's fluids existed and the other was just the absence of the first, after observing the performance of some electrical experiments in Boston by a certain Dr. Spence who arrived from Scotland. He also proposed the principle of conservation of charge and called the fluid that existed and flowed "positive". He discovered that electricity can act at a distance in situations where fluid flow made no sense. To demonstrate that, during a thunderstorm in 1752, Franklin flew a kite that had a metal tip and charged a Leyden jar during a thunderstorm demonstrating lightning was an electrical discharge. At the end of the wet, conducting hemp line on which the kite flew, he attached a metal key, to which he tied a non-conducting silk string that he held in his hand. The experiment was extremely hazardous, but the results were unmistakable: when he held his knuckles near the key, he could draw sparks from it. The next two who tried this extremely dangerous experiment were killed.
- Watson passed an electrical charge along a two miles long wire.

1752:

- Johann Georg Sulzer (1720–1779), a Swiss philosopher, published that when two dissimilar metals like lead and silver were placed in touch with the tongue a peculiar taste was observed which did not exist if only one of the metals touched the tongue. This was the forerunner of batteries.

1759:

- German physicist Franz Maria Ulrich Theodor Hoch Aepinus (1724–1802) showed in St. Petersburg, Russia that electrical effects were a combination of fluid flow confined to matter and action at a distance. He also discovered charging by induction. He was assisted in his work by the German physicist Johan Carl Wilcke (1732–1796) when he was working earlier at the Berlin Academy of Science.

1762:

- John Canton (1718–1772), an English physicist, along with Wilcke, demonstrated the principle of electric induction where the near portion of the body acquires an opposite charge to the source near which it was placed whereas the opposite end acquired similar charges. This was also demonstrated by Franklin in 1755.

1764:

- Joseph-Louis Lagrange (1736–1813), the Italian-French mathematician and astronomer, discovered the divergence theorem in connection with the study of gravitation. In 1813 it became known as Gauss's law.

1767:

- Joseph Priestley (1733–1804), a chemist and English Presbyterian minister, acting on a suggestion in a letter from Benjamin Franklin, showed that hollow charged vessels contained no charge on the inside. And based on his knowledge that hollow shells of mass have no gravity inside, he correctly deduced that the law of electric force followed an inverse squared law. Priestley conjectured that the force of attraction followed that of the gravitational forces, and so did the Swiss-Dutch mathematician Daniel Bernoulli (1700–1782) in 1760. Priestley was considered one of the great experimental scientists of the XXVIII century even though he did not take a single formal science course.

1769:

- Physician Dr. John Robison (1739–1805) of Edinburgh, Scotland, determined the force between charges by experiment and found the exponent to be −2.06 that operated on the distance. From this he conjectured that the correct power was the inverse square.

1772:

- English chemist and physicist Sir Henry Cavendish (1731–1810) presented to the Royal Society *An Attempt to Explain Some of the Principal Phenomena of Electricity, by Means of an Elastic Fluid.* Since he was indifferent to publications, his work was published 100 years later at the instigation of William Thomson (Lord Kelvin) and was compiled by James Clerk Maxwell himself when he was the Cavendish Professor later in his life. Cavendish in fact had not only derived the correct form of the inverse square law but also had invented the idea of electrostatic capacity and specific inductive capacity (resistance).

1777:

- Lagrange invented the concept of the scalar potential for gravitational fields.

1780:

- One of Luigi Galvani's (the Italian anatomist and physician, 1737–1798) assistants noticed that a dissected frog leg twitched when he touched its nerve with a scalpel. Another assistant thought that he had seen a spark from a nearby charged electric generator at the same time. Galvani reasoned that the electricity was the cause of the muscle contractions. He mistakenly thought, however, that the effect was due to the transfer of a special fluid, or "animal electricity," rather than to conventional electricity. Experiments such as this, led Luigi Galvani in 1791, to propose his theory that animal tissues generate electricity.

1782:

- Pierre-Simon Laplace (1749–1827), a French mathematician, showed that Lagrange's potential, V, satisfied the equation $\nabla^2 V = 0$.

1785:

- The French physicist Charles-Augustin Coulomb (1736–1806) used a torsion balance to verify that the electric force law had an inverse squared variation. He proposed a combined fluid/action-at-a-distance theory like that of Aepinus but with two conducting fluids instead of one. He also discovered that the electric force near a conductor was proportional to its surface charge density and made contributions to the two-fluid theory of magnetism.

1799:

- Italian physicist Alessandro Guiseppe Antonio Anastasio Volta (1745–1827), professor of Natural philosophy at the University of Pavia, 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. The different metals, separated by the moist tissue of the frog, were generating electricity. The frog's leg was simply a detector. In 1800, Volta showed that when moisture comes between two different metals, electricity is created. This led him to invent the first electric battery, which he made from thin sheets of copper and zinc separated by moist pasteboard (felt soaked in brine) known as an *electrolyte*. He called his invention a *column battery* although it came to be commonly known as the *Volta battery, Voltaic Pile*, or *Voltaic Cell*. Volta showed that electricity could be made to travel from one place to another by wire.

1800:

- English chemist William Nicholson (1753–1815) and the English surgeon Anthony Carlisle (1768–1840) discovered that water may be separated into hydrogen and oxygen by the action of Volta's pile.
- The English chemist Sir Humphrey Davy (1778–1829) developed a theory for the pile based on the contact potentials.

1812:

- Michael Faraday (1791–1867), an English bookbinder's apprentice, wrote to Sir Humphry Davy asking for a job as a scientific assistant. Davy interviewed Faraday and found that he had educated himself by reading the books he was supposed to be binding. He became an assistant of Davy and then gradually became the director of the lab after Davy's death in 1829 and occupied the chair of chemistry from 1833.

1812:

- French mathematician Siméon-Denis Poisson (1781–1840) further developed 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 vanished. This surface charge density calculation was carried out in detail for ellipsoids. He also showed that the potential within a distribution of electricity ρ satisfied the equation $\nabla^2 V = -\rho / \varepsilon_0$, where ε_0 is the permittivity of vacuum.
- Laplace showed that, at the surface of a conductor, the electric field E is perpendicular to the surface and it is given by $E = \rho / \varepsilon_0$, where ρ is the

surface charge density.

- German mathematician, astronomer, and physicist, Karl Friedrich Gauss (1777–1855) rediscovered the divergence theorem of Lagrange which we referred to as the Gauss's divergence theorem. He applied it to derive Gauss's law.

1820:

- Hans Christian Ørsted (also written as Öersted) (1777–1851), professor of philosophy at Copenhagen, Denmark, observed that a current flowing through a wire would move a compass needle placed beside it. This showed that an electric current produced a magnetic field. The French physicist Dominique François Jean Arago (1786–1853) presented these results at the French Academy which excited many scientists to repeat the experiment.
- André-Marie Ampère (1775–1836), a French mathematician and physicist, one week after hearing of Öersted's discovery, showed that parallel currents attract each other and that opposite currents repel. Arago also showed that a wire carrying a current of electricity would attract iron filings.

1821:

- Davy showed that direct current is carried throughout the volume of a conductor and established that $R \propto \ell / A$ for long wires, where R stands for resistance, ℓ for length, and A for the cross-sectional area of a conductor or line. He also discovered that resistance increased with the rise of temperature.

1822:

- Estonian-German physicist Thomas Johann Seebeck (1770–1831) discovered the thermoelectric effect by showing that a current flowed in a circuit made of dissimilar metals if there was a temperature difference between the metals.

1826:

- Georg Simon Ohm (1787–1854), a physicist and a professor of mathematics in Cologne, Germany, established the result $V = I\,R$ now known as Ohm's law. Using a galvanometer he demonstrated the relation between potential, current, and resistance. The next year he published a book *Die Galvanische Kette, Mathematisch Bearbeitet,* where he proposed the basic electrical law which much later became known as *Ohm's Law.* What Ohm did was to develop the idea of voltage as the driver of electric 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.

1827:

- Felix Savary (1787–1841) was the first experimenter to note oscillatory discharges from capacitors. He did not attach an inductor. He also assisted Ampère in many of his experiments.

1828:

- British baker George Green (1793–1841) generalized and extended the work of Lagrange, Laplace, and Poisson and attached the name *potential* to their scalar function, which was first devised by the Swiss-Russian mathematician Leonhard Euler (1707–1783) in 1744. He showed how to connect the surface and the volume integrals, what is now known as Green's theorem. He became an undergraduate student at Cambridge in October 1833 at the age of 40! He also developed the theory of electrostatic screening.

1831:

- Faraday showed that changing currents in one circuit induced currents in a neighboring circuit and illustrated that they can all be explained by the idea of changing magnetic flux introduced earlier by Niccolò Cabeo and Petrus Peregrinus (see Section 1.2). He, thus, produced electricity from magnetism.
- Ukrainian mathematician and physicist Mikhail Vassilievitch Ostrogradsky (1801–1861) rediscovered the divergence theorem of Lagrange, Gauss, and Green.

1832:

- Antoine-Hippolyte Pixii (1808–1835), an instrument maker of Paris, France, built the first direct current (DC) motor.

1834:

- Jean-Charles Athanase Peltier (1785–1845), a French watchmaker who gave up his profession at the age of thirty to carry out experimental physics, discovered the converse of Seebeck's thermoelectric effect. He found that current driven in a circuit made of dissimilar metals caused the different metals to be at different temperatures.
- Heinrich Friedrich Emil Lenz (1804–1865), a physicist from Estonia, formulated his rule for determining the direction of Faraday's induced currents. In its original form, it was a law for force rather than a law for an induced electromotive force (EMF): *Induced currents flow in such a direction as to produce magnetic forces that try to keep the magnetic flux the same.* Thus, Lenz predicted that if one pulled a conductor into a strong magnetic field, it will be repelled and it will be opposed if one would pull a conductor out of a strong magnetic field.

1836:

- John Frederic Daniell (1790–1845), an English self-taught chemist, proposed an improved electric cell that supplied an even current during continuous operation.

1837:

- Faraday discovered the idea of the dielectric constant.

1838:

- Faraday showed that the effects of induced electricity in insulators are analogous to induced magnetism in magnetic materials. In this way the terms $\boldsymbol{P}$, $\boldsymbol{D}$, and ε were realized, where $\boldsymbol{P}$ represents the polarizability, $\boldsymbol{D}$ for the electric displacement, and ε the permittivity of the medium. He formulated his notion of lines of force criticizing action at a distance.

1841:

- English physicist James Prescott Joule (1818–1889) showed that energy was conserved in electrical circuits involving current flow, thermal heating, and chemical transformations.

1843:

- Faraday proved experimentally the conservation of charge.
- The English physicist and inventor Sir Charles Wheatstone (1802–1875) is most famous for the *Wheatstone Bridge*, but he never claimed to have invented it. However, he did more than anyone else to invent uses for it, when he *found* the description of the device in 1843. The first description of the bridge was done by the English mathematician Samuel Hunter Christie (1784–1865) in 1833.

1845:

- German scientist Franz Neumann (1798–1895) connected (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, and found a potential function from which the induced electric field could be obtained, namely the vector potential $\boldsymbol{A}$ (in the Coulomb gauge), thus discovering the result which Maxwell wrote later on as $\boldsymbol{E} = -\nabla\phi - \partial \boldsymbol{A}/\partial t$, where $\boldsymbol{E}$ stands for the electric field, ϕ for the scalar electric potential, $\boldsymbol{A}$ for the magnetic vector potential, and t for time. He also derived the formula for mutual inductance for equal parallel coaxial polygons of wire.

