Omnipresent physics in technologies and other scientific fields

from the physics knowledge in secondary/high schools

by

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Chapter 2: Ohm's, Faraday's and Snell-Descartes's laws, Faraday's law and technological applications in technology

II.1 Introduction

In the first chapter, we have presented the basic laws of classical mechanics and their technical and technological applications. In this second chapter, we are concerned with the laws derived from electricity, electromagnetism and optics. Ohm's law is considered as the representative of electricity. For the electromagnetism, Faraday's law and Lenz's law are presented. The last section deals with the laws of optics for light reflection and refraction, also known as Snell-Descartes laws.

II.2. Ohm's law

II.2.1. Derivation of the law by Ohm

In January 1781, before Georg Ohm's work, Henry Cavendish experimented with Leyden jars and glass tubes of varying diameter and length filled with salt solution. He measured the current by noting how strong is the shock he felt as he completed the circuit with his body. Cavendish wrote that the "velocity" (current) varied directly as the "degree of electrification" (voltage). He did not communicate his results to other scientists at the time, and his results were unknown until Maxwell published them in 1879.

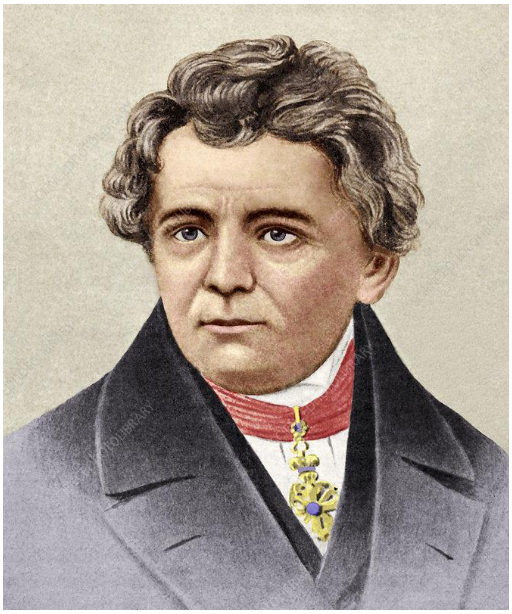


Figure 2.1: Georg Ohm, German physicist

Ohm (Figure 2.1) did his work on resistance in the years 1825 to 1826, and published his results in 1827 as the book Die galvanische Kette, mathematisch bearbeitet ("The galvanic circuit investigated mathematically"). For the theoretical explanation of his results, he drew considerable inspiration from Fourier's work on heat conduction. For experiments, he initially used voltaic batteries, but later used a thermocouple as this provided a more stable voltage source in terms of internal resistance and constant voltage. Figure 2.2 presents the experimental principle used by Ohm.

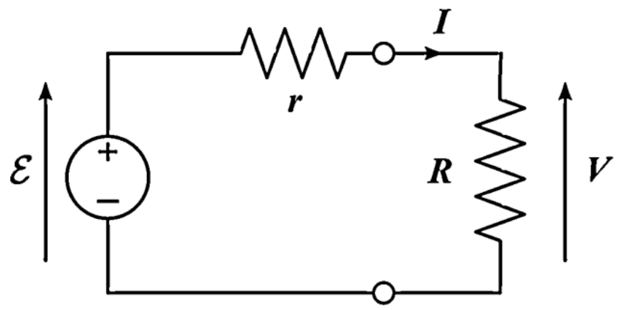


Figure 2. 2: Schematic diagram of the experiment conducted by Ohm

He used a galvanometer to measure the current, and then added test wires of varying length, diameter, and material to complete the circuit. He found that his data could be modeled through the equation (2.1):

$$x = \frac{a}{b + l} \tag{2.1}$$

where x was the reading from the galvanometer, l was the length of the conductor, the parameter a depended on the thermocouple junction temperature, and b was a constant of the entire setup. From this, Ohm determined his law of proportionality and published his results.
In modern notation, we would write:

$$I = \frac{\varepsilon}{r + R} \tag{2.2}$$

where I is the electric current, ε is the open-circuit electromotive force of the thermocouple, r is the internal resistance of the thermocouple and R is the resistance of the test wire. In terms of the length of the wire this becomes,

$$I = \frac{\varepsilon}{r + l\Re} \tag{2.3}$$

where $\Re$ is the resistance of the test wire per unit length. Thus, Ohm's coefficients are,

$$a = \frac{\varepsilon}{\Re}, b = \frac{r}{\Re} \tag{2.4}$$

If one applies the relation only on the resistance R, one obtains the following relation:

$$I = \frac{V}{\mathrm{R}} \tag{2.5}$$

where V is the voltage across the resistance.

Ohm's law was probably the most important of the early quantitative descriptions of the physics of electricity. We consider it almost obvious today. When Ohm first published his work, this was not the case; critics reacted to his treatment of the subject with hostility. They called his work a "web of naked fancies" and the German Minister of Education proclaimed that "a professor who preached such heresies was unworthy to teach science." The prevailing scientific philosophy in Germany at the time asserted that experiments need not be performed to develop an understanding of nature because nature is so well ordered, and that scientific truths may be deduced through reasoning alone. Also, Ohm's brother Martin, a mathematician, was battling the German educational system. These factors hindered the acceptance of Ohm's work, and his work did not become widely accepted until the 1840s. However, Ohm received recognition for his contributions to science well before he died.

In the 1850s, Ohm's law was known as such and was widely considered proved.

The electron was discovered in 1897 by J. J. Thomson, and it was quickly realized that it is the particle (charge carrier) that carries electric currents in electric circuits. In 1900, the first (classical) model of electrical conduction, the Drude model, was proposed by Paul Drude, which finally gave a scientific explanation for Ohm's law. In this model, a solid conductor consists of a stationary lattice of atoms (ions), with conduction electrons moving randomly in it. A voltage across a conductor causes an electric field, which accelerates the electrons in the direction of the electric field, causing a drift of electrons which is the electric current. However the electrons collide with and scatter off of the atoms, which randomizes their motion, thus converting the kinetic energy added to the electron by the field to heat (thermal energy). Using statistical distributions, it can be shown that the average drift velocity of the electrons, and thus the current, is proportional to the electric field, and thus the voltage, over a wide range of voltages.

