MEDICAL UNIVERSITY – PLEVEN
FACULTY OF MEDICINE

DIVISION OF PHYSICS AND BIOPHYSICS

LECTURE 7

INTRODUCTION TO ELECTRICITY AND MAGNETISM

The electrical nature of matter. The flow of electric charge. Electric fields and voltages. Cathode ray tubes. The oscilloscope. Magnets and magnetic fields. Electromagnets. The interaction between electricity and magnetism

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Classical (orbital) model of the atom – a positively charged nucleus made up of protons and neutrons, and a number of negatively charged electrons in orbit about that nucleus.

This model is useful for visualizing electrical processes, but quite inadequate for describing the details of atomic structure.

These details can be explained with the methods of quantum mechanics.

The usefulness of the orbital (Bohr) model of the atom, is based upon the fact that the physical parameters of electrons are "quantized" and can take on only certain discrete values.

The electron has one "quantum" of (-) charge, which is 1e= 1.6×10^{-19} C. The proton also has one quantum of charge, but it is of the opposite positive polarity. The neutron has no charge and is neutral.

The experimental evidence to date indicates that this quantum of charge is the smallest unit of charge that can be isolated and observed.

Although there is evidence that protons and neutrons are made up of smaller charged particles called quarks, they cannot be experimentally isolated and are observed only in combinations that add up to zero or one quantum of charge.

All charged objects, therefore, have an integer multiple of the quantum of charge.

The electron is the primary charge carrier in most electrical phenomena involving metal wires.

$m_e = 9.1 \times 10^{-31}$ kg; $m_p = 1836\ m_e$; $m_n = 1839\ m_e$.

THE BEHAVIOR OF ELECTRIC CHARGES

Charges of the same polarity repel each other, while unlike charges experience a strong attractive force.

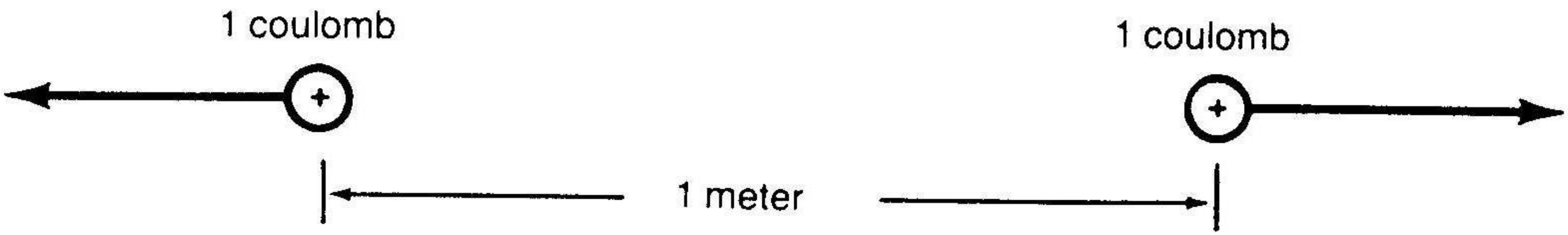
$$\boxed{F = \frac{kq_1q_2}{r^2}}$$

Coulomb's law

k = 9 x 10^9 Nm^2/C^2 in SI units.

The electrostatic force, *F,* is the force on each charge. The forces on the two charges are equal in magnitude and opposite in direction, as required by Newton's third law, and are directed along the line joining the two particles.

(a) Unlike charges attract



$$F = \frac{Kq_1q_2}{r^2} = 9 \times 10^9 \text{ newtons} \approx 1 \text{ million tons}$$

The form of Coulomb's law is like that of the universal law of gravitation:

$$F_{\text{gravity}} = \frac{G m_1 m_2}{r^2}$$

$$F_{\text{electric}} = \frac{K q_1 q_2}{r^2}.$$

Both depend upon products of the appropriate quantities (mass or charge) and both are *"inverse square" laws* since the force is inversely proportional to the square of the separation distance.

Let us compare the magnitudes of these forces.

A hydrogen atom is composed of one proton and one electron. The electrostatic force is more than 10^{39} times as strong as the gravitational force! Therefore, the gravitational force inside an atom is negligible compared to the electrostatic force, and the forces which hold atoms together are electrical forces.

In fact, *chemical bonding forces, frictional forces, forces experienced during collisions*, and most other common interaction forces are electrical in nature when viewed on an atomic scale.

THE FLOW OF ELECTRIC CHARGE

The outer electrons of metal atoms are very loosely bound and can be easily detached to move through the material.

Metals are said to be good *conductors* of electricity because of the availability of charge carriers. Metals offer very little resistance to the flow of electrons through them.