1846:

- German physicist Wilhelm Eduard Weber (1804–1891) combined Ampère's analysis, Faraday's experiments, and the assumption of the German physicist and philosopher Gustav Theodor Fechner (1801–1887) 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 stimulated much work on electromagnetic theory, which eventually leads to the work of Maxwell and the Danish physicist Ludwig Lorenz (1829–1891). It also inspired a new look at gravitation by William Thomson (Lord Kelvin, 1824–1907) to see if a velocity-dependent correction to the gravitational energy could account for the precession of Mercury's perihelion.
- William Thomson showed that Neumann's electromagnetic potential $\boldsymbol{A}$ is, in fact, the vector potential from which $\boldsymbol{B}$ may be obtained via $\boldsymbol{B} = \nabla \times \boldsymbol{A}$.

1847:

- German physiologist and physicist Hermann Ludwig Ferdinand von Helmholtz (1821–1894) wrote a memoir *On the Conservation of Force* which emphatically stated the principle of conservation of energy. He described:

> *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 regarded it as too speculative and rejected it for publication in *Annalen der Physik*. He also suggested electrical oscillation six years before William Thomson theoretically calculated this process, and ten years before the German physicist Berend Wilhelm Feddersen (1832–1918) experimentally verified it.

1848:

- German physicist Gustav Robert Kirchhoff (1824–1887) extended Ohm's work to conduction in three dimensions, gave 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 showed that in the steady state electrical currents distribute themselves so as to minimize the amount of Joule heating. He published his circuital laws in 1850.

1854:

- Faraday cleared 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.
- William Thomson, in a letter to the Irish mathematical physicist George Gabriel Stokes (1819–1903), gives the telegrapher's equation ignoring the inductance: $\partial^2 V / \partial x^2 = RC\, \partial V / \partial t$, where x is the spatial variable, R is the cable resistance per unit length, and C is the capacitance per unit length. Since this is the diffusion equation, the signal does not travel at a definite speed.
- German mathematician Georg Friedrich Bernhard Riemann (1826–1866) made an unpublished conjecture about the connection between electricity, galvanism, light, and gravity.

1855:

- Weber and the German physicist Rudolf Hermann Arndt Kohlrausch (1809–1858) determined the value of the speed of light as 3.1×10^8 meters per second based on a comparison of the measures of the charge of a Leyden jar, as obtained by a method depending on electrostatic attraction, and by a method depending on the effects of the current produced by discharging the jar.

1857:

- Kirchhoff derived the equation for an aerial coaxial cable where the inductance is important and derived the complete telegraphy equation, including solving for the circuit parameters and not by components R, L,

C and G as done later by the English physicist and electrical engineer Oliver Heaviside (1850–1925). He observed that the wave propagates with a velocity very close to the speed of light. Kirchhoff noticed the coincidence and is, thus, the first to discover that electromagnetic signals can travel at the speed of light.

1858:

- Riemann generalized Weber's unification of various theories and derived his solution using the wave function of an electrodynamical potential. He also finds the correct velocity of light. He claimed to have found the connection between electricity and optics. The results were published posthumously in 1867.

1859:

- Raymond Gaston Planté (1834–1889), a French physicist, built the first accumulator.

1862:

- Frenchmen Marcel Deprez (1843–1918), an electrical engineer, and Jacques-Arsène d'Arsonval (1851–1940), physicist and a physician, developed the d'Arsonval galvanometer.

1865:

- Scottish physicist and mathematician James Clerk Maxwell (1831–1879) wrote 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 becomes evident. He showed that the entire magnetic field intensity $\boldsymbol{H}$ around the boundary of any surface measures the quantity of electric current passing the surface. The equations $\nabla \cdot (\varepsilon E) = 4\pi\rho$, $\nabla \times \boldsymbol{A} = \boldsymbol{B}$, and $\nabla \times \boldsymbol{H} = 4\pi \boldsymbol{J}$ appear in this memoir only in scalar forms and not in the vector forms, which were first written by Heaviside.

1867:

- Danish physicist Ludwig Lorenz (1829–1891) developed an electromagnetic theory of light in which the scalar and vector potentials, in retarded form, are the starting point. This was also suggested by Riemann in 1858, but his papers were published posthumously in 1867. He showed that these retarded potentials each satisfy the wave equation and that Maxwell's equations for the fields $\boldsymbol{E}$ and $\boldsymbol{H}$ 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 was able to derive Maxwell's equations from his retarded potentials, he did not subscribe to Maxwell's view that light involves electromagnetic waves in the aether. He felt, rather, that the fundamental basis of all luminous vibrations are electric currents, arguing that space has enough matter in it to support the necessary currents.

1870:

- Helmholtz derived the correct laws of reflection and refraction from Maxwell's equations by using the following boundary conditions: $\boldsymbol{D}_n$, $\boldsymbol{E}_t$, and $\boldsymbol{B}_n$, i.e., the normal component of vector $\boldsymbol{D}$, the tangential component of vector $\boldsymbol{E}$, and the normal component of vector $\boldsymbol{B}$, are continuous at material interfaces which are non-conductors. Once these boundary conditions are taken into account Maxwell's theory is just a repeat of the theory of the Irish mathematical physicist James MacCullagh (1809–1847) (see Section 1.4). The details were not given by Helmholtz himself, but appeared rather in the dissertation of the Dutch physicist Hendrick Antoon Lorentz (1853–1928).

1874:

- Irish physicist George Johnstone Stoney (1826–1911) estimated the charge of an electron to be 10^{-20} Coulombs and introduced the term *electron*.

1876:

- American physicist Henry Augustus Rowland (1848–1901) performed an experiment inspired by Helmholtz which showed for the first time that moving electric charge is the same thing as an electric current.

1879:

- Edwin Herbert Hall (1855–1938) performed an experiment that was suggested by Rowland and discovered the *Hall Effect*, including its theoretical description by means of the *Hall term* in Ohm's law.

1880:

- Rowland showed 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. His earlier work, the first demonstration that a charged body in motion produces a magnetic field, attracted much attention.

1881:

- English physicist Sir Joseph John Thomson (1856–1940) attempted 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.
- Irish mathematical physicist George Francis FitzGerald (1851–1901) pointed 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 made the separate effect of the displacement current disappear.
- Helmholtz, in a lecture in London, pointed 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.

1883:

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

1884:

- English applied mathematician Sir Horace Lamb (1848–1934) and the English physicist, mathematician and electrical engineer Oliver W. Heaviside (1850–1925) analyzed the interaction of oscillating electromagnetic fields with conductors and discovered the effect of skin depth.
- British physicist John Henry Poynting (1852–1914) showed that Maxwell's equations predict that energy flows through empty space with the energy flux given by $\boldsymbol{E}\times\boldsymbol{B}/(4\pi)$. He also investigated energy flow in Faraday fashion by assigning energy to moving tubes of electric and magnetic flux.
- German physicist Heinrich Rudolf Hertz (1857–1894) asserted that E made by charges and E made by changing magnetic fields are identical. Working from dynamical ideas based on this assumption and some of Maxwell's equations, Hertz was able to derive the rest of them. He showed in the limit Helmholtz's theories become Maxwell's equations. He wrote Maxwell's equations in *scalar form* (12 in number, instead of Maxwell's 20 equations in scalar form) by discarding the concept of *aether* introduced by Maxwell and starting from the *sources* rather than the *potentials* as Maxwell did.

1885:

- The Ganz Company of Budapest patented the *electric transformer*, following joint research by the Austrian-Hungarian electrical engineer Károly Zipernowski (1835–1942), the Hungarian electrical engineer Miksa Déri (1854–1938), and the Hungarian mechanical engineer Ottó Titusz Bláthy (1860–1939).

1886:

- Heaviside expressed Maxwell's equations in vector form using the notation of gradient, divergence, and curl of a vector. The comment of FitzGerald about them is:

  > *Maxwell's treatise is cumbered with the debris of his brilliant lines of assault, of his entrenched camps, of his battles. Oliver Heaviside has cleared these away, has opened up a direct route, has made a broad road, and has explored a considerable trace of country.*

  Heaviside introduced the term *impedance* as the ratio of voltage over current.

1887:

- Hertz found that ultraviolet light falling on the negative electrode in a spark gap facilitates conduction by the gas in the gap. This was the first demonstration of photo-electricity. Hertz established experimentally the existence of radio waves.

1888:

- Hertz discovered that oscillating sparks can be produced in an open secondary circuit if the frequency of the primary is resonant with the secondary. He used 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 showed that his electric radiations, when passed through a slit in a screen, exhibit diffraction effects. Polarization effects using a grating of parallel metal wires were also observed. This is one of the most beautiful experiments performed in physics and it established Maxwell's theory, and prediction and generation of electromagnetic waves. Hertz produced, transmitted, and detected electromagnetic waves of wavelength 5 m and 50 cm. He used reflectors at the transmitting and receiving positions to concentrate the wave into a beam.
- German physicist Wilhelm Conrad Röntgen (1845–1923) showed that when an uncharged dielectric is moved at right angles to $\boldsymbol{E}$, a magnetic field is produced.

1889:

- Hertz presented the theory of radiation from his oscillating spark gap. He was the first to obtain a solution of Maxwell's equation with an electric source: this was the introduction of what we call today the *Hertz vector*.
- Heaviside found the correct form for the electric and magnetic fields of a moving charged particle, valid for all speeds $v < c$, where c stands for the velocity of light.
- FitzGerald suggested that the speed of light is an upper bound for any possible speed.
- English physicist John William Strutt (Lord Rayleigh, 1842–1919) presented a model of radiation in terms of wave propagation.

1890:

- FitzGerald used the retarded potentials of Lorenz to calculate the electric dipole radiation from Hertz's radiator.

1892:

- Dutch physicist Hendrik Antoon Lorentz (1853–1928) presented his electron theory of electrified matter and the aether. This theory combines Maxwell's equations, with the source terms ρ and $\boldsymbol{J}$, with the Lorentz force law, and the acceleration $\boldsymbol{f}$ of charged particles as: $m\boldsymbol{f} = q\boldsymbol{E} + q\boldsymbol{v} \times \boldsymbol{B}$, where m is the mass of a particle having a charge q and a velocity v. Lorentz concluded that the "null" result obtained by the Prussian-American physicist Albert Abraham Michelson (1852–1931) and the American chemist Edward Williams Morley (1838–1923) (see Section 1.4) was caused by an effect of contraction made by the aether on their apparatus and introduced the length contraction equation.

1895:

- The reciprocity theorem for electric waves was clearly stated and proved by Lorentz.

1.4 DEVELOPMENT OF THE THEORY OF LIGHT

The development of the theory of light is traced back to prehistoric times.

12,000 BC:
- Earliest known use of oil burning lamps.

2000–1000 BC:
- Mirrors found in Egyptian tombs.

900–600 BC:
- The Babylonians made convex lenses from crystals.

~500 BC:
- Pythagoras (582–500 BC) of Samos, Ionia, a Greek philosopher and mathematician, put forth the particle theory of light that assumed that every visible object emits a steady stream of particles that bombarded the eye. He said light consists of rays that acting like fillers travel in straight lines from the eyes to the object.
- Empedocles (492–432 BC) of Acragas, Sicily, a Greek philosopher and poet, postulated an interaction between rays from the eyes and rays from a source such as the sun.