The Ohm’s law has been generalized while considering the microstructure of the resistance. The Ohm’s law is thus written as:

$$\vec{J} = \sigma \vec{E} \tag{2.6}$$

where $\vec{J}$ is the current surface density at a given location in a resistive material (I=J S where S is the section of the electric wire), $\vec{E}$ is the electric field at that location (E=V/l where l is the length of electric wire), and σ is a material-dependent parameter called the conductivity.

The Ohm’s law can be extended to circuit powered by variable voltage and takes the following form

$$I = \frac{V}{Z} \tag{2.7}$$

where Z is the circuit impedance, and V and I are the root-mean-square or effective values of the voltage and current.

Ohm's law is vitally important to describing electric circuits because it relates the voltage to the current, with the resistance or impedance value moderating the relationship between the two.

II.2.2. Impacts of Ohm's law on technology

Because of the heating at the origin of the Ohm's law, its main applications are related to the heat delivered when the current flows in a resistance.

The heating effect of the electric current is used in electrical appliances like electric room heater, electric water heater, electric kettle, electric iron, etc. (Figure 2.3). All these elements have electric wires or conducting metallic beam or plates which become hot when electric current flows. Thus provide out heat through the Joule's relation or Joule's heating principle. The size of electric wires and conducting metallic elements are determined using Ohm's law.

Figure 2.3: Electric room heater, electric water heater, electric water kettle, electric iron

II.3. Faraday's and Lenz's laws

II.3.1. Faraday's biography

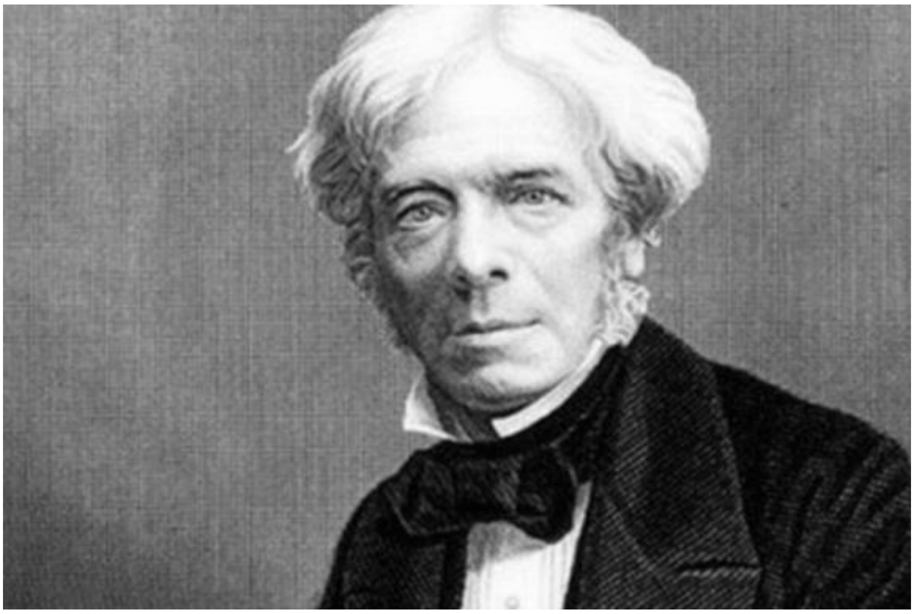


Figure 2.4: Michael Faraday, a great physicist (1791-1867)

Michael Faraday (22 September 1791 – 25 August 1867) (Figure 2.4) was an English scientist who contributed to the study of electromagnetism, electrochemistry and relationship between magnetism and light. Although Faraday received little formal education, he was one of the most influential scientists in history. It was by his research on the magnetic field around a conductor carrying a direct current that Faraday established the basis for the concept of the electromagnetic field in physics.

Faraday's breakthrough came when he wrapped two insulated coils of wire around an iron ring, and found that upon passing a current through one coil, a momentary current was induced in the other coil. This phenomenon is now known as mutual induction. The iron ring-coil apparatus is still on display at the Royal Institution. In subsequent experiments, he found that if he moved a magnet through a loop of wire, an electric current flowed in that wire. The current also flowed if the loop was moved over a stationary magnet. His demonstrations established that a changing magnetic field produces an electric field; this relation was modelled mathematically by James Clerk Maxwell as Faraday's law, which subsequently became one of the four Maxwell equations, and which have in turn evolved into the generalization known today as field theory.

In June 1832, the University of Oxford granted Faraday an honorary Doctor of Civil Law degree. During his lifetime, he was offered a knighthood in recognition for his services to science, which he turned down on religious grounds, believing that it was against the word of the Bible to accumulate riches and to pursue worldly reward. He stated that he preferred to remain "plain Mr Faraday to the end". Elected a member of the Royal Society in 1824, he twice refused to become President. He became the first Fullerian Professor of Chemistry at the Royal Institution in 1833. He was member of several academies: Foreign Honorary Member of the American Academy of Arts and Sciences, Royal Swedish Academy of Sciences, French Academy of Sciences, Royal Netherlands Academy of Arts and Sciences.

In 1848, in reconnaissance by the king, Faraday was awarded a grace and favor house in Hampton Court in Middlesex, free of all expenses and upkeep. This was the Master Mason's House, later called Faraday House, and now No. 37 Hampton Court Road. In 1858 Faraday retired to live there.

Having provided a number of various service projects for the British government, when asked by the government to advise on the production of chemical weapons for use in the Crimean War (1853–1856), Faraday refused to participate citing ethical reasons. Faraday died at his house at Hampton Court on 25 August 1867, aged 75. He had some years before turned down an offer of burial in Westminster Abbey upon his death. But, he has a memorial plaque there, near Isaac Newton's tomb.

