UNIT GUIDES

1. Physical principles of semiconductors
2. Kinematics
3. Dynamics
4. Work and energy
5. Heat and temperature
6. Thermodynamics
7. Electric field
8. Conductors, capacitors and dielectrics
9. Electric current

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The aim of this unit is to provide an introduction to different types of solids, the band theory, electrical properties of semiconductors, different types of conduction in semiconductors and semiconductor devices.

First we discuss the different types of molecular bonds and solids, distinguishing primarily between ionic, covalent and metallic solids, and introducing the free-electron model of metals, the concept of density of states and Fermi-Dirac’s distribution.

We analyze the difference between conductors, insulators and semiconductors based on their energy band structure and the separation between the valence and conduction bands. When atoms are bonded together in condensed matter, their energy levels are divided into bands. At absolute zero, insulators and semiconductors have a completely filled valence band separated by an energy gap in an empty conduction band. However, in the case of semiconductors the gap range between these two bands is about 1 eV. Conductors have partially filled conduction bands. We also distinguish between intrinsic and extrinsic semiconductors. In the latter case, the addition of a small concentration of impurities can drastically change the semiconductor electrical properties. Added donor impurity yields an n-type semiconductor, while if added impurities receiving the result is a p-type extrinsic semiconductor. At this point it is important to introduce the semiconductor equation or law of mass action, an essential equation in the study of semiconductors and semiconductor devices as well as the condition of electrical neutrality.

We describe the transport phenomena of electrical charges in semiconductors, as a consequence of the application of electric fields (drift current) or the existence of gradients of charge concentration (diffusion current). The concepts of drift velocity, current density and conductivity studied here are similar to those introduced in the case of metal conductors in the unit “Electrical current”, with the difference that in the latter case the charges are free electrons, while in a semiconductor they can be electrons (negative charges) or holes (positive charges).

The last section of the unit is dedicated to semiconductor devices, with an introduction to the basic characteristics of the diode and the transistor. We start studying the pn junction, both in forward and reverse bias, because this type of junction is the basis for the construction of diodes and transistors. We include basic operating characteristics such as the electron and hole currents, voltage-current characteristics of a diode, and the voltages and currents in a transistor. Finally we briefly discuss some applications of these devices.
Unit 2. Kinematics

Mechanics studies motion and the causes that produce it. Mechanics is the oldest branch of physics and, undoubtedly, the most highly developed. Its models have been applied to other fields, even some unrelated to physics; hence its interest as a basis for understanding other scientific and technical fields.

In the study of mechanics it is first necessary to describe the motion but without taking into account the causes that produce it. Kinematics is the branch of mechanics devoted to pure motion. In this unit we study the kinematics of a particle or material point, a body whose size and shape are not important in solving a particular mechanical problem.

Concepts such as the position vector, displacement vector, average speed and acceleration, and snapshots are reviewed. An important aspect to consider is that the velocity vector is a vector tangent to the trajectory of the particle at each point. We analyze the intrinsic components of acceleration: tangential acceleration and centripetal or normal acceleration. Tangential acceleration takes into account the change in magnitude of the velocity vector, while normal acceleration expresses the variation in the direction of the velocity vector. Normal acceleration is directed toward the centre of curvature of the trajectory at each point and is inversely proportional to the radius of curvature of this trajectory. Obviously, normal acceleration is zero for linear motion, whereas it takes constant values for circular motion because the radius of curvature of the trajectory is constant for this type of motion.

Then we study the case where the object moves in a straight line. This type of motion is known as linear motion and some particular cases are uniform linear motion, in which the acceleration is zero and the velocity is constant, and uniformly accelerated linear motion, wherein the acceleration is constant. Another important type of motion studied in this unit is circular motion, for which we analyze concepts such as angular velocity and angular acceleration and their relationship with linear velocity and linear acceleration, respectively. As examples we study uniform circular motion and uniformly accelerated circular motion. Some important questions to consider are the relationships which exists between angular velocity, linear velocity, angular acceleration and linear acceleration vectors.

The unit ends with the study of parabolic motion such as projectile motion, which allows us to see how, for purposes of analysis, it is possible to treat it as two separate linear motion problems in two perpendicular directions, one in the x direction and the other in the y direction, with only time as the common element. Some issues such as the height and range of a projectile are also analyzed.

It is important to take into account throughout this unit that motion is a relative concept and should therefore always refer to a particular frame of reference chosen by the observer.
Unit 3. Dynamics

This unit deals with dynamics, which is the branch of mechanics that analyzes the relationship between movement and its causes: the forces. In physics, the causes of interactions between bodies (whether or not they are in contact, near to or far from each other) are described by forces. The unit begins with a brief description of different types of forces (contact, friction, normal stress, long range, etc.) and the fundamental forces of nature (gravitational, electromagnetic, strong and weak interactions).