~400 BC:
- Plato (427–347 BC) of Athens, Greece, a philosopher, belonged with respect to this matter to the Pythagoras school of thought.
- Aristotle (384–322 BC) of Stageria, Macedonia, a philosopher, concluded that light was like a wave and therefore differed from the prevalent school of the Pythagoras school of thought.

~300 BC:
- Euclid (325–265 BC) of Alexandria, Egypt, a Greek mathematician, wrote among many other works, *Optica*, dealing with vision theory and perspective. He defined the laws of reflection and refraction and stated that light travels in straight lines.

280 BC:
- The Egyptians built the first lighthouse.
- The Chinese used optical lenses and were the first to use corrective lens.

150 BC:
- Convex lenses were in existence at Carthage during this time.

1st century AD:
- Hero of Alexandria, a Greek inventor, published *Catoptrica* where the law of reflection relating the angle of incidence equal to the angle of reflection was demonstrated.

2nd century:
- Claudius Ptolemy (100–170) from Alexandria, a Greek astronomer and geographer, wrote on optics, derived the law of reflection from the assumption that light rays traveled in straight lines (from the eyes), and tried to establish a quantitative law of refraction.

1000:

- Abu Ali al-Hasan Ibn al-Haitham (Alhazen) (965–1038) of Basra, Persia, an Arab mathematician, wrote *Kitab al-Manazir* [translated into Latin as *Opticae Thesaurus Alhazeni* in 1270 by the Polish friar, theologian and scientist Erazm Ciolek Witelo (1230–1280)] on optics, dealing with reflection, refraction, lenses, parabolic and spherical mirrors, aberration and atmospheric refraction. Al-Haitham argued that sight is due only to light entering the eye from an outside source and there were no beam emanating from the eye itself. He gave an example of the pin-hole camera. He used spherical and parabolic mirrors and was aware of spherical aberration.

1093:

- Chinese philosopher, astronomer and mathematician Shen Kua (1031–1095) wrote *Meng ch'i pi t'an* (Brush Talks from Dream Brook) where he discussed concave mirrors and focal points. He noted that the image in a concave mirror is inverted.

1220:

- English theologian and scientist Robert Grosseteste (1168–1253) wrote on optics and light, experimenting with lens and mirrors. In his work *De Iride* (On the Rainbow) and *De Luce* he wrote:

> *This part of optics, when well understood, shows us how we may make things a very long distance off appear as if placed very close, and large near things appear very small, and how we may make small things placed at a distance appear any size we want, so that it may be possible for us to read the smallest letters at incredible distances, or to count sand, or seed, or any sort or minute objects.*

1270:

- English philosopher Roger Bacon (1214–1294), a student of Grosseteste, was the first to apply geometry to study optics. He considered that the speed of light is finite and propagated in the medium similar to that of sound. In *Opus Malus*, he discusses the magnifying glass, eyeglasses and the telescope. He followed the work of Alhazen and spoke of convex and concave lenses. He postulated that the color of the rainbow was due to the reflection and refraction of sunlight through the rain drops.
- Polish theologian and scientist Erazm Ciolek Witelo (1230–1280) wrote *Perspectiva* treating geometric optics, including reflection and refraction, which became the standard text for several centuries. He also reproduced the data given by Ptolemy on optics, though he was unable to generalize or extend the study.
- Eyeglasses, convex lenses for the far-sighted, were first invented in or near Florence (as early as the 1270s or as late as the late 1280s – concave lenses for the near-sighted appeared in the late 15th century).

1275:

- German Dominican scholar, scientist, philosopher, and theologian Albert Magnus (later St. Albertus Magnus) studied the rainbow effect of light and speculated that the velocity of light is extremely fast but finite.

1304:

- German Dominican monk Theodoric (Dietrich) of Freiberg proposed the hypothesis that each raindrop in a cloud makes its own rainbow. He verified his hypothesis by observing the diffraction of sunlight through a circular bottle. The French physicist, physiologist, mathematician, and philosopher René Descartes (1595–1650) presents a nearly identical theory roughly 350 years later.

1500:

- Italian renaissance painter, architect, engineer, mathematician, musician, inventor, anatomist, sculptor, and philosopher Leonardo da Vinci (1452–1519) mentioned diffraction in his notebooks and studied reflection, refraction, and mirrors.

1590:

- Dutch lens makers, Hans Janssen and his son Zacharias Janssen (1580–1638) invented the first compound (twin lens) microscope.

1593:

- Giambattista della Porta (1540–1615), a natural philosopher, described the use of convex lens in order to improve the formation of images.

1604:

- Austrian mathematician and astronomer Johannes Kepler (1571–1630) developed the inverse square law for light and claimed that the speed of propagation is infinite.

1609:

- The Italian astronomer and physicist Galileo Galilei (1564–1642) from Pisa, developed a telescope modeled after the German-Dutch lens maker Hans Lippershey (1520–1619).

1611:

- Kepler discovered total internal reflection.

1618:

- Italian Jesuit physicist, mathematician, and geometer Francesco Maria Grimaldi (1618–1663) discovered diffraction patterns of light and became convinced that light was a wave-like phenomenon. In 1665, in a posthumous report, it was found that he gave the name of diffraction to the bending of light around opaque bodies.

1621:

- Lawyer and mathematician Willebrord van Roijen Snell (1580–1626) from Leiden, The Netherlands, experimentally determined the law of angles of incidence and reflection for light and for refraction between two media. He did not publish his discovery, which remained unknown till 1703 when it was published by the Dutch mathematician and physicist Christiaan Huygens (1629–1695).

1630:

- Vincenzo Cascariolo, a shoemaker in the city of Bologna, Italy, discovered fluorescence.

1637:

- French physicist, physiologist, mathematician, and philosopher René Descartes (1596–1650) published *La Dioptrique* explaining the formation of the rainbow and the laws of reflection and refraction. He theorized that light is a pressure wave flowing through the second of his three types of matter of which the universe was made. He invented properties of this fluid that made it possible to calculate the reflection and refraction of light. The *modern* notion of the aether was born. He did not believe in action at a distance and also thought that the velocity of light was infinite.

1638:

- Galileo Galilei attempted to measure the speed of light by a lantern relay between distant hilltops. He got a very large answer.

1657:

- French lawyer and mathematician Pierre de Fermat (1601–1665) showed that the principle of least time was capable of explaining refraction and reflection of light. Fighting with the Cartesians began. This principle for reflected light was anticipated long ago by Hero of Alexandria.

1667:

- English inventor, natural philosopher, experimental scientist, physicist, and architect Robert Hooke (1635–1703) reported 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 the Irish philosopher, physicist, and chemist, Robert Boyle (1627–1691). These rings are now known as Newton's rings.

1669:

- Danish scientist and physician Rasmus Bartholin (1625–1698) discovered polarization by observing light through Iceland spar, which is a naturally occurring transparent crystal (optical quality calcite, $CaCO_3$). It separates an image into two displaced images when looked through along certain directions. Bartholin, not only saw double, but also performed some experiments and wrote a 60-page memoir about the results. This was the first scientific description of a polarization effect (the images are polarized perpendicular to each other).

1671:

- English scientist and mathematician Sir Isaac Newton (1642–1727) destroyd 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 argued against light being a vibration of the aether, preferring that it be something else that was capable of traveling through the aether. He did not insist that this something else consisted of particles, but allowed that it may be some other kind of emanation or impulse.

1672:

- Newton was the first to publish that white light was composed of different colors that were refracted at different angles of the prism.

1675:

- Ole Christensen Römer (1644–1710), the Danish astronomer, demonstrated the finite speed of light via observations of the eclipses of the satellites of Jupiter. He calculated the speed as 225,000 km per second.

1678:

- Dutch mathematician and physicist Christiaan Huygens (1629–1695) introduced his famous construction and principle defending the wave theory of light. He discovered the polarization of light by double refraction in calcite. To him light was still a longitudinal wave. He also accepted the presence of an all pervading medium called aether. He did not publish his work till 1690.

1690:

- Huygens, in *Traité de Lumiere*, provided the first numerical value for the speed of light of 2.3×10^8 m/s as opposed to Römer, who estimated it from observations.

1704:

- Newton published *Opticks* arguing that the corpuscles of light created waves in the aether.

1720:

- Wilhelm Jacob s'Gravesande (1688–1742), a Dutch physicist, was the proponent of the corpuscular theory of light and spread it after Newton's death.

1728:

- English astronomer James Bradley (1693–1762) showed that the orbital motion of the Earth changed the apparent motions of the stars in a way that was consistent with light having a finite speed of travel.

1800:

- Sir Frederick William Herschel (also known as Wilhelm Friedrich Herschel) (1738–1822), a German born British astronomer, discovered the infrared region of sunlight.

1801:

- English physicist Thomas Young (1773–1829) correctly concluded that light must be a transverse wave. His wave theory also explained the interference of light.
- German astronomer Johann Georg von Soldner (1776–1833) made a calculation for the deflection of light by the sun assuming a finite speed of light corpuscles and a non-zero mass. The result, 0.85 arc-sec, was rederived independently by English physicist Sir Henry Cavendish (1731-1810) and in 1911, by the German-Swiss-American scientist and physicist Albert Einstein (1879–1955), but went unnoticed until 1921.
- German physicist Johann Wilhelm Ritter (1776–1810) found that sun emits invisible ultraviolet radiation.

1803:

- Thomas Young explained the fringes at the edges of shadows by means of the wave theory of light. He explained the formation of colored bands in soap films:

  > *Thus, when a film of soapy water is stretched over a wine glass, and placed in a vertical position, its upper edge becomes extremely thin, and appears nearly black, while the parts below are divided by horizontal lines into a series of colored bands ...*

  and Newton's rings:

  > *... and when two glasses, one of which is slightly convex, are pressed together with some force, the plate of air between them exhibits the appearance of colored rings, beginning from a black spot at the center, and becoming narrower and narrower, as the curved figure of the glass causes the thickness of the plate of air to increase more and more rapidly. ...*

  establishing that there was an 180° change of phase when light was reflected from the surface of a denser medium, e.g., light traveling in air reflecting from the surface of glass or metal.

1808:

- French mathematician Pierre-Simon Laplace (1749–1827) gave an explanation of double refraction using the particle theory, which Young attacked as improbable.
- French physicist Étienne Louis Malus (1775–1812) discovered that light reflected at certain angles from transparent substances as well as the separate rays from a double-refracting crystal had the same property of *polarization*. In 1810, he received the prize of the French Académie des Sciences and embolded the proponents of the particle theory of light because no one saw how a wave theory can make waves of different polarizations.

1811:

- French physicist Dominique François Jean Arago (1786–1853) showed that some crystals alter the polarization of light passing through them.
- The French physicist Augustin-Jean Fresnel (1788–1827) and Arago discovered that two beams of light polarized in perpendicular directions do not interfere.

1812:

- French physicist Jean-Baptiste Biot (1774–1862) showed that Arago's crystals rotate the plane of polarization about the direction of propagation.

1814:

- Fresnel independently discovered the interference of light and explained it in terms of the wave theory.

