

ELECTRICITY AND MAGNETISM

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Summary

The phenomena, concepts and principles of electricity and magnetism are reviewed, illustrating some of their applications -some of them related to living systems- along the way. Following the historical order, forces and energies associated with electric charges at rest, with electric charges moving inside conductors, with permanent magnets and electromagnets, with time-varying magnetic fields, with time-varying electric fields, and with electromagnetic waves -in empty space and in material media- are successively studied. The unity of the electric, magnetic and optical phenomena and the variety of their applications are emphasized.

1. Introduction

1.1 General Introduction

Planet Earth occupies a unique position in our solar system since it is the only planet where life is known to exist and thrive. It has been conjectured that life might exist on planets of other solar systems, and there are programs aimed to get in touch with other

civilizations in such places, but no proof about them has been found up to now. Life on earth occurs in the seas, rivers and lakes, underground and on the surface. Its diverse forms and their distributions around the globe have been possible by the steady supply of energy by the sun in the form of electromagnetic radiation tempered by the earth's atmosphere. The orbiting of the earth around the sun combined with the precession of its axis during such a process, account for the seasonal changes in the distribution of the solar energy at different latitudes, which in turn translate into the seasonal rhythms of the diverse species. The earth also possesses a magnetic field and electrical discharges occur in its atmosphere, with the consequent influences in the behavior and in the populations of some species. Knowledge of electricity and magnetism is an important tool for those interested in life support systems.

In the following subsections phenomena associated with electric charges at rest, electric charges moving in conductors, permanent magnets and electromagnets, electromagnetic induction, Maxwell's electromagnetic field, and electromagnetic radiation are qualitatively studied successively, identifying the key concepts, the corresponding principles, the representative devices, and some of their applications. This phenomenological study is aimed at a non-specialized readership. Then in the succeeding sections the same topics of the preceding subsections are further studied through a technical and quantitative presentation, emphasizing the evolution of some of the concepts and the unity of the laws governing electric, magnetic and optical phenomena. This part should be useful to students and practitioners of physical sciences and engineering, as well as to non-specialists interested in attaining a deeper understanding of the subject.

1.2 Electric Charges at Rest

Electrostatics is the study of phenomena associated with electrically charged bodies at rest. In normal circumstances matter is electrically neutral. Some substances can acquire an electric charge when rubbed against each other, like a glass rod and fur, a plastic comb and hair, the wind and clouds. Such substances are called insulators or dielectrics, and are also characterized for not allowing the motion of charges through them. In contrast there are conducting substances like metals that cannot be charged by rubbing, but facilitate the motion of charges through them. Conductors can acquire an electric charge when insulated and in contact with another charged body, or when in touch with the ground and in the vicinity of charged bodies. These examples illustrate the electric charging by rubbing, by contact and by electrostatic induction, respectively.

Electrically charged bodies exert forces of attraction or repulsion depending on the signs of their charges. It is recognized that there are positive and negative charges, with attractions between charges of opposite sign and repulsions between charges of the same sign. Coulomb measured the forces between charged spheres using a torsion balance and formulated the law of the inverse of the square of the distance in 1785. Priestley had established experimentally the validity of such a law twenty years earlier on the basis of the gravitational analogy, which leads to the conclusion that a hollow charged conductor has no charge on the inside.

The gravitational analogy also allows understanding that the electrostatic forces are

conservative and that the Coulomb potential energy of a pair of point charges is inversely proportional to their distance.

The Coulomb force is proportional to the magnitudes of the electric charges. The total electrostatic force of a collection of charges on another charge is simply the vector sum of the respective Coulomb forces, and it turns out to be proportional to the magnitude of the charge. This allows the introduction of the force per unit charge at any point, which is called the electric field intensity. There is correspondingly the potential energy per unit charge, which is called the electrostatic potential.

The work of Laplace of 1784 including his equation for the gravitational potential was extended for the electrostatic situation including the source term by Poisson in 1813.

A capacitor is formed by two conductors separated by empty space or by an insulator. It serves to store electric charge; the Leyden jar was its most popular form in the late 1700's. The charges in the conductors have the same magnitude and opposite signs, and there is a potential difference between them. The charge is proportional to the potential difference. The constant of proportionality is called the capacitance of the capacitor and is a measure of the charge stored per each unit of potential difference. The capacitance of a capacitor with the insulator is larger than with empty space.