Then Newton’s laws are introduced, which are established in terms of force and mass. These laws are the inertia law, the fundamental equation of dynamics and the law of action and reaction. An important aspect to bear in mind is that the concept of an inertial frame of reference is fundamental to Newton’s laws of motion. Newton’s second law -which relates force, mass and acceleration- is a fundamental law of nature, the basic relationship between force and motion, as the first law only applies to inertial frames of reference. Regarding Newton's third law, it is important to understand that action and reaction forces are applied to different bodies, so even if they are equal and opposite, they are not balanced.

As an example of a force of great interest, we study the force of gravity -one of the fundamental forces of nature -the law of universal gravitation and the best known example of gravitational attraction: weight, the force with which the earth attracts an object.

A section of great importance in this unit is the application of Newton's laws to solve problems of dynamics. In this section we analyze problems involving pulleys, inclined planes, strings and tension, friction, banked curves, etc. It is necessary to clarify the general procedure of how to solve these problems. It is important to examine examples in which the magnitude of the normal force is not always equal to the weight of a body. In all cases it is necessary to examine in detail the relationships between the forces and the motion produced. In order to solve these problems correctly, it is essential to draw the correct free body diagram that shows the body being studied alone, free from its surroundings, with the vectors for all the forces acting on it.

The unit ends with the study of two important concepts in physics -linear momentum and angular momentum and their conservation laws. It should be understood that Newton’s second law can also be expressed in terms of the linear momentum; in fact, the net force acting on a particle is equal to the rate of change in its linear momentum. This expression of Newton’s second law relating the net force applied on a body and its linear momentum must be used when analyzing, for example, variable mass systems.
Unit 4. Work and energy

In this unit we analyze two of the most important concepts in physics, work and energy, which will appear in all the units of this course. The importance of the concept of energy arises from the energy conservation law: energy is a quantity that can be converted from one type of energy to another, but can not be created or destroyed.

First we define the work done by a force, both in the case where the force is constant and the motion is linear, and in the general case in which the force is variable and the motion is curvilinear. Different persons or different machines may take different amounts of time to do the same amount of work. The term used to describe this rate of performance of work is power. The concept of work allows us to define kinetic energy and the kinetic energy theorem, which states that the work done by the net force on a particle is equal to the change in its kinetic energy. It is important to note that kinetic energy is the energy of an object due to its movement and if the object is moving, it can produce work by modifying its kinetic energy.

Then we study conservative and non-conservative forces and introduce potential energy, which is not associated with the motion of a particle but, as in the example of the force of gravity, with the position of the particle in the gravitational field. Another interesting example of potential energy is elastic potential energy. In the case of conservative forces we introduce the law of conservation of mechanical energy, which is one of the fundamental laws of nature. It is important to note that when a system does work on another, energy is transferred between the two systems. There are many forms of energy and if the energy of a system is conserved, the total energy does not change even if part of it changes its form or nature from one type to another. Generalization of the law of conservation of energy when non-conservative forces act on a system -for which there is no potential energy.

It is important to note that one way to transfer energy (absorbed or transferred) is to exchange work with the surroundings. If this is the only source of energy transferred (energy can be transferred even when there is an exchange of heat between a system and its surroundings due to a temperature difference, as discussed in the unit “Heat and temperature”), the law of conservation of energy is expressed by saying that the work done on the system by external forces is equal to the variation in total energy of the system. This is the work-energy law and it is a powerful tool for studying a wide variety of systems.

The theory of collisions is one of the most important applications of the law of conservation of momentum. We will deal only with collisions between two bodies. The final section of the unit focuses on the study of collisions, both elastic and inelastic. In an elastic collision kinetic energy is conserved. An inelastic collision is one in which kinetic energy is not conserved, for instance, because some energy is lost due to friction.
Thermodynamics is the branch of physics devoted to the study of energy processes, which involve heat, mechanical work, and other aspects of energy and energy transfer, and the relationship between processes and thermal properties of matter. The unit begins by introducing the concept of temperature and thermal equilibrium with the zeroth law of thermodynamics, thermometers and temperature scales, and the constant-volume gas thermometer. Heat is the energy transferred between a system and its environment (or surroundings), due solely to a temperature difference between the system and some part of its environment. Thus, in a system where there is a temperature difference heat flows from the warmer region to the cooler, until the temperatures are equalized.

After studying thermal expansion we present the ideal-gas equation and some ideal gas problems. An ideal gas is an idealized model which works best at very low pressures and high temperatures when the gas molecules are far apart and in rapid motion.