1815:

- Scottish scientist and writer David Brewster (1781–1868) established his law of complete polarization upon reflection at a special angle now known as Brewster's angle.

1816:

- Arago, an associate of Fresnel, visited Young and described 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 saw that it can be explained if light is transverse instead of longitudinal. This idea is communicated to Fresnel in 1818 and he immediately saw how it clears up many of the remaining difficulties of the wave theory.

1819:

- French Académie des Sciences proposed as their prize topic for the 1819 Grand Prix a mathematical theory to explain diffraction. Fresnel wrote a paper giving the mathematical basis for his wave theory of light and in 1819 the committee, with Arago as chairman, and including Poisson, Biot, and Laplace, met to consider his work. It was a committee which was not well disposed to the wave theory of light, most believing in the corpuscular model. However, Poisson was fascinated by the mathematical model which Fresnel proposed and succeeded in computing some of the integrals to find other consequences. He wrote

> *Let parallel light impinge on an opaque disk, the surrounding being perfectly transparent. The disk casts a shadow – of course – but the very centre of the shadow will be bright. Succinctly, there is no darkness anywhere along the central perpendicular behind an opaque disk (except immediately behind the disk).*

This was a remarkable prediction, but Arago asked that Poisson's predictions based on Fresnel's mathematical model be tested. Indeed the bright spot was seen to be there exactly as the theory predicted. Arago stated in his report on Fresnel's entry for the prize to the Académie des Sciences :

> *One of your commissioners, M. Poisson, had deduced from the integrals reported by [Fresnel] the singular result that the centre of the shadow of an opaque circular screen must, when the rays penetrate there at incidences which are only a little more oblique, be just as illuminated as if the screen did not exist. The consequence has been submitted to the test of direct experiment, and observation has perfectly confirmed the calculation.*

Fresnel was awarded the Grand Prix and his work was a strong argument for a transverse wave theory of light.

1823:

- Physicist Joseph von Fraunhofer (1787–1826), from Germany, published his theory of diffraction.

1825:

- Fresnel showed that combinations of waves of opposite circular polarization traveling at different speeds can account for the rotation of the plane of polarization.

1827:

- Fresnel published a decade of research on 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.
- French engineer and physicist Claude-Louis Marie Henri Navier (1785–1836) published the correct equations for vibratory motions in one type of elastic solid leading to the well known Navier-Stokes equations (the second name refers to the Irish mathematical physicist George-Gabriel Stokes, 1819–1903). This begins the quest for a detailed mathematical theory of the aether based on the equations of continuum mechanics.

1828:

- French mathematician Augustine-Louis Cauchy (1789–1857) presented 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. He wrote 789 mathematical papers!

1837:

- British mathematician George Green (1793–1841) attacked 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 derived the correct boundary conditions from general dynamical principles. This advance makes the elastic theories not quite fit with light.

1839:

- Irish mathematical physicist James MacCullagh (1809–1847) invented 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 $\boldsymbol{E}$ and $\boldsymbol{B}$ in Maxwell's theory.
- Irish-Scottish physicist William Thomson (Lord Kelvin, 1824–1907) removed 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.

- Cauchy and Green presented more refined elastic aether theories. Cauchy does it by removing the longitudinal waves by postulating a negative compressibility, and Green using an involved description of crystalline solids.

1845:

- British scientist Michael Faraday (1791–1867) discovered 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).

1846:

- English astronomer Sir George Biddell Airy (1801–1892) modified MacCullagh's elastic aether theory to account for Faraday rotation.
- Faraday, inspired by his discovery of the magnetic rotation of light, wrote a short paper speculating that light might be electromagnetic in nature. He thought it might be transverse vibrations of his beloved field lines.

1849:

- French physicist Armand–Hippolyte-Louis Fizeau (1819–1896) repeated Galileo's hilltop experiment (9 km separation distance) with a rapidly rotating toothed wheel and measured the velocity of light, as $c = 3.15\times10^8$ m/s.
- Irish mathematical physicist George Gabriel Stokes (1819–1903) published a long paper on the dynamical theory of diffraction in which he showed that the plane of polarization must be perpendicular to the direction of propagation.

1850:

- French applied physicist Jean-Bernard-Léon Foucault (1819–1868), improved on Fizeau's measurement and used his apparatus to show that the speed of light is less in water than in air. He also measured the velocity of light, finding a value that is within 1 percent of the true figure.
- Stokes's law relating to the curl of a vector is stated without proof by Lord Kelvin. Later, Stokes assigns the proof of this theorem as part of the examination for the Smith's Prize. Presumably, he knew 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 the Stokes's theorem.

1867:

- French physicist and mathematician Valentin Joseph Boussinesq (1842–1929) suggested 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.
- German mathematician George Friedrich Bernhard Riemann (1826–1866) proposes a simple electric theory of light in which Poisson's

equation is replaced by $\nabla^2 V - (1/c^2)\partial^2 V/\partial t^2 = -4\pi\rho$.

1872:

- French physicist Éleuthère Élie Nicolas Mascart (1837–1908) looked 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 was found with a sensitivity of $v/c \approx 10^{-5}$.

1873:

- Scottish physicist and mathematician James Clerk Maxwell (1831–1879) published his *Treatise on Electricity and Magnetism*, which discusses everything known at the time about electromagnetism from the viewpoint of Faraday. He states:

> *In several parts of this treatise an attempt has been made to explain electromagnetic phenomena by means of mechanical action transmitted from one body to another by means of a medium occupying the space between them. The undulatory theory of light also assumes the existence of a medium. We have now to show that the properties of the electromagnetic medium are identical with those of the luminiferous medium.*
>
> *But the properties of bodies are capable of quantitative measurement. ... If it should be found that the velocity of propagation of electromagnetic disturbances is the same as the velocity of light, and this not only in air, but in other transparent medium then we have strong reasons for believing that light is an electromagnetic phenomenon, and the combination of the optical with the electrical evidence will produce a conviction of the reality of the medium similar to that which we obtain, in the case of other kinds of matter, from the combined evidence of the senses.*

- Maxwell also produced the first color picture.

1881:

- Prussian-American physicist Albert Abraham Michelson (1852–1931) and the American chemist Edward Williams Morley (1838–1923) attempted to measure the motion of the Earth through the aether by using interferometry. They found no relative velocity. Michelson interpreted this result as supporting Stokes's hypothesis in which the aether in the neighborhood of the Earth moves at the velocity of Earth.

1.5 WHO WAS MAXWELL?

The name of James Clerk Maxwell is synonymous with the development of modern physics. He laid the basic foundation for electricity, magnetism, and optics [12-14]. The theory on electromagnetism is one of the few theories where the equations have not changed since its original conception, whereas their interpretations have gone through revolutionary changes at least twice [15-17]. The first revolution was by Hertz and Heaviside and the second by Larmor, as discussed in the next section. Maxwell's work on electromagnetic theory was only a small part of his research. As the English physicist and mathematician Sir James Hopwood Jeans (1877–1946) [18] pointed out: *In his hands electricity first became a mathematically exact science and the same might be said of other larger parts of Physics*. In whatever area he worked, he brought new innovation. He published five books and approximately 100 papers. Maxwell can be considered as one of the world's greatest scientists even if he had never worked on electricity and magnetism. His influence is everywhere, which surprisingly is quite unknown to most scientists and engineers! As the German physicist Max Karl Ernst Ludwig Planck (1858–1947) [18] said:

> *His name stands magnificently over the portal of classical physics and we can say this of him: by his birth James Clerk Maxwell belongs to Edinburgh, by his personality he belongs to Cambridge, by his work he belongs to the whole world.*

Here we provide ***a cursory overview of some of his achievements***, which are still in vogue today. Hopefully, this will make one more familiar with Maxwell, as electromagnetics [23], the physical basis of wireless, took shape under him. As pointed out in [12], the name of Maxwell invokes according to well known scientists: *One scientific epoch ended and another began with James Clerk Maxwell* – Albert Einstein, and *From a long view of the history of mankind – seen from, say, ten thousand years from now – there can be little doubt that the most significant event of the nineteenth century will be judged as Maxwell's discovery of the laws of electrodynamics* – Richard Feynman.

His first publication *On the Description of Oval Curves, and those having a plurality of foci* was done at the age of 14 in 1846. It dealt with drawing curves on a piece of paper using pins, string, and pencil. He varied the number of times he looped the string around each pin to generate various egg shaped graphs. Earlier, René Descartes had discovered the same set of bi-focal ovals, but Maxwell's results were more general and his construction method much simpler [11]. It turned out that such constructions have significant practical applications in optics. He also wrote in 1855 on *Description of a new form of Platometer*, an instrument for measuring areas of plane figures drawn on a paper.

In 1855, he published the first-part of his paper *On Faraday's Lines of Force*, and the second part in the following year. His objective was: *to find a physical analogy which will help the mind to grasp the results of previous investigations without being committed to any theory founded on the physical science from which that conception is borrowed so that it is neither drawn aside from the subject in the pursuit of analytical subtleties nor carried beyond the truth by a favorite hypothesis*. The laws of electricity were compared with the properties of an incompressible fluid, the motion of which was retarded by a force proportional to the velocity, and the fluid is supposed to posses no inertia.

In the latter part of the paper he proceeded to consider the phenomenon of Electromagnetism and showed how the laws discovered by Ampère lead to conclusions identical with that of Faraday. *On Physical Lines of Force* he further speculated that the magnetic field were occupied by molecular vortices the axes of which coincide with the lines of force.

In 1855, he published a paper on *Experiments on Colour as Perceived by the Eye*. He wrote two papers on the sensitivity of the retina to color. To achieve this he developed equipments to look into the eye which was a modification of the ophthalmoscope originally developed by Helmholtz [13]. At the point of the retina where it is intersected by the axis of the eye there is a *yellow spot*. Maxwell observed that the nature of the spot changes as a function of the quality of the vision. The macular degeneration of the eye affects the quality of vision and is the leading cause of blindness in people over 55 years old. Today, the extent of macular degeneration of the retina is characterized by this *Maxwell spot test*. Maxwell also worked on the generation of white light by mixing different colors and in 1860, published the paper *On the Theory of Compound Colors and its Relations to the Colors of the Spectrum*. In this, he extended the work of Young who first postulated only three colors, red, green and violet are necessary to produce any color including white and not all the colors of the spectrum are necessary as first illustrated by Newton. Maxwell created a color triangle and illustrated that any color can be generated with a mixture of any three primary colors and that a normal eye has three sorts of receptors as illustrated in his 1861 paper *On the Theory of Three Primary Colors*. He chose the three primary colors as red, green, and blue colored light. Today, color television works on this principle, but Maxwell's name is rarely mentioned [11]. However, other choices for the primary colors are equally viable. He demonstrated these principles by pasting different color papers on a spinning top. He provided a methodology of generating any color represented by a point inside a triangle whose vertex represented the three primary colors. The new color is generated by mixing the three primary colors in a ratio determined by the respective distance of the point representing the new color from the vertices of the triangle. In the present time, this triangle is called a chromatist diagram and differs in details from his original. He took the first color photograph in 1861. He also developed a *color box* to replace his spinning top to standardize his experiments which could generate any color by impinging sunlight through various slits of different colors. He used polarized light to reveal strain patterns in mechanical structures and developed a graphical method for calculating the forces in the framework. He was the first to show that in color blind people, their eyes are sensitive only to two colors and not to three as in normal eyes. Typically, they are not sensitive to red. He suggested using spectacles with one red lens and one green for color blind people. He was the first to develop the fish eye lens [11].