The electrons in rubber, ceramics, and other materials are very tightly bound to their parent atoms and it is very difficult for electric charge to move through these materials. Such materials are called *insulators.*

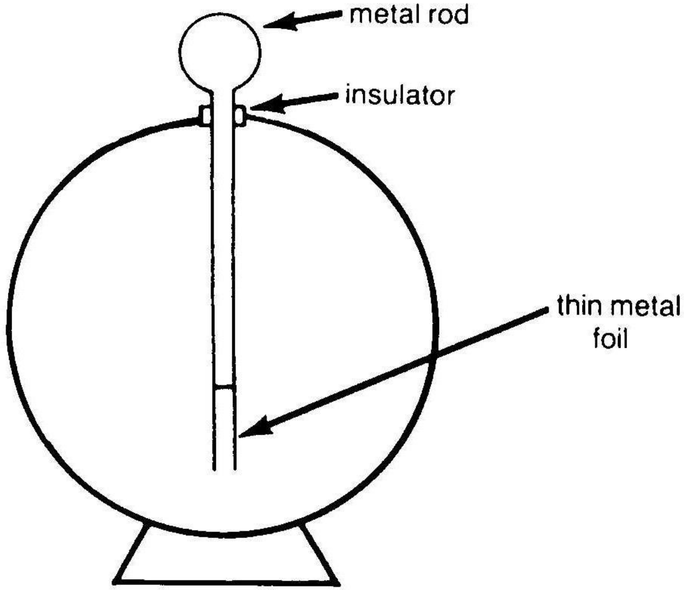
There is a limited class of materials which offer intermediate resistance to charge flow and are known as *semiconductors.* They are used for the manufacture of transistors and other solid-state electronic devices.

The movement of charges can be illustrated with the use of an electroscope. The device is composed of a metal rod with two strips of very thin metal foil attached to the bottom. The lower part of the rod is usually enclosed in glass to protect the delicate foil strips, and the rod is separated from the case by means of an insulator such as rubber.

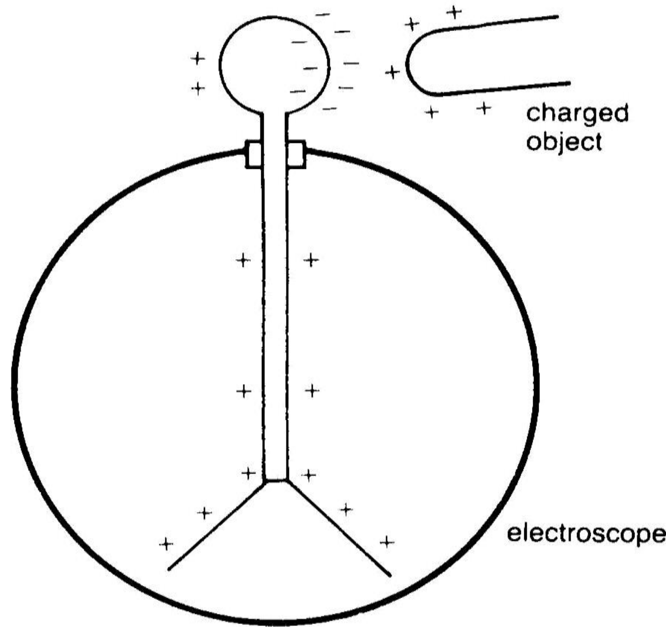
If the electroscope is uncharged, the two foil strips will hang loosely.

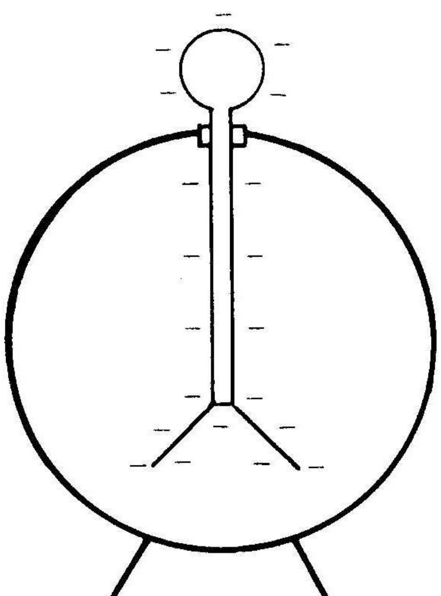
If the electroscope has a net negative or positive charge, the foil strips will repel each other. If a positively charged rod is brought close to the top of an uncharged electroscope, the net positive charge will attract some electrons from other parts of the rod, causing the top of the electroscope to be negatively charged.

The bottom of rod and the foil strips will then be positively charged, since they will have a deficiency of electrons. The repulsion of like charges will cause the foils to separate.