Next, we study heat capacity and specific heat. The heat capacity of a substance is defined as the thermal energy needed to raise the temperature of the substance one degree.

In the study of phase changes we introduce the concept of latent heat of fusion and vaporization. An important point is that the temperature remains constant during a phase change such as when ice melts or water boils.

Finally, we analyze the mechanisms of heat transfer, basically conduction because of its interest in engineering. Clearly, this phenomenon is of great interest in construction when considering, for example, the thermal insulation of houses. It is customary to classify the different processes of heat transfer into three basic types, although they often occur simultaneously. In heat transfer by conduction, the heat flow occurs due to the transfer of thermal energy from molecules of higher translational kinetic energy (higher temperature) to those of lower kinetic energy (lower temperature) without causing any mass transport. Conduction occurs within a body or between two bodies in contact. First we study Fourier's law, analyzing various problems of conductivity in the steady state such as in the case of a wall, both simple and compound, sphere and cylinder. Finally we briefly present the mechanisms of heat transfer by convection and radiation. Convection depends on movement of mass from one region of space to another and takes place in a liquid or a gas as a result of the actual movement of heated particles within it. Radiation is heat transfer by electromagnetic radiation, such as sunshine, with no need for matter to be present in the space between bodies. Every body emits this type of energy due to its temperature. Radiation is emitted in all directions, spreading at the speed of light. When it “strikes” against another body it can be reflected, transmitted or absorbed by it.
In this unit we analyze fundamental concepts of this branch of physics such as thermodynamic systems, state variables and functions, types of thermodynamic processes, etc., and introduce the first and second laws of thermodynamics.

Besides heat, there may be an energy transfer between a system and its surroundings through work, which does not depend on a temperature difference. Although energy can be transferred in the form of work by different types of forces (electric, magnetic, etc.), this unit will address the mechanical work done by the forces exerted by a system on its surroundings and vice versa, considering the particular case of work done by the force of fluid pressure to move a piston. This is the work done during volume changes.

After making reference to the state functions and equations, we introduce the first law of thermodynamics, which states that in any process in which heat is added to a system and the system performs work, the total energy transferred to the system is equal to the change in its internal energy.

Thus, internal energy is introduced by the first law, and is related to the concepts of heat and work. The first law is just another way of stating the law of conservation of energy and reflects the results of many experiments on the work performed by or on a system, the heat added or subtracted, and the system’s own internal energy. An important aspect is calculation of work for quasi-static processes: isochoric, isobaric and isothermal, and the pV diagrams for an ideal gas.

Next, we study the heat capacities and specific heats of gases, both at constant volume and at constant pressure, and the Mayer relationship between these specific heats, as well as the adiabatic process of an ideal gas.

Then we study heat engines, the wording of the second law of thermodynamics, and the efficiency of heat engines and refrigerators, before moving on to the Carnot cycle. From both the practical and theoretical perspective, the Carnot cycle is of great importance as a heat engine operating with this ideal reversible cycle which sets an upper limit to the efficiency of all heat engines.

Finally we introduce the concepts of thermodynamic temperature and entropy and calculate the entropy changes in various thermodynamic processes. The unit concludes with the study of the relationship between entropy, disorder, irreversibility and the second law of thermodynamics, indicating that the entropy of an isolated system may increase but can never decrease, and the entropy of the universe increases in all real processes.
Unit 7. Electric field

This unit is devoted to electrostatics, i.e., the study of an electric field and potential created by electric charges and continuous distributions of charge, which are at rest in our frame of reference. We begin with a brief discussion of the concept of electric charge and the electrical nature of matter, with special emphasis on the conservation and quantization of electric charge. We introduce Coulomb’s law, an experimental law describing the force between two stationary point charges. Subsequently, we introduce the concept of electric field and its representation by means of electric field lines. The superposition principle follows from the observation that each charge produces its own electric field, independently of the other charges present around it, and that the resulting electric field is the vector sum of each individual field.

There are often situations in which a large number of charges are so close that the total electrical charge can be considered continuously distributed in space, and it is necessary to use the charge density to describe a distribution of a large number of discrete charges. Volume, superficial and linear charge densities are introduced. In this context, some examples of how to calculate the electric field due to various types of continuous distributions of charge (line segment, ring and disk) are presented. Then we analyze the motion of point charges in electric fields, particularly in uniform fields, whether the electric charge enters the field with a velocity parallel or perpendicular to the direction of the field.