A building at London South Bank University, which houses the Institute of Electrical Engineering departments is named the Faraday Wing, due to its proximity to Faraday's birthplace in Newington Butts. A hall at Loughborough University was named after Faraday in 1960. Near the entrance to its dining hall is a bronze casting, which depicts the symbol of an electrical transformer, and inside there hangs a portrait, both in Faraday's honor. An eight-story building at the University of Edinburgh's science & engineering campus is named for Faraday, as is a recently built hall of accommodation at Brunel University, the main engineering building at Swansea University, and the instructional and experimental physics building at Northern Illinois University. The former UK Faraday Station in Antarctica was named after him.

Streets named for Faraday can be found in many British cities (e.g., London, Fife, Swindon, Basingstoke, Nottingham, Whitby, Kirkby, Crawley, Newbury, Swansea, Aylesbury and

Stevenage) as well as in France (Paris), Germany (Berlin-Dahlem, Hermsdorf), Canada (Quebec City, Deep River, Ottawa), and the United States of America (Reston).

A Royal Society of Arts blue plaque, unveiled in 1876, commemorates Faraday at 48 Blandford Street in London's Marylebone district. From 1991 until 2001, Faraday's picture featured on the reverse of Series E £20 banknotes issued by the Bank of England. He was portrayed conducting a lecture at the Royal Institution with the magneto-electric spark apparatus.

The Faraday Institute for Science and Religion derives its name from the scientist, who saw his faith as integral to his scientific research. The logo of the institute is also based on Faraday's discoveries. It was created in 2006 by a $2,000,000 grant from the John Templeton Foundation to carry out academic research, to foster understanding of the interaction between science and religion, and to engage public understanding in both these subject areas.

Still, in honor and remembrance of his great scientific contributions, several institutions have created prizes and awards in his name. This includes:

- The Institute of Electric Technology (IET) Faraday Medal,
- The Royal Society of London Michael Faraday Prize,
- The Institute of Physics Michael Faraday Medal and Prize,
- The Royal Society of Chemistry Faraday Lectureship Prize.

II.3.2. Faraday’s law of induction

Electromagnetic induction was discovered independently by Michael Faraday in 1831 and Joseph Henry in 1832. Faraday was the first to publish the results of his experiments. In Faraday's first experimental demonstration of electromagnetic induction (August 29, 1831), he wrapped two wires around opposite sides of an iron ring (torus) (an arrangement similar to a modern toroidal transformer). Based on his assessment of recently discovered properties of electromagnets, he expected that when current started to flow in one wire, a sort of wave would travel through the ring and cause some electrical effect on the opposite side. He plugged one wire into a galvanometer, and watched it as he connected the other wire to a battery. Indeed, he saw a transient current (which he called a "wave of electricity") when he connected the wire to the battery, and another when he disconnected it. This induction was due to the change in magnetic flux that occurred when the battery was connected and disconnected. Within two months, Faraday found several other manifestations of electromagnetic induction. For example, he saw transient currents when he quickly slid a bar magnet in and out of a coil of wires, and he generated a steady (DC) current by rotating a copper disk near the bar magnet with a sliding electrical lead ("Faraday's disk").

Michael Faraday explained electromagnetic induction using a concept he called lines of force. However, scientists at the time widely rejected his theoretical ideas, mainly because they were not formulated mathematically. An exception was James Clerk Maxwell, who in 1861–1862, used Faraday's ideas as the basis of his quantitative electromagnetic theory. In Maxwell's papers, the time-varying aspect of electromagnetic induction is expressed as a differential equation which Oliver Heaviside referred to as Faraday's law even though it is different from the original version of Faraday's law, and does not describe motional electromotive force. Heaviside's version (see Maxwell–Faraday equation below) is the form recognized today in the group of equations known as Maxwell's equations.

Faraday's law of induction (briefly, Faraday's law) is a basic law of electromagnetism predicting how a magnetic field will interact with an electric circuit to produce an electromotive force (EMF), a phenomenon known as electromagnetic induction.

The most widespread version of Faraday's law states: The electromotive force around a closed path is equal to the negative of the time rate of change of the magnetic flux enclosed by the path. The closed path here is, in fact, conductive.

For a loop of wire in a magnetic field, the magnetic flux Φ_B is defined by the relation:

$$\Phi_B = BS \tag{2.8}$$

where S is the surface and B is the magnetic field. Let us indicate that at the university level, the magnetic flux is defined with double integrals.

Faraday's law states that the EMF is also given by the rate of change of the magnetic flux:

$$\varepsilon = -\frac{d\Phi_B}{dt} \tag{2.9}$$

where ε is the electromotive force (EMF). The laws of induction of electric currents in mathematical form was established by Franz Ernst Neumann in 1845. The direction of the electromotive force is given by Lenz's law.

II.3.3. Lenz's biography and law

Lenz was born in Dorpat in 1804, at that time in the Governorate of Livonia in the Russian Empire. After completing his secondary education in 1820, Lenz studied chemistry and physics at the University of Dorpat. He traveled with the navigator Otto von Kotzebue on his third expedition around the World from 1823 to 1826. On the voyage, Lenz studied climatic conditions and the physical properties of seawater. The results were published in "Memoirs of the St. Petersburg Academy of Sciences" (1831). After the voyage, Lenz began working at the University of St. Petersburg, Russia, where he later served as the Dean of Mathematics and Physics from 1840 to 1863 and was Rector from 1863 until his death in 1865. Lenz also taught at the Petrischule in 1830 and 1831, and at the Mikhailovskaya Artillery Academy.

Lenz began studying electromagnetism in 1831. Besides the law named in his honor, Lenz also independently discovered Joule's law in 1842. To honor his efforts on the problem, it is also given the name the "Joule–Lenz law," named also for James Prescott Joule.