On the General laws of Optical Instruments published in 1858, Maxwell laid down the conditions which a perfect optical instrument must fulfill, and showed that if an instrument produce perfect image of an object, i.e., image free from astigmatism, curvature and distortion, for two different positions of the object, it will give perfect image at all distances.

His paper in 1858 was on the nature of Saturn's rings, which won him the Adams prize [named after the English astronomer John Couch Adams (1819–1892), the discoverer of Neptune]. It took him two years to do this work. The problem that he addressed was under what conditions the rings of Saturn would be stable if they were (1) solid, (2) fluid, or (3) composed of many separate pieces of matter. Maxwell showed that a solid ring could be stable except in one arrangement where about 80% of its mass was concentrated at one point on the circumference and the rest distributed throughout. Since telescopic observations reveal otherwise, this cannot be a possible solution. He also used a Fourier analysis to show that the ring would break up if it were of a single fluid, as waves would be generated. The only solution is that the ring consisted of separate bodies. He showed that it could vibrate in four different ways as long as its average density was low enough compared with that of Saturn. When he considered only two rings, one inside the other, he found that some arrangements were stable, but others not. Also, because of friction, he predicted that the inner ring will move inward and the outer ring outward on a very long time scale. Here, we have almost the only example of a piece of work that Maxwell himself completed and left in perfect form. Airy said that this was one of the most remarkable applications of mathematics he has ever seen [18]. His conclusions received observational confirmation 38 years later when the American astronomer James Edward Keeler (1857–1900) obtained spectroscopic proof that the outermost portions of the rings were rotating less rapidly than the inner portions [18]. He also built a hand cranked model to demonstrate the motion of the rings. Some say this research led him directly to the next topic.

Next, he worked on the kinetic theory of gases and published a paper in 1860. He tried to determine the speed with which the smell fills the air when a perfume-bottle is opened. In order to address this problem he derived the Maxwell distribution for molecular velocities. The distribution turned out to have the well-known bell-shaped curve now known as the normal distribution. This was done to represent various motions of the molecules in a single equation, representing a statistical law [11]. His discovery opened up an entirely new approach to physics, which led to statistical mechanics, to a proper understanding of thermodynamics, and to the use of probability distributions in quantum mechanics. No one before Maxwell ever applied a statistical law to a physical process. He also predicted a new law of viscosity for gases in 1860, which was a magnificent piece of work, but was not devoid of flaws. His work inspired the Austrian mathematician, physicist, and inventor of statistical mechanics Ludwig Boltzmann (1844–1906), and their works led to the *Maxwell-Boltzmann* distribution of molecular energies. In 1866, he wrote *Dynamical Theory of Gases* and produced the first statistical law of physics. He wrote a paper on Boltzmann's theorem in 1879 on the *Average Distribution of Energy* in a system of material points. This enabled people to explain the properties of matter in terms of the behavior, en masse, of its molecules. One of the ideas in the paper was the method of ensemble averaging, where the whole system is much easier to analyze, rather than dealing with individual components. Interestingly, this mode of analysis is quite prevalent nowadays in most signal processing and communications theory applications. However, his result for the specific heat of air was off from the measurement. Instead of trying to explain this discrepancy in his theory by ingenious attempts, he said: *Something essential to the complete statement of the physical theory of molecular encounters must have hitherto escaped us, and that the only thing to do was to adopt the attitude of thoroughly conscious ignorance that is the prelude to every real advance in science* [11]. He was right. The explanation came 50 years later from quantum theory. He was also the first to suggest using a centrifuge to separate gases, which is still being used in modern times.

He developed a coherent set of units of measurement of electricity and magnetism in 1863. They were later adopted almost unchanged as the first internationally accepted system of units, which became known misleadingly as the Gaussian system, which is a combination of the Electrostatic units and the Electromagnetic units. He also introduced the dimensional analysis in physics which is used currently and yet nobody wonders who first thought about it. He also produced the first standard of electrical resistance in 1868.

Sir Ambrose Fleming wrote [18]: *In electricity course, he gave us a new and powerful method of dealing with problems in networks and linear conductors. Kirchoff's corollaries of Ohm's Law had provided a means only applicable in the case of simple problems in which one could foresee the direction of flow of current in each conductor. But that was not possible in complicated networks. Maxwell initiated a new method by considering the actual current in each wire to be the difference of two imaginary currents circulating in the same direction round each mesh of the network. In this way, the difficulty of foreseeing the direction of the real currents was eliminated. The solution of the problem was then reduced to the solution of a set of linear equations and the current in any wire could be expressed as the quotient of two determinants. After Maxwell's death, in 1885 I communicated a paper to the Physical Society of London in which the method was extended so as to give an expression for the electrical resistance of any network between any two points.* One would immediately recognize this as a method for writing the loop equations that are currently available in all undergraduate textbooks dealing with electrical circuits, and yet no mention is made of Maxwell, the inventor of this technique!

When creating his standard for electrical resistance, he wanted to design a governor to keep a coil spinning at a constant rate. He made the system stable by using the idea of negative feedback. He worked out the conditions of stability under various feedback arrangements. This was the first mathematical analysis of control systems [11]. This work did not get any attention till 1940, when gun control radars were in demand during the Second World War. After the war the American mathematician Norbert Wiener (1894–1964) took things further and developed the science of cybernetics, based on his paper *On Governors* in 1868.

He wrote the *Dynamical Theory of Electromagnetism* using the Quaternion convention. However, he wrote the final equations in the scalar form even though he used the terms "curl", "convergence" and "gradient". Nowadays, convergence is replaced by its negative, which is called divergence, and the other two are still in the standard mathematical literature. These are available *On the Mathematical Classification of Physical Quantities.* Maxwell identified light with electromagnetic waves and introduced the concept of aether as the basic medium of the electromagnetic field to retain the possibility of a mechanical interpretation. He presented his first paper on the new theory before the Royal Society in 1864 and published the comprehensive *Treatise on Electricity and Magnetism* in 1873 [15].He also showed that radiation pressure from the sun exists, which has a force of 4 pounds per square mile.

In 1868 [23], *On a Method of making a Direct Comparison of Electrostatic with Electromagnetic Force; with a note on the Electromagnetic Theory of Light*, he measured the speed of light by using 2,600 batteries to produce 3,000 volts. The goal was to balance the electrostatic attraction between two charged metal plates against the magnetic repulsion between two current carrying coils and built a balance arm to do this. He got a result of 288,000 km/sec as compared to the current accepted value of 299,792.5 km/sec.

He, along with the English biologist Thomas Henry Huxley (1825–1895), was the joint scientific editor of the 9th edition of Encyclopedia Britannica. Maxwell always delivered scientific lectures for the common people using models. He also was very prolific in writing limericks, as we will see later.

He wrote a book on The *Theory of Heat* in 1871 and provided a completely new formulation of the relationships between pressure, volume, temperature, and entropy and expressed them through differential equations known as Maxwell's relations [11]. He introduced the "Maxwell demon", as termed by Lord Kelvin, i.e., the molecule-sized creature which was going to defy the second law of thermodynamics [19]. The goal was that this demon can separate low velocity molecules from high velocity ones by opening an aperture and, thus, making heat flow from a colder region to a hotter one defying the second law of thermodynamics. Hence, the demon is generating a perpetual motion machine: the machine will keep on working till the temperature difference between the two regions fell back to zero and then we would be back to where we started. This cannot really happen. And why it cannot happen, the answer according to Maxwell, is:

(1) The second law of thermodynamics is a statistical law. So that if one throws a bucket of water into the sea, one cannot get the same bucket out again as the law applies to molecules in masses and not to individuals.
(2) If we are sufficiently nimble fingered like the demon, we could break the second law. The reason we cannot is because we are not clever enough.

The Austro-Hungarian physicist Leo Szilard (1898–1964) in 1929 showed that the very act of acquiring information about a system increases its entropy proportional to the amount of information gathered. Through such work of Szilard and others, Maxwell's demon helped the creation of information theory, now an essential part of communication and computing [11].

He also wrote a paper *On Hills and Dales* in 1870, extending the work of Cayley published in 1859. The surface of the Earth has high areas or hills and low areas with a bottom point. There are also ridges, valleys, or dales, and passes. He thought that the numbers of each of these features must be somehow related by mathematical rules. His original ideas about the Earth's surface have now evolved into a branch of topology called global analysis [11].

Even though Maxwell has influenced development in many areas of physical sciences and had started a revolution in the way physicists look at the world, he is not very well known, unfortunately, outside some selected scientific communities. In fact, when the Royal Society of London held its tercentenary celebration, Queen Elizabeth II presided and praised a number of former Fellows – presumably listed by the Society. Inexplicably, Maxwell was not among them [11,12]. He has been more widely commemorated elsewhere, even in countries without a strong scientific tradition. For example, the governments of Mexico, Nicaragua, and San Marino are among those who have issued postage stamps in his honor. Some claim that the reason Maxwell was not so well known (he was not even knighted) is because he was too humble and never proselyte his theory. There may be some truth to that. In addition, there may be other reasons as outlined below.

J. J. Thomson, speaking at the centenary celebration of Maxwell, said that, according to his teacher, the mathematician William Hopkins (1793–1866) at Cambridge,

> *Maxwell was unquestionably the most extraordinary man he had met with in the whole course of his experience; that it appeared impossible for Maxwell to think wrongly on any physical subject, but that in analysis he was far more deficient. ... The public lectures were however read and he was compelled by the manuscript to keep to the track.*

In the same celebration, Sir James Jeans succinctly summarized his contributions

> *as of purely abstract in nature. As a consequence, Maxwell did not alter the face of civilization as Faraday did, or at least did not alter it so immediately or in a manner obvious to the eye. It could hardly have been written of him during his lifetime, as it was of Faraday, that our life is full of resources which are the results of his labours; we may see at every turn some proof of the great grasp of his imaginative intellect. Faraday had used his clear vision and consummate skill as an experimenter to explore those strata of nature which lie immediately under our hands; Maxwell used his clear vision and consummate skill as a theorist to explore the deeper strata in which the phenomenon of the upper strata have their origin.*

However, as Sir James Jeans pointed out [18]:

> *It was not keeping with Maxwell's methods that he should finish off a piece of work so completely that nothing could be added to it, his plan was rather to open up wide vistas which*

> *could provide work in their detailed exploration for the whole generations yet to come. ... It was his power of profound physical intuition coupled with adequate, although not outstanding mathematical technique, that lay at the basis of Maxwell's greatness.*

Sir Horace Lamb [18] said:

> *He had his full share of misfortunes with the blackboard, and one gathered the impression, which is confirmed I think by the study of his writings, that though he had a firm grasp of essentials and could formulate great mathematical conceptions, he was not very expert in the details of minute calculations. His physical instincts saved him from really vital errors.*

However, there may be an additional reason that he was not recognized during his life time for his work, which is that he had an eccentric side to his personality. He had a tendency to make insulting remarks, largely in the form of sardonic limericks [12]! During the 1874 British Association meeting at Belfast he delivered himself of several poems, in one of which he refers to members of this highly respected body in this way [20, p. 637]:

So we who sat, oppressed with science,
As British asses wise and grave,
Are now transformed to Wild Red Lions...