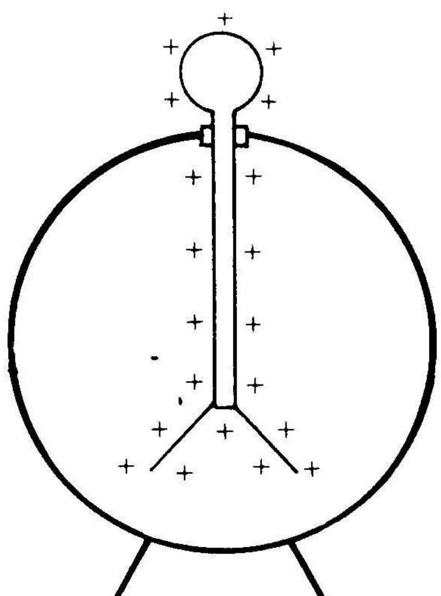


(a) uncharged electroscope

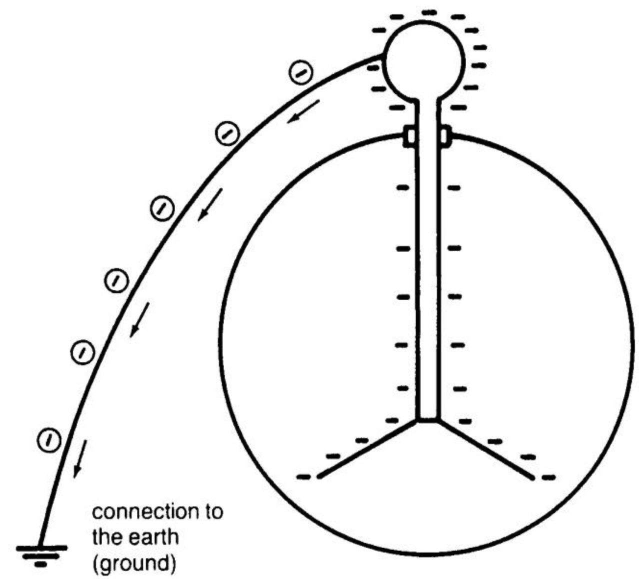




(b) negatively charged electroscope



(c) positively charged electroscope



Even though the electrons are the mobile particles, an excess positive charge will distribute itself as readily as an excess negative charge. If the metal chassis of an electrical appliance becomes charged, the entire chassis will have an excess charge since the charges will be distributed by their mutual repulsion.

If an additional conducting path is provided in the form of a wire connected to the earth, the excess charges will move along that wire to "ground" since the earth is a conductor and the charges can move much further apart on the surface of the earth. This removal of excess charge is one of the functions of a "ground" wire.

At ordinary temperatures, the electrons in a wire are extremely agitated and move constantly at speeds of thousands of m/s as a result of their internal energy, behaving somewhat like a contained electron gas.

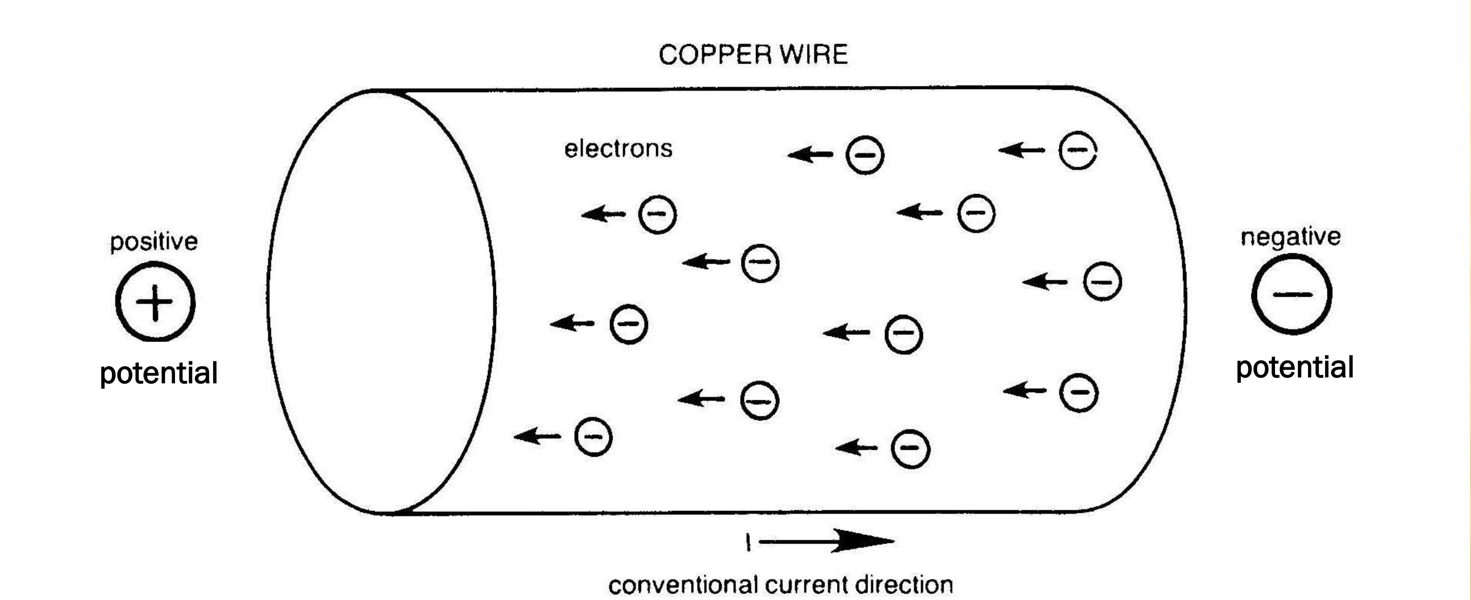
The electrical influence superimposes only a small drift velocity on the order of cm/s upon the high speed random thermal motion. This small velocity is quite sufficient to conduct large electric currents through wires.