Lenz's law, formulated in 1834, describes "flux through the circuit", and gives the direction of the induced electromotive force and current resulting from electromagnetic induction. Lenz's law of electromagnetic induction states that the direction of the current induced in a conductor by a changing magnetic field (as per Faraday's law of electromagnetic induction) is such that the magnetic field created by the induced current opposes the initial changing magnetic field which produced it. The direction of this current flow is given by Fleming's right hand rule.

Lenz died in Rome in 1865, after suffering from a stroke.

II.3.4. Lorentz's biography and Lorentz's force

Hendrik Antoon Lorentz was born at Arnhem, The Netherlands, on July 18, 1853, as the son of the nursery-owner Gerrit Frederik Lorentz and his wife Geertruida van Ginkel. When he was four years old, his mother died, and in 1862 his father married Luberta Hupkes. In those days, the grade school did not only have school hours in the morning and in the afternoon, but also in the evening, when teaching was more free. In this way, when in 1866 the first highschool (H.B.S.) at Arnhem was opened, Hendrik Lorentz, as a gifted pupil, was ready to be placed in the 3rd form. After the 5th form and a year of study of the classics, he entered the University of Leyden in 1870. He obtained his B.Sc. degree in mathematics and physics in 1871, and returned to Arnhem in 1872 to become a night-school teacher. At the same time, he was preparing for his doctoral thesis on the reflection and refraction of light. In 1875, at the early age of 22, he obtained his doctor's degree, and only three years later he was appointed to the Chair of Theoretical Physics at Leyden, newly created for him. In spite of many invitations to chairs abroad, he always remained faithful to his Alma Mater. From 1912 onward, when he accepted a double function at Haarlem as Curator of Teyler's Physical Cabinet and Secretary of the “Hollandsche Maatschappij der Wetenschappen” (Dutch Society of Sciences), he continued at Leyden as Extraordinary Professor, delivering his famous Monday morning lectures for the rest of his life. The far-seeing directors of Teyler’s Foundation thus enabled his unique mind to be freed from routine academic obligations, permitting him to spread his wings still further in the highest level of science.

From the start of his scientific work, Lorentz took it as his task to extend James Clerk Maxwell’s theory of electricity and of light. Already in his doctoral thesis, he treated the reflection and refraction phenomena of light from this standpoint which was then quite new. His fundamental work in the fields of optics and electricity has revolutionized contemporary conceptions of the nature of matter.

In 1878, he published an essay on the relation between the velocity of light in a medium and the density and composition of the medium. The resulting formula, proposed almost simultaneously by the Danish physicist Lorenz, has become known as the Lorenz-Lorentz formula.

The Lorentz force law describes the effect of the electric field and magnetic field upon a point charge. The electromagnetic force F on a test charge at a given point and time is a certain function of its charge q and velocity $\vec{v}$, which can be parameterized by exactly two vectors $\vec{E}$ and $\vec{B}$, in the functional form:

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) \tag{2.10}$$

This is valid, even for particles approaching the speed of light (that is, magnitude of $\vec{v}$ $= |\vec{v}|$ $\approx$ c). The two vector fields $\vec{E}$ and $\vec{B}$ are defined throughout space and time. They are called the "electric field" and "magnetic field" respectively. The fields are defined everywhere in space and time with respect to what force a test charge would receive regardless of whether a charge is present to experience the force.

II.3.5. Laplace’s force

When a wire carrying an electric current is placed in a magnetic field, each of the moving charges, which constitute the current, experiences the Lorentz force, and together they can create a macroscopic force on the wire (called the Laplace's force). By combining the Lorentz force law above with the definition of electric current, the following equation results, in the case of a straight and stationary wire

$$\vec{F} = I\,\vec{l} \times \vec{B} \qquad (2.11)$$

where $\vec{l}$, is a vector whose magnitude is the length of wire, and whose direction is along the wire, aligned with the direction of conventional current charge flow I. The multiplication symbol means vector product. If the wire is not straight but curved, the force on it can be computed by applying this formula to each infinitesimal segment of wire $d\ell$, then adding up all these forces by integration. Formally, the net force on a stationary, rigid wire carrying a steady current I is :

$$\vec{F} = I \int d\vec{\ell} \times \vec{B} \qquad (2.12)$$

Lorentz's force is microscopic. It is applied to charge moving carriers in a magnetic field while Laplace's force is macroscopic. It is applied to any electric conductor.

II.3.6. Impacts of the electromagnetism laws on technology

II.3.6.1. Electric transformer

An important application of Faraday's Law of Induction is the transformer (Figure 2.5), invented by Nikola Tesla. In this device, alternating current, which changes direction many times per second, is sent through a coil wrapped around a magnetic core. This produces a changing magnetic field in the core, which in turn induces a current in the second coil wrapped around a different part of the same magnetic core.

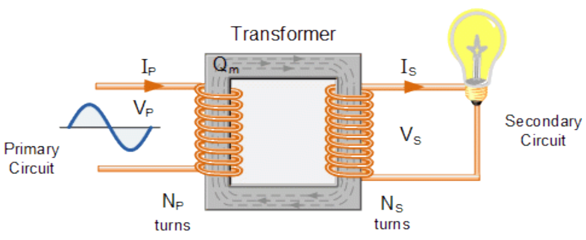


Figure 2.5: Schematic representation of a monophasic electric transformer (left) and real transformer (right).

II.3.6.*2*: Production of electricity (hydroelectricity, wind electric energy)

The Faraday's law indicates that if a magnetic flux varies in a closed electrical circuit, then there is the generation of an induced electromotive force following the relation

$$\varepsilon = -\frac{d\Phi_B}{dt} \qquad (2.13)$$

The existence of this electromotive force is at the origin of an induced electric current. This principle is the basis of the production of electricity in hydroelectric power plant. One needs to construct a system which makes the variation of the flux because of mechanical action. This mechanical action is created by water flow which acts on the turbine blades so that the turbine rotates, then creating the rotation of a rotor having magnets (Figure 2.6).