[The Red Lions are a club formed by members of the British association to meet for relaxation after the graver labors of the day].

And after hearing a lecture by the Scottish physicist Peter Guthrie Tait (1831–1901) in 1876, he wrote [20, p.646]:

Ye British asses, who expect to hear
Ever some new thing,
I've nothing to tell but what, I fear,
May be a true thing.

For Tait comes with his plummet and his line,
Quick to detect your
Old bosh new dressed in what you call a fine
Popular lecture.

And again in 1878 where he devoted the Rede lecture on the invention of the telephone as:

> *One great beauty of Professor Bell's invention is that the instruments at the two ends of the line are precisely alike...The perfect symmetry of the whole apparatus – the wire in the middle, the two telephones at the ends of the wire; and the two gossips at the ends of the telephones may be very fascinating to a mere mathematician, but would not satisfy the evolutionist of the Spencerian type, who would consider anything with both ends alike, to be an organism of the very low type, which must have its functions differentiated before any satisfactory integration can take place.*

It is rather amusing to note that in recent times this statement of Maxwell in many places has been used to claim that Maxwell was against the evolutionary theory of Darwin, which the British philosopher and sociologist Herbert Spencer (1820–1903) popularized [21]. However, according to Sir John Ambrose Fleming [18], who attended the lecture: *It was a brilliant discourse, illustrated by flashes of wit, apt analogies and much learning but it was not of the type most useful to convey to unscientific hearers an idea of the mode in which a telephone operates.*

Maxwell's personality often showed two additional unusual characteristics [11]. The first is that he could return to a subject, often after a gap of several years, and take it to new heights using an entirely new approach. He did this twice with electromagnetism. The second is that often his intuition led him to correct results even when he had made mistakes along the way. He was tolerant of the mistakes of others, but was very critical of the failure to be honest and open to the readers. He rebuked Poisson for telling lies about the way people make barometers and Ampère for describing only perfected experiments to demonstrate his law of force and hiding the poor experiments by which he had originally discovered the law.

1.6 WHAT WAS/IS MAXWELL'S ELECTROMAGNETIC THEORY?

Interestingly there is no clear cut answer to this question as we will see. This section is derived from the writings of several scientists who themselves modified his theory. First, we describe what Maxwell presented, followed by the modifications made by others. As elucidated by Sir James Jeans [18]

> *Maxwell pictured electromagnetic theory of light in terms of a medium whose properties could be specified completely in terms of a single mathematical constant. He saw that if the value of this constant could once be discovered, it ought to become possible to predict all phenomena of optical theory with complete mathematical precision. Maxwell showed that the constant in question ought to be merely the ratio of electromagnetic and electrostatic units of electricity and his first calculations suggested that this was in actual fact equal*

> *to the constant of the medium which measured the velocity of light.*
>
> *The first mention of the great discovery comes in a letter, which he wrote to Michael Faraday on 19th October 1861: I suppose the elasticity of a sphere to react on the electrical matter surrounding it, and press it downwards. From the determination by Kohlrausch and Weber of the numerical relation between static and the magnetic effects of electricity, I have determined the elasticity of the medium in air, and assuming that it is the same with the luminiferous aether, I have determined the velocity of propagation of transverse vibrations. The result is 193,088 miles per second. Fizeau has determined the velocity of light as 193,118 miles per second by direct experiment.*
>
> *Even though the two numbers quoted above agreed to within 30 miles per second, oddly enough both are in error by more than 6,000 miles a second. When Maxwell came to publish his paper,* A Dynamical Theory of the Electromagnetic Field, *probably the most far reaching paper he ever wrote, he gave the two velocities in terms of kilometers per second Kohlrausch and Weber (310,740,000 meters a second) and Fizeau (314,858,000 meters a second) and is nowhere near the figure. Happily he seems to have realized that the velocity of light was not at all accurately known, and so he did not allow himself to be deterred, as Newton had been, by a substantial numerical disagreement in his law of universal gravitation.*

According to English physicist Sir Oliver Lodge (1851–1940):

> *Maxwell perceived that a magnetic field was wrapped around a current, and that a current could equally well be wrapped around a magnetic field, that in fact the relation between that was reciprocal, and could be expressed mathematically by what he subsequently called* curl. *When the two fields coexisted in space, the reaction between them could be expressed as the curl of a curl, and this he simplified down to the well known wave equation, the velocity of propagation of the wave being the reciprocal of the geometric mean of an electric and a magnetic constant. This velocity for a time he called the number of electrostatic units in a magnetic unit, and proceeded to devise experiments whereby it could be measured. Experiments made by him at King's College resulted in some near approach to the velocity of light, so that thenceforth, in his mind light became an electromagnetic phenomenon. He was assisted in his ideas by an imaginative constructive model of the aether, a model with rolling wheels and sliding particles, which subsequently he dropped, presumably as being too*

> *complex for reality and remained satisfied with his more abstract equations, which were reproduced in his great* Treatise *in 1873.*

This provides one reason why Maxwell's theory was so difficult to follow. By never identifying his physical pictures with reality, Maxwell left himself free to discard one picture and adopt another as often as expediency or convenience demanded. He described his method of procedure in the following words:

> *If we adopt a physical hypothesis, we see the phenomenon only through a medium, and are liable to that blindness to facts and rashness in assumption which a partial explanation encourages. We must therefore discover some method of investigation which allows the mind at every step to lay hold of a clear physical conception, without being committed to any theory founded on physical science for which that conception is borrowed.*

Maxwell considered Faraday's line of force similar to the lines of flow of a liquid. Maxwell himself wrote to Lord Kelvin [13]:

> *I suppose that the "magnetic medium" is divided into small portions or cells, the divisions or cell walls being composed of a single stratum of spherical particles these particles being "electricity". The substance of the cells I suppose to be highly elastic both with respect to compression and distortion and I suppose the connection between the cells and the particles in the cell walls to be such that there is perfect rolling without slipping between them and that they act on each other tangentially. I then find that if the cells are set in rotation, the medium exerts a stress equivalent to a hydrostatic pressure combined with a longitudinal tension along the lines of axes of rotation. ... Thus there will be a displacement of particles proportional to the electro-motive force, and when this force is removed, the particle will recover from displacement. I have calculated the relation between the force and the displacement on the supposition that the cells are spherical and that cubic and linear elasticities are connected as in a perfect solid. I have found from this the attraction between two bodies having given free electricity on their surfaces. And then by comparison with Weber's value of the statical measure of a unit of electrical current I have deduced the relation between elasticity and density of the cells. The velocity of the transverse undulations follows from this directly and is equal to 193,088 miles per second, very nearly that for light.*

Even though the final results of the original Maxwell's theory are valid even today, however, the intermediary steps used to arrive at the conclusion was in question [16]. The first problem was associated with the definition of the charge. For example, consider a positively charged ball that is placed inside an infinite dielectric medium. Modern theory defines the positive surface charge on the surface of the conductor as seen in Figure 1.1. This charge creates an electric field which produces polarization throughout the dielectric. Next we divide the dielectric using an imaginary surface *C*. One part (*A*) of the dielectric lies between the conducting sphere and *C*; the other part (*B*) lies between *C* and goes to infinity. The innermost boundary of *A* which actually touches the sphere, according to modern theory will carry a negative polarization charge which is smaller in magnitude than the conduction charge on the sphere. The outermost boundary of *A*, characterized by the surface *C* bears a positive polarization charge numerically equal to the negative polarization charge on the inner surface of *A*. The charge on the outermost boundary of *A* is exactly compensated by a negative polarization charge on the innermost boundary of *B*, i.e., by a charge on surface *C* considered as the inner boundary of *B*. Accordingly no space charge at all exists and we have only the positive conduction charge and the numerically smaller negative polarization charge on the surface of the dielectric which is immediately adjacent to it as shown in Figure 1.1 [16]. Now if we use Maxwell's interpretation of the same situation using his quote: *The charge therefore at the bounding surface of a conductor and the surrounding dielectric; which in the old theory was called the charge of the conductor, must be called in the theory of induction (Maxwell's theory) the surface charge of the surrounding dielectric* [15, Vol. I, Art 111].

In Maxwell's theory, we begin with a displacement ***D*** which exists throughout the dielectric and which points away from the center of the sphere. Since the displacement points away from the center of the sphere, it enters *B*'s inner boundary in a direction parallel to that boundary's inward-directed normal. According to Maxwell's definition of charge, the inner boundary of *B* has a positive charge on it numerically equal to ***D*** as shown in Figure 1.2. In addition, the innermost boundary of *A* (surface *C*) coincides with the innermost boundary of *B*. Therefore, the outermost boundary of *A* has on it a negative charge equal

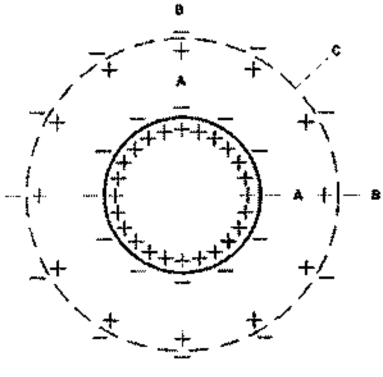

Figure 1.1. Modern picture for a conducting sphere embedded in a dielectric.

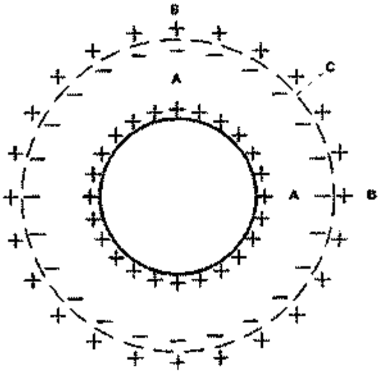

Figure 1.2. Maxwellian picture for a conducting sphere embedded in a dielectric.

and opposite to the positive charge on the inner boundary of *B* as shown in Figure 1.2. Since the boundaries coincide, no net charge can exist anywhere in the dielectric. At the surface of the sphere and the innermost boundary of the dielectric the displacement enters the dielectric boundary parallel to its inwardly directed normal and so we have on this surface a positive charge. But since no displacement at all exists within the sphere, its surface is unchanged. Consequently, the positive charge on the inner surface of the dielectric is uncompensated. The result is that what modern theory calls the positive surface charge of the conductor, Maxwell's theory called the positive surface charge of the inner surface of the dielectric [16].

Maxwell considered magnetism as a phenomenon of rotation and electric currents as a phenomenon of translation. So in any magnetic field the medium is in rotation about the lines of magnetic force. Maxwell's theory sought unity through a highly plastic set of field equations coupled to Hamilton's principle, named after the Irish mathematician William Rowan Hamilton (1805–1865). In current bearing linear circuits, Maxwell thought that the currents were linked by rigid constraints to an intervening medium called the aether. Thus, the most difficult concepts for the modern reader to grasp in the original Maxwell's theory are the concepts of "charge" and "current". In modern theory, charge is the source of the electric field and current is the source of the magnetic field. In his theory, charge is produced by the electric field; current, in the usual sense, is the rate of change of charge over time, and is only indirectly related to the magnetic field. Therefore, in Maxwellian theory, charge is a discontinuity of the displacement ***D*** and not in ***E***. Maxwell's goal was to create a theory of electromagnetism which made no use whatsoever of the microstructure of the matter. To Maxwell, the conduction current was effectively a continuous series of charging and discharging. The conduction current then is the process and growth of displacement. Maxwell proposed all currents are closed. In this fashion, he introduced the displacement current. Maxwell quite explicitly limited electric polarization to the boundary conditions on the flux characteristics of electric displacement and magnetic induction. Maxwell did not apply boundary conditions to explain the phenomenon of reflection and refraction. This was achieved by Hertz and Heaviside.