This slow drift velocity is *not* the speed with which an electrical signal is sent on a wire; we do not have to transport a given electron from one end of the wire to the other to get an electric current flow.

As soon as an electron moves in one end of the wire, it repels its nearest neighbor, which transmits the repulsive force down the length of the wire at the speed of light, 3×10^8 m/s!

Def. Electric current is the flow rate of charge.
It is analogous to the volume flow rate of a liquid through a pipe (Poiseuille's law).

For historical reasons, the direction of electric current flow is from positive to negative in a wire, as if the positive charge were flowing. This is the conventional direction of current used in scientific literature.



ELECTRIC FIELDS AND VOLTAGES

If you brought a small positive test charge near another concentration of positive charge, the test charge would experience a repulsive force.

You could say that there is an "electric force field" around the concentration of charge which will repel any other positive charge but attract a negative charge.

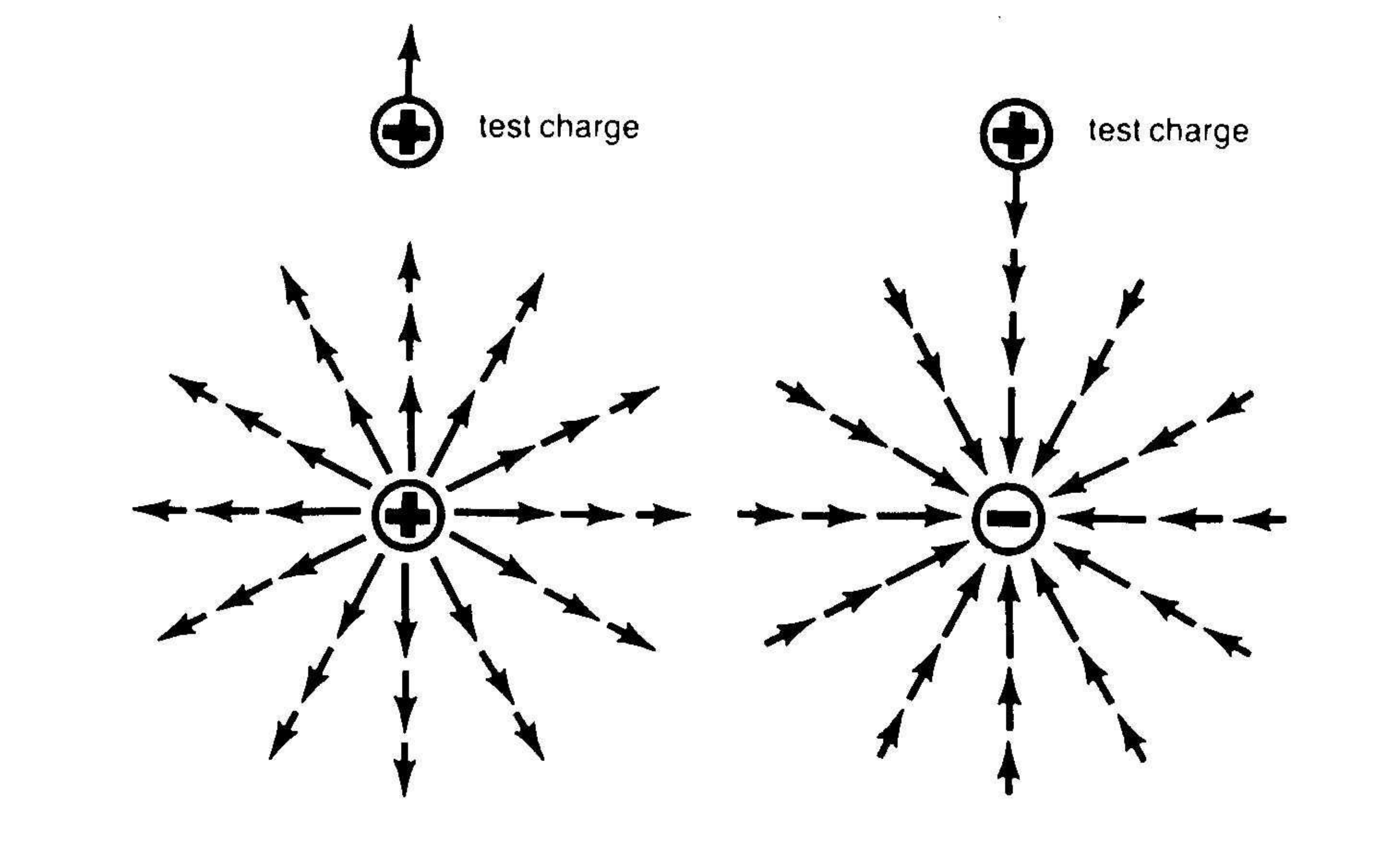
Def. The electric field strength at any point is defined as the force per unit charge $E=F/q$