Figure 2.6: A turbine with its blades

As described in physics textbooks of the secondary school, if w is the rotation velocity of the rotor, then the flux varies with the time in the following manner:

$$\Phi_B = \vec{\mathbf{B}}\vec{S} = BS\cos(wt)\,. \qquad (2.14)$$

Consequently, the generated voltage is

$$E(t) = -w\ BS\ \sin(wt) = E_0\ \cos(wt+\pi/2) \qquad (2.15)$$

where E_0=wBS.

As it appears, the amplitude of the voltage (amplitude of the sinusoidal function) depends on w, B and S. Thus, it can be increased so that high voltage is produced. This high voltage is transported through the electric lines to the consumer after receiving transformations such as the one in transformers to reduce the amplitude of the voltage at a level appropriate for the consumers (electric machines, office and domestic appliances).

In the same manner, wind electricity is obtained. The mechanical force moving the rotor now comes from the wind pressure as it appears in Figure 2.7.

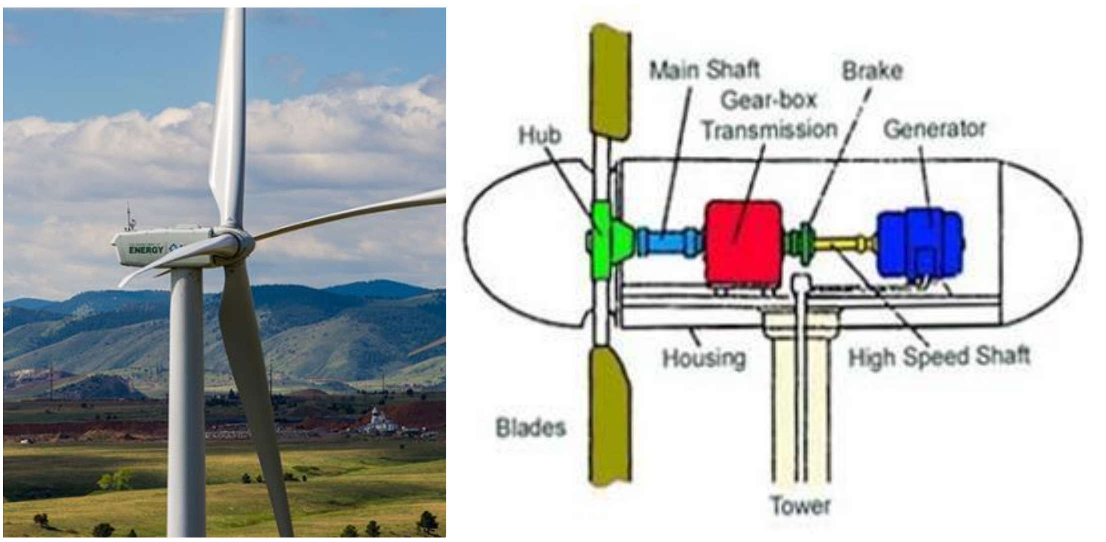


Figure 2.7: An aero generator with its internal structure

II.3.6.3. Microphone and loudspeaker

Figure 2.8 presents the schematic structure of an electrodynamic microphone.

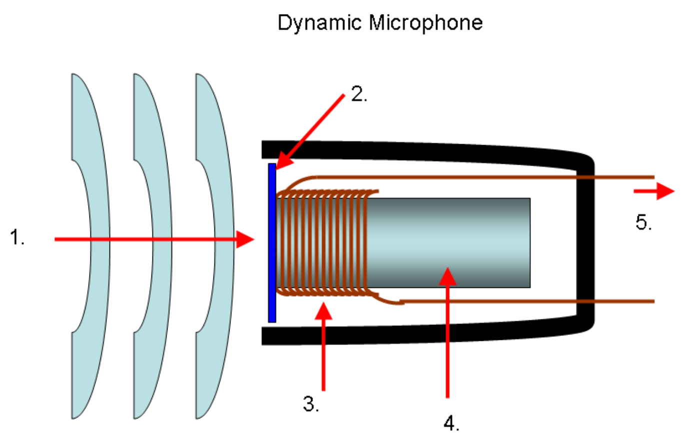


Figure 2.8: Structure of an electrodynamic microphone (1-air pressure, 2- membrane, 3-electric wire, 4-magnet, 5- electric cable)

The electrodynamic microphone also uses the Faraday's law. Consider an empty cylinder on which electric wire is wrapped. Fixed one end of the empty cylinder on an elastic membrane so that the cylinder moves when the membrane executes motion because of an external pressure. If the cylinder moves in a magnetic field whose lines are perpendicular to the electric wire, there is a flux variation. An electric signal is thus produced.

In the case of the electrodynamic microphone, the pressure is the consequences of air vibration due to the sound produced by a human voice or any other natural and artificial sound producing system. The generated electrical signal can propagate along the electrical lines or other transportation media (after some transformation if necessary).

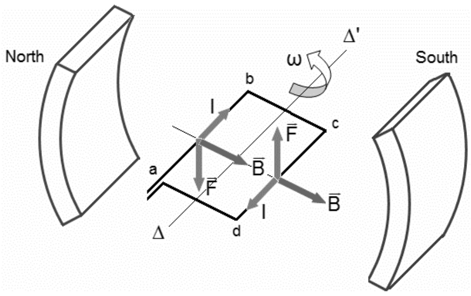
At the other side, when the message arrives at the loudspeaker, it is in the form of electric current. The electrodynamic loudspeaker is constructed in the same manner as the electrodynamic microphone. Now, because of the current flowing in the electrical circuit, a Laplace force is created and sets the cylinder into motion. In its turn, the membrane which is fixed on the cylinder vibrates and generates air pressure which propagates out in the air as sounds.

II.3.6.4. Electric motors

An electric motor is a device ensuring conversion of electrical energy to mechanical energy. Here the Laplace force or the Laplace torque is the principle behind the electric motors. In case of translational or linear electric motors, the principle is similar to what was explained for the loudspeaker. Because of the electric current flowing through an electric conductor in a region where a magnetic field exists, the Laplace force is created and sets the electric conductor into motion. The motion can be steady or accelerated. It can also be a one-way motion or an alternating motion depending on the variation of the electric current. The Newton's second law is applied to find the linear motor velocity.