In the European continent, physicists of the period were intimately familiar with field equations. However, each of them attempted to obtain Maxwell's field equations as a limiting case of Helmholtz's (entirely non Maxwellian) polarization theory of aether and matter. Maxwell's theory was based on a property of vortex notion, which Helmholtz had deduced (1858). Even those who no longer reached the Maxwell equations via Helmholtz (like H. A. Lorentz after 1892 or Hertz after 1890) continued to bear unmistakable marks of the Helmholtz polarization theory. However, there is a marked distinction between the two theories due to the difference between those who viewed electricity as a by-product of the field processes from those who did not [16]. Helmholtz's theory makes a distinction between conduction and polarization charge, with free charge being their sum. Helmholtz's theory consisted of three components [16]:

(1) expression for electromagnetic potentials and the forces derived from them
(2) a continuity equation linking charge and current, and
(3) a model for an electrically and magnetically polarizable medium.

The conflict between Helmholtz's and Maxwell's theories occurs where one would expect to find it, i.e., in the continuity equation. In Helmholtz's theory, all fields involve interaction between charge densities, and these interactions are not in fact propagated [16]. Only the polarizations propagate, charge interactions are always instantaneous. The basic difference is that in Maxwell's theory charge is the discontinuity in the electric displacement whereas in Helmholtz's theory it is with the discontinuity in the electric field. Thus, the problem with Helmholtz's theory is then at material interfaces where there will be charges as the electric field is discontinuous and where the displacement is not. Jules Henri Poincaré (1854–1912) [19], the French mathematician, theoretical scientist, and philosopher of science, said on Maxwell's *Treatise* that was published in 1873: *I understand everything in this book except what is meant by a body charged with electricity.*

In summary, Maxwell's *Treatise* provided an immense fertile theory, but in a form which was awkward, confusing, and on some points simply wrong [22, p. 108]. It was especially ill-tuned to handling the propagation problems that were coming into increasing prominence in the 1880s in connection with advances in telegraphy, telephony, and the study of electromagnetic waves. Before Maxwell's theory could gain wide acceptance and come into general use, it required substantial revision and clarification; both its physical principles and their mathematical expressions had to be put into a simpler and more easily grasped form. The most important steps in this process were taken in the mid 1880s by Poynting, FitzGerald, and Heaviside on the flow of energy for an electromagnetic field [22].

Maxwell was able to show [15, Art. 783 & 784; Equations 8 & 9] that in free space $(d^2J)/(d\,t^2) + \{d(\nabla^2\Psi)\}/(d\,t) = 0$, where ψ is the scalar electric potential. He then made an important assertion, for which he provided no real justification: "$\nabla^2\Psi$", he said, *which is proportional to the volume density of the free electricity, is independent of t*, i.e., he claimed that the electric potential is determined solely by the spatial distribution of charge which in a non-conductor does not change. This is the assumption usually made in electrostatics, and Maxwell simply extended it to general electromagnetic theory without alteration or explanation. Time independence implied that the electric potential adjusted instantaneously across all space to any changes in the positions or magnitudes of the charges. It also implied $(d^2J)/(d\,t^2) = 0$, so that as Maxwell wrote ***J** must be a linear function of t, or a constant, or zero and we may therefore leave **J** and ψ out of account in considering wave disturbances.* In practice, Maxwell generally took $J = 0$ and so worked out what we now call the *Coulomb Gauge*, a gauge well suited to electrostatic problems but with the serious drawback in treating changing fields that it requires the electric potential to be propagated instantaneously [22]. FitzGerald differed from Maxwell on this point and instead of assuming the two potentials to be independent as Maxwell did, FitzGerald put $J = -(d\Psi)/(dt)$ or equivalently: $\nabla \bullet A + (d\Psi)/(dt) = 0$. This *Lorenz Gauge*, as it was later called, is much better suited to treating propagation phenomenon than was Maxwell's *Coulomb Gauge* with $J = 0$. This new gauge thus eliminated the question of the instantaneous propagation of the electric potential. However, FitzGerald found that Heaviside had independently done it already [22]! As FitzGerald and Rowland put it in 1888, *That* ψ *should be murdered from treating propagation problems* [22]. Soon after, the same fate happened to A, as Heaviside puts it, *not merely the murder of Maxwell's* ψ, *but of that wonderful three legged monster with a scalar parasite on its back, the so called electrokinetic momentum at a point – that is the vector potential itself* [22]. That is the first complete modification of Maxwell's theory done by Heaviside and Hertz to get rid of the potentials and to start the problem with the sources, i.e., currents and charges.

Poynting in 1883 showed how the energy from an electric current passes from point to point, i.e., by what paths and according to what law does it travel from the part of the circuit where it is first recognizable as electric and magnetic to the parts where it changed into heat and other forms. In addition, Heaviside in 1884–1885 cast the long list of equations that Maxwell had given in his *Treatise* into the compact and symmetrical set of four vector equations now universally known as *Maxwell's equations*. Heaviside independently developed Poynting's theorem six months later. Reformulated in this way, Maxwell's theory became a powerful and efficient tool for the treatment of propagation problems, and it was in this new form (*Maxwell Redressed*, as Heaviside called it) that the theory eventually passed into general circulation in the 1890s. Heaviside's distance from the mainstream of British mathematical physics made it easier for him to dispense with the potentials and the Lagrangian methods favored by members of the Cambridge school and to approach the problem from a new and, as he believed through his vector operational calculus, into more fruitful directions [22].

After Maxwell's books on the treatise were published, in the European Continent, the Berlin Academy of Science announced a prize for research on the following problem: *To establish experimentally any relation between electromagnetic forces and the dielectric polarization of insulators, that is to say, either an electromagnetic force exerted by polarizations in non-conductors, or the polarization of a non-conductor as an effect of electromagnetic induction.* At that time Hertz was working with Helmholtz at the Physical Institute in Berlin. Helmholtz suggested to Hertz that, should he address this problem, the resources of the institute will be available to him. However, at that time Hertz gave up the idea because he thought a solution was not possible, as he found no adequate sources for generation of high frequencies. However, he continued thinking about this problem. Hertz addressed this problem when he went to the Technical High School at Karlsruhe. However, before he moved there he was at the University of Kiel. There he did not have much experimental equipment. So he worked on the theoretical aspects of the Maxwell's theory. In his book, he himself addresses the question as to what exactly is Maxwell's theory. In his words:

> *Maxwell left us as the result of his mature thought a great treatise on Electricity and Magnetism; it might therefore be said that Maxwell's theory is the one propounded in that work. But such an answer will scarcely be regarded as satisfactory by all scientific men who have considered the question closely. Many a man has thrown himself with zeal into the study of Maxwell's work, and even when he has not stumbled upon unwanted mathematical difficulties, has never the less been compelled to abandon the hope of forming for himself an altogether consistent view of Maxwell's ideas. I have fared no better myself. Notwithstanding the greatest admiration for Maxwell's mathematical conceptions, I have not always felt quite certain of having grasped the physical significance of the statements. Hence, it was not possible for me to be guided directly by Maxwell's book. I have rather been guided by Helmholtz's work, as indeed may plainly be seen from the manner in which the experiments are set forth. But unfortunately, in the special limiting case of Helmholtz's theory which lead to Maxwell's equations, and to which the experiments pointed, the physical basis of Helmholtz's theory disappears, and indeed it does, as soon as action-at-a-distance is disregarded. I therefore endeavored to form for myself in a consistent manner the necessary physical conceptions, starting from Maxwell's equations, but otherwise simplifying Maxwell's theory as far as possible by eliminating or simply leaving out of consideration those portions which could be dispensed within as much as they could not affect any possible phenomena... To the question, "What is Maxwell's Theory?" I know of no shorter or more definite answer than the following: - Maxwell's theory is Maxwell's system of equations. Every theory which leads to the same system of equations, and therefore comprises the same possible phenomena, I would consider as being a form or special case of Maxwell's theory; every theory which leads to different equations, and therefore to different possible phenomena, is a different theory. Hence, in this sense, and in this sense only, may the two theoretical dissertations in the present volume be regarded as representations of Maxwell's theory. In no sense can they claim to be precise rendering of Maxwell's ideas. On the contrary, it is doubtful whether Maxwell, were he alive, would acknowledge them as representing his own views in all respects.*

What Hertz missed was the core idea of the discontinuity in the displacement. The quandary of Hertz forced him into an uneasy compromise with the traditional Helmholtzian view on charge. Hertz distinguished the free electricity from which one calculates forces, and which is alterable by non-conducting means, from the true electricity, which is alterable only by conduction. So, though Hertz referred the measure of true charge to the divergence of the displacement, he preserved Helmholtzian wording because he had not seen how to avoid it. Whereas, a Maxwellian would write apparent charge as $\nabla \cdot \boldsymbol{E}$, Hertz wrote of free charge and felt it necessary to retain the idea of bound charge to grant free charge physical significance, though he refused to consider why such a thing as bound charge exists. We see now the significance of Hertz's famed rejection of the Maxwellian distinction between electric intensity and displacement in the free aether. Without this distinction, it is impossible, in Maxwellian theory, to understand the existence of a charged surface in vacuum because charge is due to the discontinuity in the displacement. The fact that in free aether $\boldsymbol{D}$ reduces to $\boldsymbol{E}$ is merely a mathematical artifact. This is due to the definition of capacity of the aether being unity. The conceptual and physical distinction between displacement and intensity is still essential. Not knowing or understanding this distinction goes to the heart of Maxwell's theory. Hertz felt free to ignore it where it seemed mathematically to make no difference. In addition, Hertz started from the sources of the fields which were charges in electrostatics and currents in magnetostatics and not treat the potentials as fundamental quantities in analogy to a mechanical model as Maxwell did. Hertz showed that at a dielectric boundary the tangential components of the electric fields are continuous and the normal component is discontinuous. He obtained similar boundary conditions for a magnetic media.

In short [22], Hertz defined the electric and magnetic constants as unity in free space, thus eliminating displacement as a primary quantity. While this somewhat simplified the mathematical structure of Maxwell's theory, it was fatal to its dynamical basis. Heaviside raised this point with Hertz in 1890 after reading his first paper *On the Fundamental Equations of Electrodynamics.* He asked, *Can you conceive of a medium for electromagnetic disturbances which has not at least two physical constants, analogous to density and elasticity? If not, is it not well to explicitly symbolize them, leaving to the future their true interpretation?* Heaviside was calling on Hertz not to sacrifice for the sake of a small and perhaps illusory mathematical simplification, the dynamical aether, filled with stresses, strains, and stored energy on which Maxwell had built his theory. The British Maxwellians took this dynamical aether much more seriously than did their Continental counterparts, insisting that even on those points where Maxwell's theory required clarification and correction, this could and should be done without reducing the theory to a mere set of equations. The important modifications Heaviside had made to Maxwell's theory, including his abandonment of the potentials in favor of his four equations in the vector form that we call Maxwell's equations today, he said, meant as sustentative changes or new departures, but were directed solely at bringing out the leading points of the theory more clearly than had Maxwell himself. Both Heaviside and FitzGerald drew a careful distinction between *Maxwell's Treatise* and *Maxwell's theory* and said that Maxwell's book gave only an imperfect account of the real nature of the theory [22].