Def. A "point charge" is a concentration of charge at a mathematical point.

Def. The direction of the electric field is defined as the direction of the force on a positive test charge.

The electric field around charges can be represented by "lines of force".

The electric field extends radially outward from a positive point charge and radially inward toward a negative point charge.



The electric field strength drops off rapidly with the distance from the charge

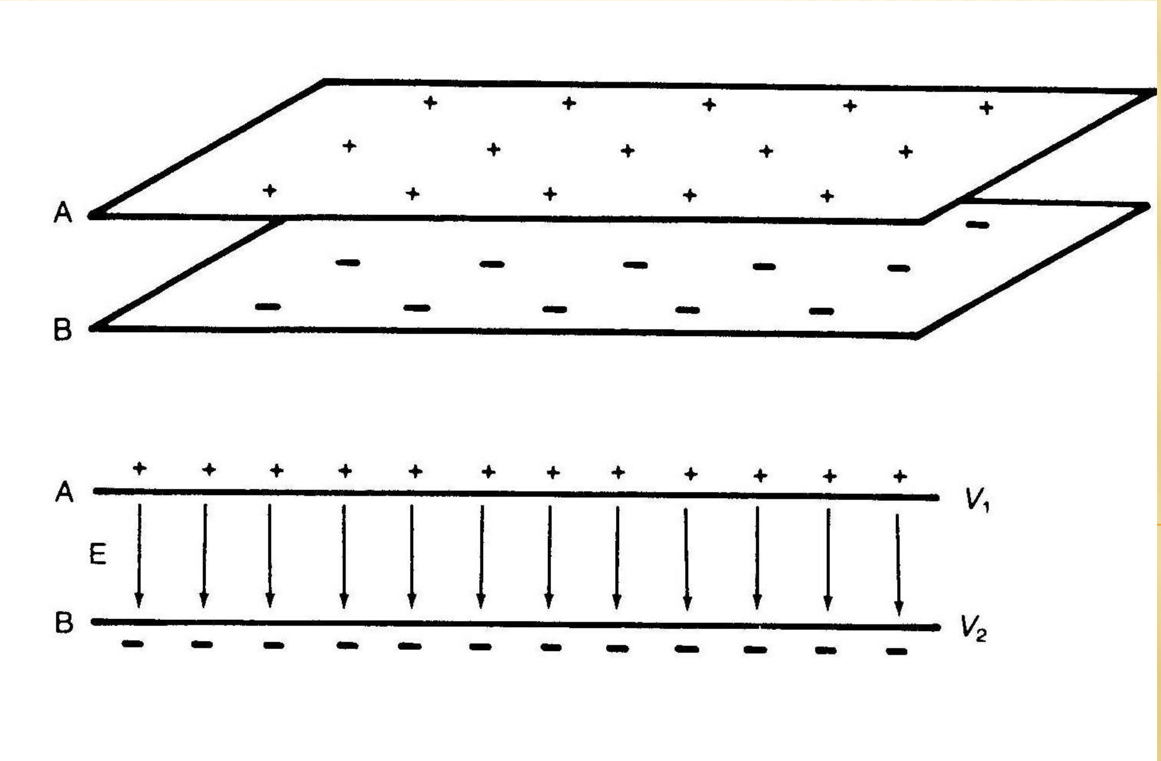
$$E = \frac{kQ}{r^2}$$

Def. The electric potential is defined as the electric potential energy per unit charge.