A well as the gravitational force between two masses, the electric force between two point electric charges is directed along the line joining the two charges and depends on the inverse square of their separation. Like the gravitational force, the electric force between charges at rest is conservative and there is a potential energy function associated with this force. We say that the electrostatic field is conservative. The potential energy per unit charge is called electric potential. Then we obtain the potential due both to a point charge and due to various continuous distributions of charge. It should be noted that we cannot speak of absolute electric potential at a point in space, but only of a potential difference between two points. If one wishes to speak of electric potential at a given point we must take arbitrarily, as a reference value, the potential at any given point. From the relationship between the electric field and the electric potential, we show how one can be calculated if the other is known. Equipotential surfaces are also introduced as surfaces that have the same potential at all points and we see how at each point of an equipotential surface the electric field is perpendicular to the surface; thus the electric field lines are perpendicular to the equipotential surfaces.

It is essential to study both the electric flux and Gauss’s law, which relates the electric field at the point of a closed surface to the net charge enclosed within it. Gauss’s law can be deduced from Coulomb’s law and is one of the four Maxwell equations of electromagnetism. This law provides a practical method for calculating the electric field of simple charge distributions that possess a certain symmetry (spheres, cylinders, lines, planes, etc.), using the concept of Gaussian surface.

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Based on the concepts outlined in the previous unit, in this unit we also examine conductors in electrostatic equilibrium. One can define a conductor as a material in which the electric charges can move freely. Using Gauss’s law we show that the charge and the electric field inside a conductor in electrostatic equilibrium is zero, so if the conductor is charged? The charge must be on its surface. Also using Gauss’s law we obtain the electric field at the surface of a conductor, an equation known as Coulomb’s theorem, proving that the electric field is always perpendicular to the conductor surface. It also shows how the electric potential is constant at all points of a conductor in electrostatic equilibrium and, therefore, its surface is an equipotential surface. Of particular interest is the study of the behaviour of a conductor when it is placed in an external electric field and the fact that the electric field is more intense in points near very small radii of the conductor, such as the edges or sharp areas, or the concept of corona discharge, the phenomenon by which many non-conductive materials are ionized in very high electric fields and become conductors. The magnitude of the electric field for which the dielectric breakdown occurs in a material is called dielectric strength. Finally, some systems of conductors are studied, especially those containing cavities in which other conductors are placed.

The last part of the unit is devoted to the study of capacitance, capacitors, dielectrics and electrostatic energy. The concept of capacitance of a conductor and a capacitor is introduced. A capacitor is a useful device for storing electric charge and energy, and consists of two conductors in close proximity but isolated from each other, which when connected to a potential difference, such as a battery, become equal and opposite electric charges. We study different types of capacitors such as the plane-parallel plate capacitor, the cylindrical and spherical capacitors.

We analyze the energy stored in capacitors during the charging of a capacitor and we introduce the concept of energy density of an electrostatic field. The energy stored in an electric field is equal to that required to create the field. Other issues to consider are the association of capacitors and the variations in capacity, field, potential and electric charge of a capacitor when a dielectric material is inserted between its plates, depending on whether the capacitor is isolated or not. It is important to mention that the function of the dielectric placed between the plates of a capacitor is not only to increase its capacity, but also to provide a mechanical support to separate the two conductors, which must be very close, and to increase the resistance to dielectric breakdown in the capacitor because the dielectric strength of a dielectric is generally greater than that of air.
This unit is dedicated to electric current, that is, the motion of electric charges from one region to another. The unit begins with a description of the nature of electricity, introducing the concepts of current intensity and current density. Current is a scalar that represents the charge that flows through a section of a conductor per unit of time, while current density is a vector quantity whose flow through a given surface is precisely the current intensity. An important aspect is the expression that relates current density to microscopic quantities such as the concentration of electric charges, the charge on each particle and drift velocity.

Then we study Ohm’s law and introduce the concept of resistance, as well as the expressions for the equivalent resistance of resistors in series and in parallel. Using the expression for current density vector we obtain a vector equation for Ohm’s law that relates current density and applied electric field by means of conductivity or its inverse, resistivity. It is important to present some numerical values of conductivity (or resistivity) for conductors, semiconductors and insulators, and to note that while the resistivity of a metallic conductor increases with temperature, the resistivity of a semiconductor decreases when the temperature increases.

The existence of an electric current through wires that constitute a circuit involves a dissipation of energy in the form of heat due to the Joule effect; thus, to maintain a current other elements are necessary to provide energy to the circuit. This is the function of generators, devices that transform some energy into electrical energy, and which are characterized by electromotive force.

Finally, we briefly describe the use of ammeters and voltmeters as electrical measuring instruments, which allow us to measure current intensity and potential difference or voltage experimentally. We also discuss how to use a voltmeter and an ammeter together to measure resistance and power.
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