1.3 Electric charges moving in conductors

In an electrostatic situation the electric charges added to a conductor move until their distribution ensures that they remain in fixed positions. This is achieved when the force on any of them vanishes, which is guaranteed if the electric intensity field is zero in the body of the conductor. Consequently all the points of the conductor are at the same potential and the charge is distributed on its surface.

If two regions on the surface of a conductor are maintained at different potentials, its free charges move producing an electric current in the direction from the region of higher potential to the region of lower potential. The intensity of the current in any cross section is the net amount of electricity crossing it per second. To simplify the analysis a conductor in the shape of a cylinder is assumed, and the potential difference is applied between its ends. The galvanic cell and the voltaic pile were sources of steady potential difference available at the end of the 1700's and became amply used in the new century.

Ohm established that the electric current in a conductor connected to one of these sources has an intensity proportional to the potential difference or voltage of the source. The constant of proportionality is called conductance and its reciprocal is the resistance of the conductor. For the cylindrical geometry the conductance is proportional to the area of the cross section and inversely proportional to the length, and the constant of proportionality is called the conductivity. The electric field intensity inside the cylindrical conductor is uniform and equal to the potential difference divided by the length. The current is stationary and uniformly distributed in every cross section of the cylinder.

Electric charge is conserved in all processes. In the electrification by rubbing, the

electric charges in each body are zero at the beginning, and are of the same magnitude and opposite signs at the end, so that the net charge is still zero. The charge in a given volume of matter may change with time, as in a radioactive source emitting positively charged alpha particles; at any instant the time rate of change of the source's charge equals the negative of the total current intensity across the surface of the sample.

A conductor carrying electric currents gets heated. This is called the Joule effect and has many familiar applications, including illumination when part of the conducting circuit is heated to the point of incandescence.

1.4 Permanent magnets and electromagnets

Lodestones capable of attracting and orienting iron shavings were known in ancient Greece in the locality of Magnesia, which originated the name of magnets and magnetism. Magnetic needles get oriented in the geographical south-north direction and found application in navigation since old times. Gilbert published *De Magnete* in 1600, which included his observations on the effect of a magnetized sphere, a *terrella*, on magnetized needles suggesting that the earth acts as a spherical magnet. A Coulomb force between magnetic poles following the inverse of the square of the distance law was also established at the end of the 1700's.

Up to 1820, electric and magnetic phenomena had been studied independently of each other. In the summer of that year Oersted discovered electromagnetism when he observed the orientation effect of a current along a straight conducting wire on magnetic needles in its vicinity. Iron shavings on a horizontal cardboard, pierced by conducting wire in a vertical position, form a magnetic spectrum of circles coaxial with the wire. This was expressed by Ampere's right hand rule: If the thumb indicates the direction of the current, the fingers curling around the thumb describe the directions of orientation of magnetic needles.

Biot and Savart carried out experiments to measure the force on a magnetic pole due to a current in an element of conductor establishing that it is perpendicular to the current element and to the radial direction from the position of the current element to the position of the pole, and inversely proportional to the square of the distance between such positions. Ampère established that parallel wires with currents in the same (opposite) directions attract (repel) each other with forces inversely proportional to their distance of separation. Other configurations of electric currents in loops and collections of loops, called coils or solenoids, produce magnetic fields analogous to those of permanent magnetic needles, and magnets of different shapes.

Different applications involve the construction of electromagnets, electromagnetic motors, instruments to measure magnetic fields and electric currents, etc.

1.5 Electromagnetic induction

The discovery of electromagnetism suggested the possibility of a complementary effect in which magnets, permanent or electric, could produce electric forces and currents. Biot, Savart and Ampère themselves searched for such an effect without any success.

Faraday in 1831 discovered the conditions to produce what he originally called magneto-electric induction, but which eventually took the name of this subsection. His first successful experiment involved an iron ring with two independent coil windings in opposite sides; one was connected to a voltaic pile and the other one was connected to a galvanometer.

He observed that when the switch of the first one was closed, the galvanometer indicated the circulation of a transient current in one direction; when the current in the first one was stationary, the galvanometer indicated no current; when the current in the first one was switched off, the galvanometer indicated again a transient current but in the opposite direction of the previous one. Faraday observed the corresponding effects in other configurations: a permanent magnet approaching or receding from a coil induces electric currents in the latter in opposite directions; the same happens when the coil enters or leaves a region of magnetic field; alternating currents can be induced in coils rotating in a region of magnetic field.