- Let us take a set of parallel metal plates. If one plate has an excess (+) charge and the other an excess (-) charge, then there is an electric field between the plates directed toward the negative plate, since a positive charge placed between the plates would experience a force toward the negative plate. Since electrical potential is the electric potential energy per unit charge, the positive plate has a high potential. The negative plate has a lower potential.

- The standard direction for all electric currents is the direction which positive charge would flow, downhill from high potential to low potential.

Parallel plates can be used to store electric charge in a state of elevated electric potential energy (i.e., high voltage). The stored charge can then be released to do work. A set of parallel plates is referred to as a *capacitor*.



The capacitance is defined as the charge which can be stored per 1 volt of electric potential difference. [C]=F=C/V.

E.g. If 0.001 C can be stored on a capacitor by generating a voltage of 10^3 V between the plates, then C=1μF.

The charge will remain on the capacitor indefinitely if there is no conducting path available to "discharge" the capacitor. If a wire is connected between the two charged plates, electrons will move quickly from the negative plate to the positive plate to neutralize the unbalanced charge.

The process of discharging a capacitor releases energy.

Def. The defibrillator is essentially a large capacitor.

An electrical energy of several joules may be stored in the defibrillator. When the electrodes are connected across the patient's body, the body forms a conducting discharge path and a large current flows for an instant.

Cell membranes maintain unbalanced charge layers which can store electrical energy and aid in the transport of charged electrolyte ions across the membranes.

Similar biological "capacitors“ in nerve cells can discharge to produce the electrical impulses involved in the transfer of nerve signals.

A configuration similar to the parallel plates can be used to create an "electron gun." If an electron is released from the negative plate, it will be accelerated toward the positive plate.

Since the mass of the electron is quite small, it can attain very high speeds in such processes. As the electron travels between the plates, its E_p is converted into E_k.

Since the potential difference *V* between the plates is a measure of the electric potential *energy per unit charge,* then $E_p = qV$, where *q* is the charge in coulombs.

CATHODE RAY TUBES. THE OSCILLOSCOPE

Def. A cathode ray tube is a device which forms a visual display of the electron beam from an electron gun.

The electron gun is placed in an evacuated glass tube and aimed so that the high speed electron beam strikes a phosphor coating on one end of the tube.

When struck by the beam, the phosphor coating gives off light, forming a visual image of the electron beam. Because of the historical practice of calling the negative electrode the "cathode," the electron beam is often called a "cathode ray."