The magnetic field is generated by a permanent magnet or by an electromagnet. The magnet or the electromagnet stands in a fixed position and is called the stator or inductor. The mobile component on which the Laplace force is applied is called the rotor (even if the rotor is mainly used for rotational motion motors).

For rotational motion motors, the configuration of the parts containing the electric conductor is so that the generated Laplace's force is oriented to create only the rotation. In that case, the Laplace's torque is used to calculate the motor or rotor velocity. The rotor or armature which as the name suggests is rotatable. It is subjected to the Laplace force or torque due to the current and magnetic field (figure 2.9).



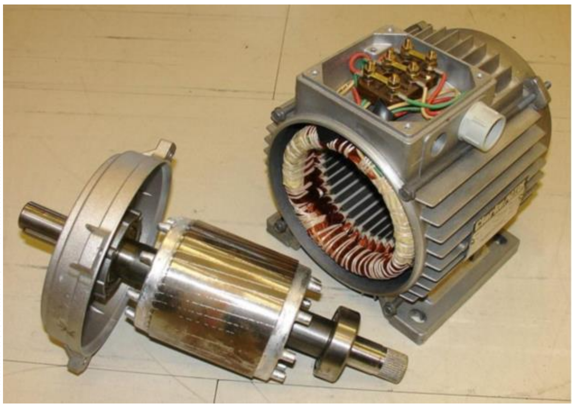


Figure 2.9: Schematic representation of Laplace forces inside an electric motor and an example of electric motor with the rotor and stator set aside

II.3.6.5. Magnetic Levitation train

The concept of electromagnetism is used in high speed Maglev trains (Figure 2.10). They use powerful electromagnetic force or EMF to provide both magnetic levitation of the train and propulsion. The electromagnets which are fixed in the tracks perform two main functions. First, they have to magnetically levitate the train and make it to float in air, and second, another set of electromagnets helps to move the train by magnetic force.

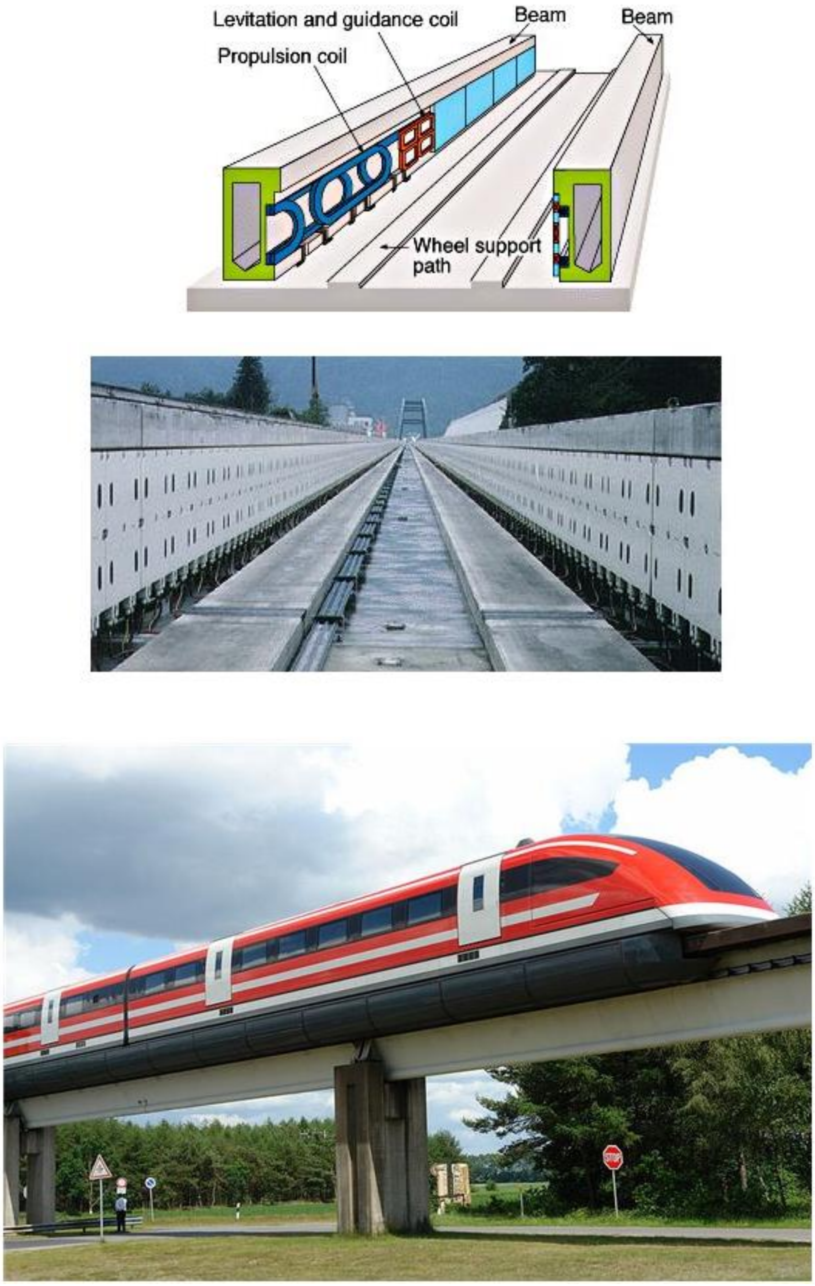


Figure 2.10: Levitation train: structure of the rails (above) and a train on a railway (below)

In these specially designed tracks, electromagnetic coils for magnetic levitation are placed at regular intervals and are called guideways. A set of large electromagnets or permanent magnets will be placed in the undercarriage of the train and will levitate the train 1 to 8 cm above the guideway. The guideway coil also helps to keep the train in track.