The Maxwellian and Continental ideas were so profound that only Lorenz was able to retain the substantial character of charge while incorporating certain Maxwellian elements that did not violate basic preconceptions. Lorenz's theory computes interparticle actions directly by using retarded forces and it employs careful microphysical averaging. However, Lorenz's theory very much obscures the difference between ionic motions and the basic field equations.

In 1886, Hertz observed while examining some of the apparatus used in lecture demonstrations that the oscillatory discharge of a Leyden jar or induction coil through a wire loop caused sparks to jump a gap in a similar loop a short distance away. He recognized this as a resonance phenomenon and saw that such sparking loops could serve as very sensitive detectors of oscillating currents and, thus, of electromagnetic waves. This provided him with the proper experimental tool which had eluded Lodge, FitzGerald, and others.

Heaviside, on the other hand, differentiated between the absolute and the relative permeability and permittivity, defining the relative quantities as the ratio of the absolute value for a medium and that for free space. Heaviside rewrote Maxwell's equations in the vector form that we use today using the above modifications. There are conductors and non-conductors or insulators and since the finite speed of propagation in the non-conducting space outside conductors was unknown, attention was almost entirely concentrated upon the conductors and an assumed field which was supposed to reside upon or in them, and to move about, upon, or through them. And the influence on distant conductors was attributed to instantaneous action-at-a-distance, ignoring an intermediate agent. Maxwell explained these actions of the intermediate agent of an intervening medium being transmitted at finite speed. In Heaviside's words:

> *What is Maxwell's Theory or what should we agree to understand by Maxwell's theory? The first approximation to the answer is to say there is Maxwell's book as he wrote it; there is his text and there are his equations, together they make his theory. But when we come to examine it closely, we find that this answer is unsatisfactory. To begin with, it is sufficient to refer to papers by physicists, written say during the twelve years following the first publication of Maxwell's Treatise, to see that there may be much difference of opinion as what his theory is. It may be, and has been, differently interpreted by different men, which is a sign that it is not set forth in a perfectly clear and unmistakable form. There are many obscurities and inconsistencies. Speaking for myself, it was only by changing its form of presentation that I was able to see it clearly, and so as to avoid inconsistencies. It is therefore impossible to adhere strictly to Maxwell's theory as he gave it to the world, if only on account of its inconvenient form... But it is clearly not admissible to make arbitrary changes in it and still call it his. He might have repudiated them utterly. But if*

> *we have good reason to believe that the theory as stated in his treatise does require modification to make it self-consistent and to believe that he would have admitted the necessity of the change when pointed out to him, then I think the resulting modified theory may well be called Maxwell's.*
>
> *Maxwell defined the Ampère's law defining the electric current in terms of magnetic force. This makes the electric current always circuital implying that electric current should exist in perfect non-conductors or insulators. It is the cardinal feature of Maxwell's system. But Maxwell's innovation was really the most practical improvement in electrical theory conceivable. The electric current in a non-conductor was the very thing wanted to coordinate electrostatics with electrokinetics and consistently harmonize the equations of electromagnetic. It is the cardinal feature of Maxwell's system when dealing with Faraday's law where the voltage induced in a conducting circuit was conditioned by the variation of the number of lines of force through it. Instead of putting this straight into symbols, they went in a more round about way and expressed an equation of electro-motive force containing a function called the vector potential of the current and another potential, the electrostatic, working together but not altogether in the most harmoniously intelligible manner – in plain English muddling one another. It is I believe a fact, which has been recognized that not even Maxwell himself quite understood how they operated in his general equations of propagation. We need not wonder, then, that Maxwell's followers have not found it a very easy task to understand what his theory really meant, and how to work it out. It was Maxwell's own fault that his views obtained such slow acceptance; and in now repeating the remark, do not abate one of my appreciations of his work, which increases daily.*

To understand the problem, one must introduce the Maxwellian concept of a current. It was apparently not possible to incorporate conductivity into the dynamical structure of the Maxwellian theory. Maxwell did not himself incorporate conductivity directly into the dynamical structure of the theory. Rather, he treated Ohm's law as an empirical, independent fact, and subtracted the electromagnetic intensity it requires from the induced intensity.

It is important to point out that Heaviside's duplex equations, as he called them, can be found in Maxwell's own writing in 1868, *Note on the Electromagnetic Theory of Light*. Maxwell gave a clear statement of the second circuital law relating the magnetic current to the curl of the electric force, crediting it to Faraday and asserting that it afforded "the simplest and most comprehensive" expression of the facts. But despite the advantages of this simple equation, particularly in treating electromagnetic waves, Maxwell did not use it at all in his *Treatise* in 1873 and it remained unknown even to his close students till 1890 when Maxwell's scientific papers [23] were published. It is rather amusing to note that even Lodge (one of the Maxwellians) actually credited this equation to Heaviside in his Presidential Address to the Physical Society in February 1899, when the Irish physicist and mathematician Joseph Larmor (1857–1942) pointed out to him that it was in the writing of Maxwell himself [22]!

In summary, why Maxwell's theory was not accepted for a long time by contemporary physicists was that there were some fundamental problems with his theory. Also, it is difficult to explain using modern terminology as to what those problems were. As stated in [16] *Maxwellian theory cannot be translated into familiar to the modern understanding because the very act of translation necessarily deprives it of its deepest significance, and it was this significance which guided British research. It assumed that field and matter can always be treated as a single dynamical system, subject to modification according to the circumstances.* In modern days, we reject this very basis of the Maxwellian theory! Maxwell's paper in 1862 *On Physical Lines of Force* described an elaborate mechanism for aether. He was deeply attached to the mechanism despite certain problems with it and remained throughout his life till 1879 strongly committed to the principle to model building. Yet, in 1864, his paper on *A Dynamical Theory of the Electromagnetics*, avoided specifying the structure of the aether, but nevertheless, presumed the field to be governed by what he called dynamical laws. This is done by treating $\boldsymbol{H}$ as a velocity and $\boldsymbol{D}$ as the curl of the corresponding mechanical displacement. Through such assumption, it does not mean that the true structure of the aether is fully understood. Maxwell's theory was based on the assumption that all electromagnetic phenomenon, including boundary conditions, can be obtained by applying Hamilton's principle to suitably chosen field energy densities which contain the appropriate electrical parameters like permittivity and permeability for the material medium. Modern theory implies that this can at best work on certain occasions as the macroscopic fields ($\boldsymbol{D}$, $\boldsymbol{H}$) are not a simple dynamical system but a construct obtained by averaging over the true state and the combined field vectors ($\boldsymbol{E}$, $\boldsymbol{B}$) with material vectors ($\boldsymbol{P}$, $\boldsymbol{M}$). Hence, where modern theory introduces the electron, the Maxwellian theory invented new forms of energy. This was possible because the Maxwellians were quite willing to invent modifications to the basic equations governing the electromagnetic field – as long as the results held up experimentally. Modern theory seeks unified explanations in an unmodifiable set of field equations coupled through the electron motions to intricate microphysical models. Maxwellian theory sought unity through a highly plastic set of field equations coupled to Hamilton's principle. In Maxwell's theory, the goal was to create a theory of electromagnetism which made no use whatsoever of the microstructure of matter. Hence, the basic problem in understanding Maxwell's theory by a modern reader is to decipher what exactly did he mean by the words *charge* and *current*! Some of this confusion depends on Maxwell's having altered at least once his choice for the sign for the charge density in the equation which links it to the divergence of the electric flux $\boldsymbol{D}$. The conduction current in Maxwell's theory cannot be simply explained! The details of these subtleties may be found in [16]. Finally, as pointed out by Hunt, [22]: *When the 1880s began, Maxwell's theory was virtually a trackless jungle. By the second half of the decade, guided by the principle of energy flow, Poynting, FitzGerald and above all Heaviside have succeeded in taming and pruning that jungle and in rendering it almost civilized.*

In modern electrodynamics, we do not regard the field itself as a material structure, so we do not consider the stresses that may act upon it. Electromagnetic radiation, for example, transports energy and momentum but stresses arise only when the radiation impinges on material structures. The Maxwellians did not think in this way. For them energy inhomogeneity, whether matter is present or not, implies stress. Indeed after the discovery of Poynting's theorem, they realized that the free aether must be stressed when transmitting radiation, and so must move. In Maxwellian theory, the electromagnetic field transmits stress and is itself acted upon by stress. In modern theory, the field only acts; it is not acted upon [16].

In summary, the great difficulty with Maxwellian theory is that one cannot setup correspondences between mechanical and field variables which lead to consistent results unless one ignores conductivity, as illustrated by Heaviside. Heaviside's demonstration of this fact was based on the Green's potential function. He suggested using $\boldsymbol{E}$ as the velocity instead of $\boldsymbol{H}$ in the mechanical model and this requires a complete reconstruction of Maxwellian theory, as Maxwell did it the other way around.

From 1894 to 1897, the British electromagnetic theory abandoned the basic principles of Maxwellian theory and the entire subject was reconstructed on a new foundation – the electron, developed by Joseph Larmor in consultation with George FitzGerald [16]. Larmor had effected a revolution in the Maxwellian theory, one in which the electron had become the fundamental for generation of the field. Heaviside felt that Larmor's ideas of the electron as a nuclear of intrinsic twist was not sufficiently fundamental. The major impact of Larmor's theory was the destruction of the idea that continuum theory can serve as a sufficient basis for electromagnetism. Maxwell's theory with its fundamental assumption that the electromagnetic field can be subjected to precisely the same type of analysis as the material continuum was an artifact after 1898. This was the second conceptual modification of Maxwell's theory after Hertz, and Heaviside even though the basic equations still remained the same. Larmor's student, John Gaston Leathem, connected mathematically displacement with polarization by writing $\boldsymbol{D} = \boldsymbol{E} + \boldsymbol{P}$ and thus effectively destroying the Maxwell-FitzGerald theory of using Hamilton's principle as a starting point based on a continuous energy function [16].

From this time onwards, future work on electromagnetism, in Britain and in the Continent, depended directly on microphysics based on the electron rather on the macrophysics. Hence there was a complete divorce between the matter and the field [16]. Thus, the nature of conduction, the stumbling block in the Maxwell's theory, led to the final modification by Larmor by incorporating the microscopic view of matter through the introduction of the electron as the source of charge, the flow of which results in a current. These sources now produce the fields.

In short, the current perception of Maxwell's theory consists of Maxwell's system of equations supplemented by his radical concept of displacement current.

1.7 CONCLUSIONS

This chapter provided an introduction of the developments made up to the time of Maxwell in the creation of the theory of electromagnetism based on merging the different theories related to magnetism, electricity, and light. This is a unique theory where the fundamental equations did not change even though the philosophy went through two complete modifications. We have provided a brief outline of who Maxwell was as his name is synonymous with electromagnetic waves and that is the basis of wireless. The four of his equations that we use today under the heading of Maxwell's equations were written by Oliver Heaviside who first put them in the vector form. We have also provided what was/is his theory that resulted in the explosion of wireless.

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