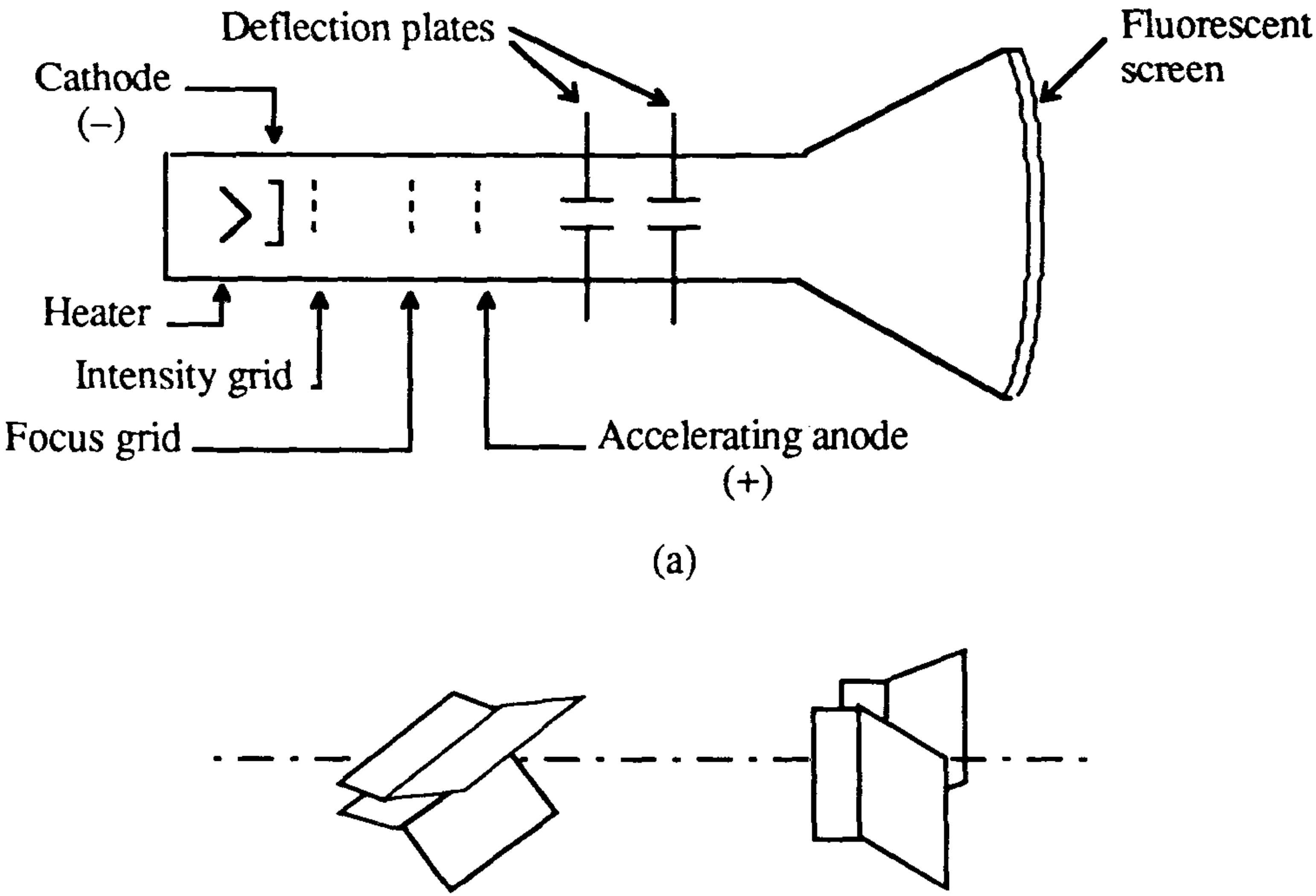
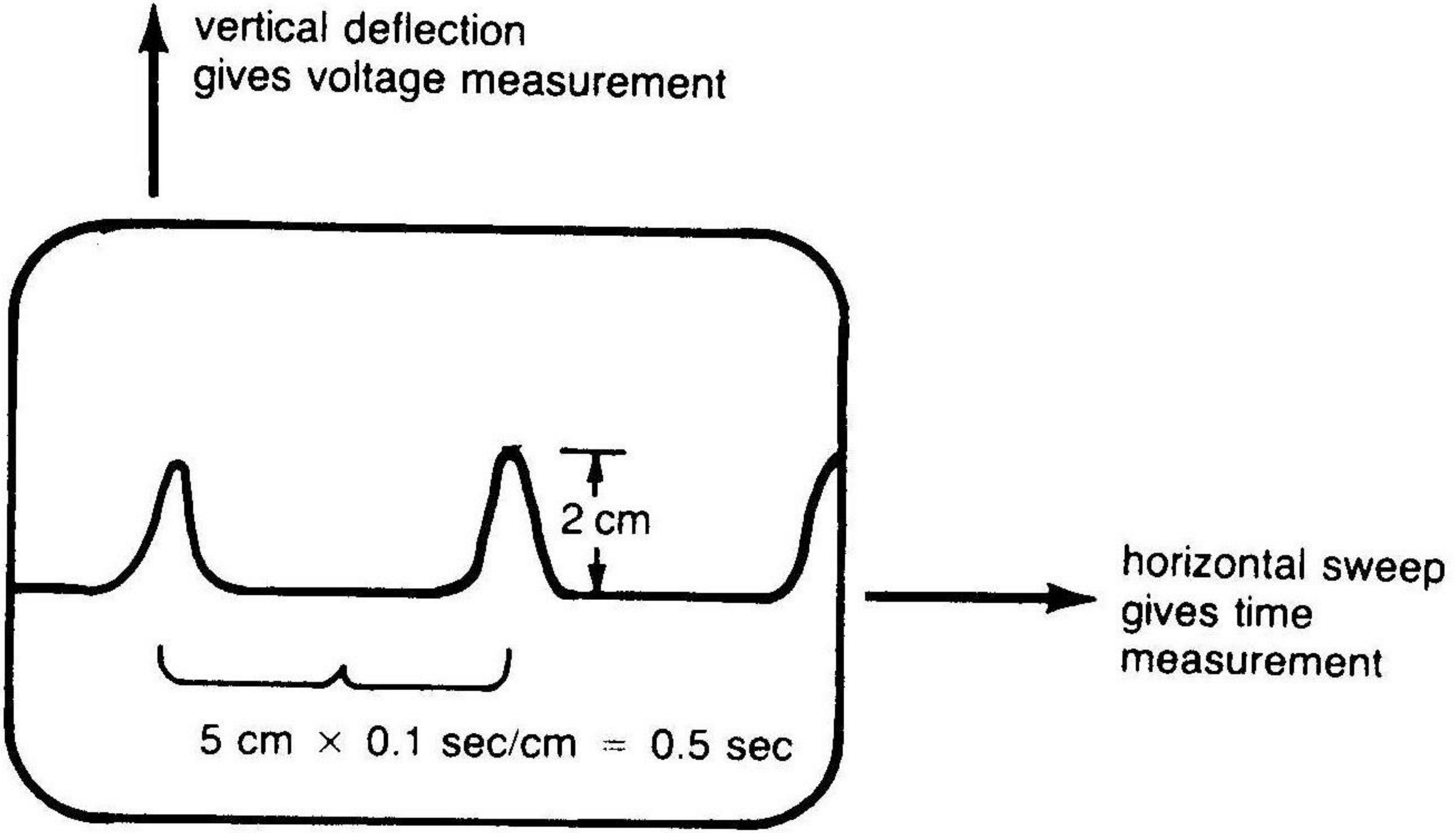


Figure 1. Cathode-ray tube: (a) schematic, (b) detail of the deflection plates.