Faraday formulated the law of electromagnetic induction: The electromotive force induced in a circuit is proportional to the time rate of change of the magnetic flux crossing the area of the circuit. Lenz recognized the rule for the direction of the induced electromotive force and the induced current as a left hand rule: If the thumb indicates the direction of the change in the magnetic flux, the fingers curling around the thumb give the direction of the electric field and the current. This guarantees the conservation of energy in the process. Faraday started to associate a physical existence to the magnetic and electric field lines of force.

Some of the configurations employed by Faraday in his experiments contain the elements of alternating current generators, transformers, etc.

1.6 Maxwell's electromagnetic field

Newton's law of universal gravitation, Coulomb's laws of electrostatics and magnetostatics, and Ampere's law of electromagnetism describe the forces between pairs of point masses, point electric charges, point magnetic poles, and parallel wires as interactions at a distance.

Faraday thought about these interactions as taking place in two stages: the masses, charges, poles and current elements are sources of gravitational, electrical, and magnetic lines of force; the existence and action of the latter is manifested by their effects on other masses, charges, poles and current elements, respectively, in other positions. This point of view proved very fruitful in the study of time-dependent electromagnetic situations.

Faraday was recognized by his experimental researches in electricity and magnetism, but some of his conceptions were not accepted by many of his contemporaries. Maxwell decided to put Faraday's experimental results and theoretical conceptions in the mathematical language of the times. By starting from Faraday's lines of force, Maxwell arrived at the theoretical formulation of the electromagnetic field identifying its dynamical properties.

The so-called Maxwell's equations are the mathematical description of the laws of electromagnetism, as generalization and extension of the laws of electrostatics and magnetostatics to the situation of time dependent charge and current sources, and electric and magnetic fields. Faraday's law of electromagnetic induction is already included, dealing with a time dependent phenomenon. Maxwell recognized the incompatibility of Ampere's law of magnetostatics with the conservation of electric charge, as illustrated by the magnetic field associated with the straight current in the discharge of a capacitor; he saw the possibility of removing such an incompatibility by introducing the displacement current, which turns out to be the time rate of change of the electric flux, and which becomes also a source of circulating magnetic field. The latter is governed by a righthand rule and is a true electromagnetic induction phenomenon complementary to that of Faraday's.

From the equations of balance of energy and momentum of charged particles interacting via the electric and magnetic fields, Maxwell recognized the properties of energy density, energy current density, momentum density and momentum current density associated with the fields.

1.7 Electromagnetic radiation

The most important prediction of Maxwell's 1864 dynamical theory of the electromagnetic field was the existence of electromagnetic waves, as the result of the combined effect of Faraday's magneto electric induction and Maxwell's electromagnetic induction.

Coulomb's law and its time dependent extension recognize that electrical charges are the sources of divergent electric field. Ampère's law and its time dependent extensions recognize that electric currents are the sources of circulating magnetic field. Both types of fields are significantly stronger in the vicinity of the sources; the energy and momentum carried by them at large distances from their sources become practically zero. In contrast, the electric and magnetic fields associated with the induction effects of Faraday and Maxwell do not depend on the charges and currents themselves directly, but only on their time variations which are inherited by the fields themselves. Such fields remain significant at large distances from the charge and current sources, and the energy and momenta carried by them are also finite and significant.

The units of electric charge and of electric current were defined independently on the basis of Coulomb's law of electrostatics and of Ampere's law of electromagnetism, respectively. In the cgs system the corresponding units of charge turn out to have different values and different dimensions. $1\text{emu}/1\text{esu} = 3 \times 10^{10} \text{cm/s}$ was the value determined by Kohlrausch and Weber in 1850 by measuring the charge in a capacitor and the current of its discharge through a coil. This is the speed of the electromagnetic waves predicted by Maxwell's synthesis of the laws of electromagnetism. Its value is close to the measured speed of light so that it was inferred that light might be a type of electromagnetic wave.

Maxwell's theory and prediction of electromagnetic waves were not accepted

immediately. The production and detection of such waves by Hertz twenty years later, with wavelengths of the order of 1m that he could measure in his laboratory and frequencies of the order of 3×10^8 cps confirmed the prediction and led to the acceptance of the theory.

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Biographical Sketch

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