The propulsion coil will create an alternating magnetic flux in the electromagnet so that the front part of the train will be attracted and back parts of the train will be in repulsion adding more force for the forward movement. Thus an alternating current is given to the propulsion coils creating a magnetic lock with the train. Thus the frequency of the alternating current is made to synchronize with the speed of the train.

II.3.6.6. Electro-magnetic lifting cranes

Electromagnetic lifting cranes are used to lift and transport steel scraps, sheets, medium and thick plates, and steel bars (Figure 2.11). They use electromagnetism to magnetize the coil for lifting and demagnetize the electromagnetic coil for dropping the materials in the required place.

An electromagnetic container lifter works in the similar manner for transporting the container from the ship to the port and vice versa.

Figure 2.11: Electromagnetic lifting cranes

II.4. Snell-Descartes laws

II.4.1. Formulation of the laws and historical facts

II.4.1.1. The law of reflection of light

Euclid's Optics (Greek: Ὀπτικά), is a work on the geometry of vision written by the Greek mathematician Euclid around 300 BC. In this book, he described the law of light reflection. This states that light travels in straight lines and reflects from a surface at the same angle at which it hits it (Figure 2.12). Both angles are measured with respect to the normal to the mirror.

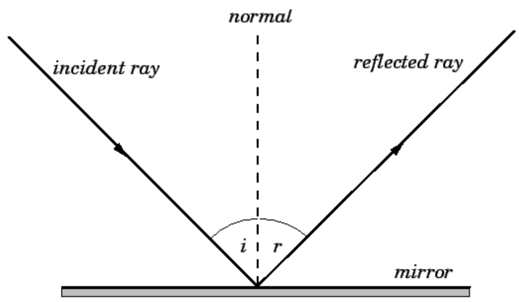


Figure 2.12: Reflection of a light ray

II.4.1.2. The laws of Snell and Descartes for the refraction of light

Refraction explains how a ray of light changes direction when it travels between different media. This is either because it slows down or because it speeds up. Refraction occurs when light hits the surface of water or travels through the atmosphere, and it is the atmospheric refraction that causes the stars to 'twinkle'.

The Roman astronomer Claudius Ptolemy (100-170AD), first tried to experimentally derive the law of refraction in the 2nd century BC. Ptolemy measured the angle that a beam of light hits a boundary (the angle of incidence) and the angle at which it leaves (the angle of refraction) through different media. He came to the conclusion that the angle of incidence is proportional to the angle of refraction. But, he could not derive the full equation. But, as we know today, the Ptolemy conclusion is valid only when the incident angle is small so that the sine of the angles can be approximated to the value of that angles in radians. Despite its obvious inaccuracy, Ptolemy's theory of refraction persisted for more than ten centuries.

The Iraqi mathematician Ibn Sahl discovered the full law of refraction in 984. Sahl showed that the angle of incidence is related to the angle of refraction using the law of sines.

The Dutch mathematician Willebrord Snellius rediscovered the sine law of refraction in 1621. Snellius's theory was not published in his lifetime. In 1637, the French natural philosopher Réné Descartes rediscovered the law again, independently and was the first to publish in his La Dioptrique (1637) the now familiar formulation of the law of refraction in terms of sines. Although there was much controversy at the time regarding plagiarism, Descartes was apparently unaware of Snell's work. Thus, in English speaking countries the law of refraction is called ``Snell's law". But, in French speaking countries, it is called ``Descartes's law".

Snell's law (also known as Snell-Descartes law and the law of refraction) is a formula used to describe the relationship between the angles of incidence and refraction, when referring to light or other waves passing through a boundary between two different isotropic media, such as water, glass, or air.

Snell's law states that the ratio of the sines of the angles of incidence and refraction is equivalent to the ratio of phase velocities in the two media, or equivalent to the reciprocal of the ratio of the indices of refraction (see Figure 2.13):

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2} = \frac{n_2}{n_1} \tag{2.17}$$

with each angle measured from the normal of the boundary, the v_i are the velocity of light in the respective medium.

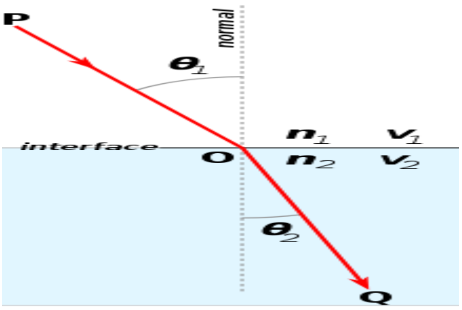


Figure 2.13: Refraction of light

The speed v with which light propagates through a medium is inversely proportional to the refractive index of the medium

$$v_1 = \frac{c}{n_1} \text{ and } v_2 = \frac{c}{n_2} \tag{2.18}$$

where c is the speed of light in the vacuum.

II.4.2. Impacts of the geometrical optics laws on technology

II.4.2.1. Applications of the reflection law

- We use mirrors to see ourselves. This is based on the reflection law.
- The wing and rear-view mirrors of a car are made of a convex and plane mirrors respectively (Figure 2.14). The two wing mirrors enable the driver to see objects on both sides of the car. The rear-view mirror enables the driver to see things behind the car.

Figure 2.14: Car mirror uses the reflection law. The light coming from a car at the rear hits the mirror and reflects to the driver's eye.

- Parabolic mirrors are used in torches and cars headlamps as reflectors (Figure 2.15). A small lamp is placed at the focus point of the mirror to produce parallel rays.

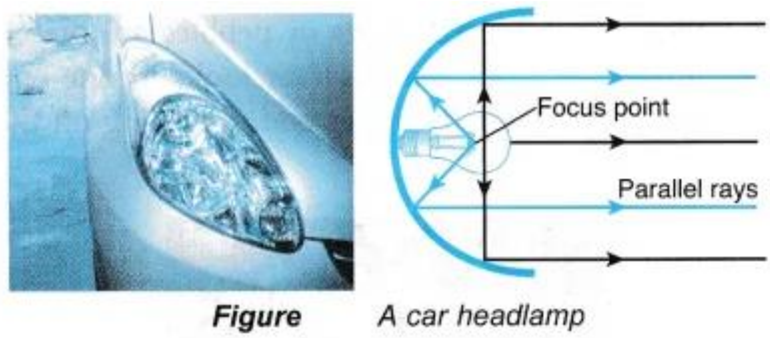


Figure 2.15: Parabolic mirrors used torches and cars headlamps as reflectors

- Spherical mirrors, specifically the convex ones are used as blind corner mirrors on the raad to help drivers view traffic around (Figure 2.16).

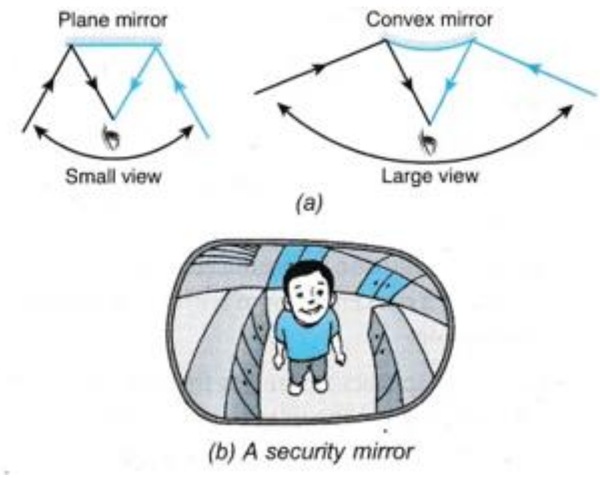


Figure 2.16: Convex mirrors to see in car blind corners

- A microscope uses a mirror to reflect light to the specimen under the microscope (Figure 2.17). But, it also uses a convergent lens system to increase the size of the images of objects not visible by the naked eye such as microbes (lens are also based on the refraction law).

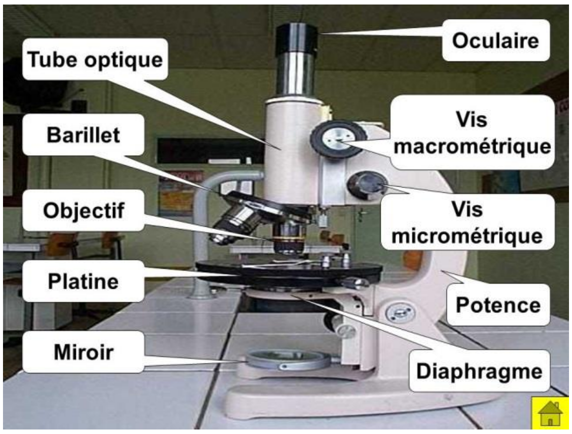


Figure 2.17: A microscope

- An astronomical reflecting telescope uses a large parabolic mirror to gather dim light from distant stars (Figure 2.18). A plane mirror is used to reflect the image to the eyepiece.

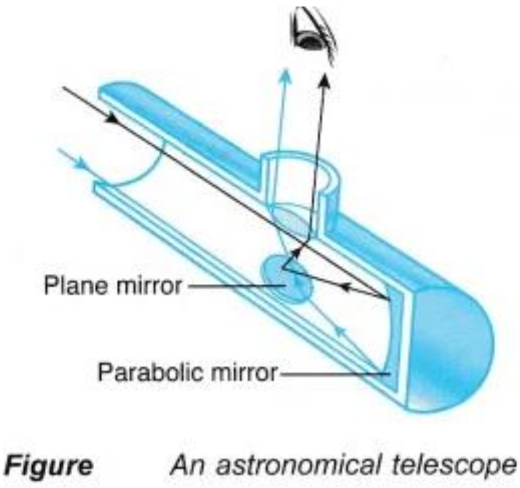


Figure 2.18: An astronomical telescope

II.4.2.2. Applications of the refraction law

Refraction law has many applications in optics and technology.

- The medical eye glasses use the refraction and lens laws to correct our eyes in case of eyes diseases (myopia or nearsighted, hyperopia or farsighted, astigmatism, presbyopia) (Figure 2.19).

Figure 2.19: Medical eye glasses

- A lens uses refraction to form an image of an object for many different purposes, such as magnification (magnifying glass, microscope, astronomical telescope).

- A prism uses refraction to form a spectrum of colors from an incident beam of light. Refraction also plays an important role in the formation of a mirage and other optical illusions.

- Optical fibers use total internal reflection to transmit light. It has a solid core of dense glass surrounded by a less dense cladding. The light ray passing through the inner core is reflected back instead of being refracted to the rarer cladding (Figure 2.20).

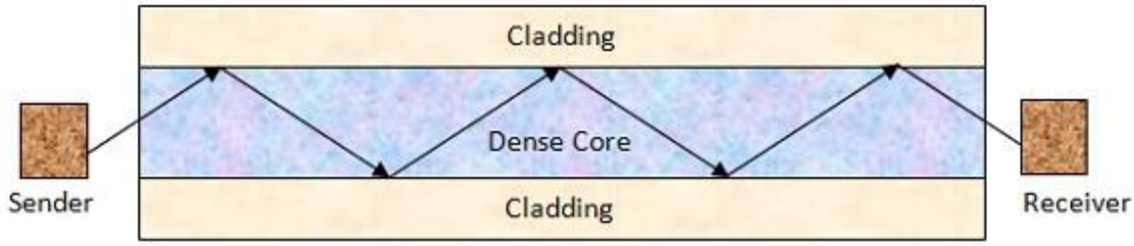


Figure 2.20: Light reflection during propagation in optical fibers

II.5. Conclusion

Some applications of some classical physics laws have been presented after the presentation of some historical facts explaining how these laws have been obtained and giving some details on the physicists who have been at the origin of these laws. At it has been found, each law leads to several applications in technology and engineering. We would like to emphasize on the facts that we have just given a very short list of applications and the reader could find more applications in the literature and in their daily life. And more other applications are still to come.

The next chapter considers the modern physics.