- ✓ The position of the electron beam on the phosphor screen can be moved easily and very rapidly to form a moving display of electrical signals, such as an ECG signal.

- ✓ The movement of the beam is accomplished by two sets of deflection plates.

- ✓ The amount of deflection of the beam is proportional to the voltage between the deflection plates. Therefore, the deflection of the beam can be calibrated to give a visual measurement of the voltage of the deflection plates.

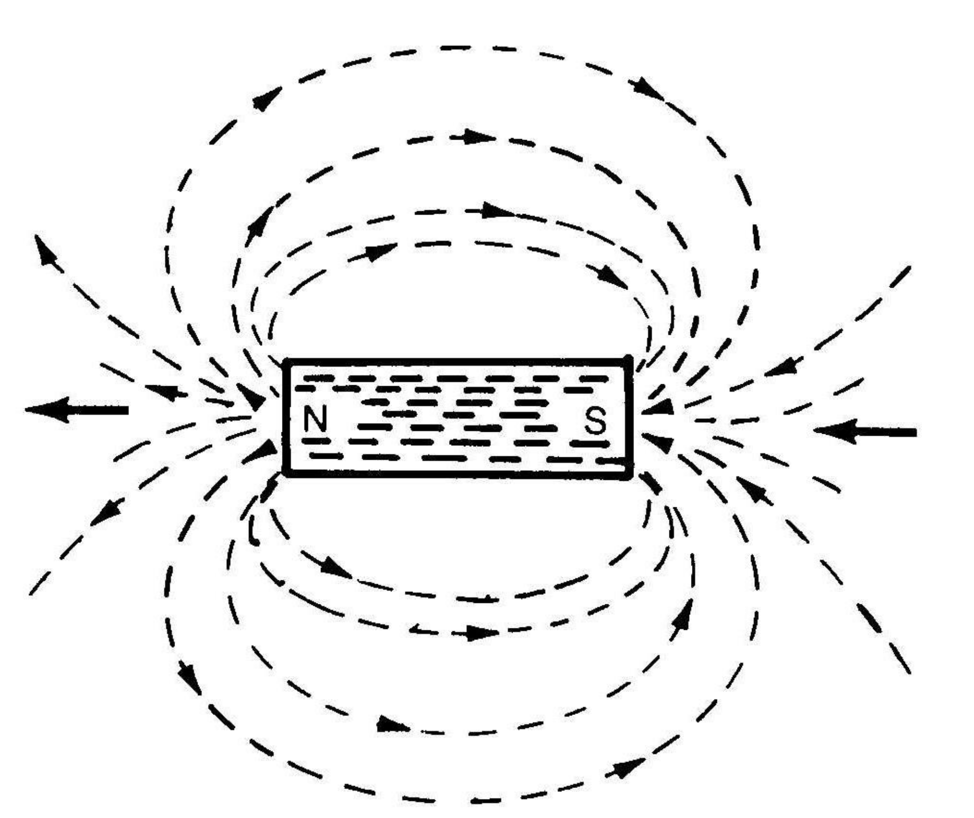

vertical deflection
gives voltage measurement
2 cm
horizontal sweep
gives time
measurement
5 cm × 0.1 sec/cm = 0.5 sec

MAGNETS AND MAGNETIC FIELDS

Simple magnets have two "poles" which are designated as north and south poles. If the north poles of two magnets are brought close together, they will repel each other, but the north pole of one magnet will attract the south pole of another.

These poles always occur in pairs. There is apparently no magnetic analog to the point charge as a source of electric fields.

The behavior of magnets can be described in terms of a magnetic field, but this field is not directed radially outward from the source like the electric field due to a point charge.



Arrows directed along the field lines indicate the direction of the magnetic field.

The density of the lines indicates the relative strength of the magnetic field. The field is strongest at the poles and it is directed outward from the north pole of the magnet.

A small test magnet would tend to line up with the magnetic field with its north pole directed along the direction of the magnetic field.

This is the principle of operation of the ordinary magnetic compass. The compass needle is a small, freely suspended magnet which can rotate to align its north pole with the direction of the earth's magnetic field. It can be used to map the direction of a magnetic field.

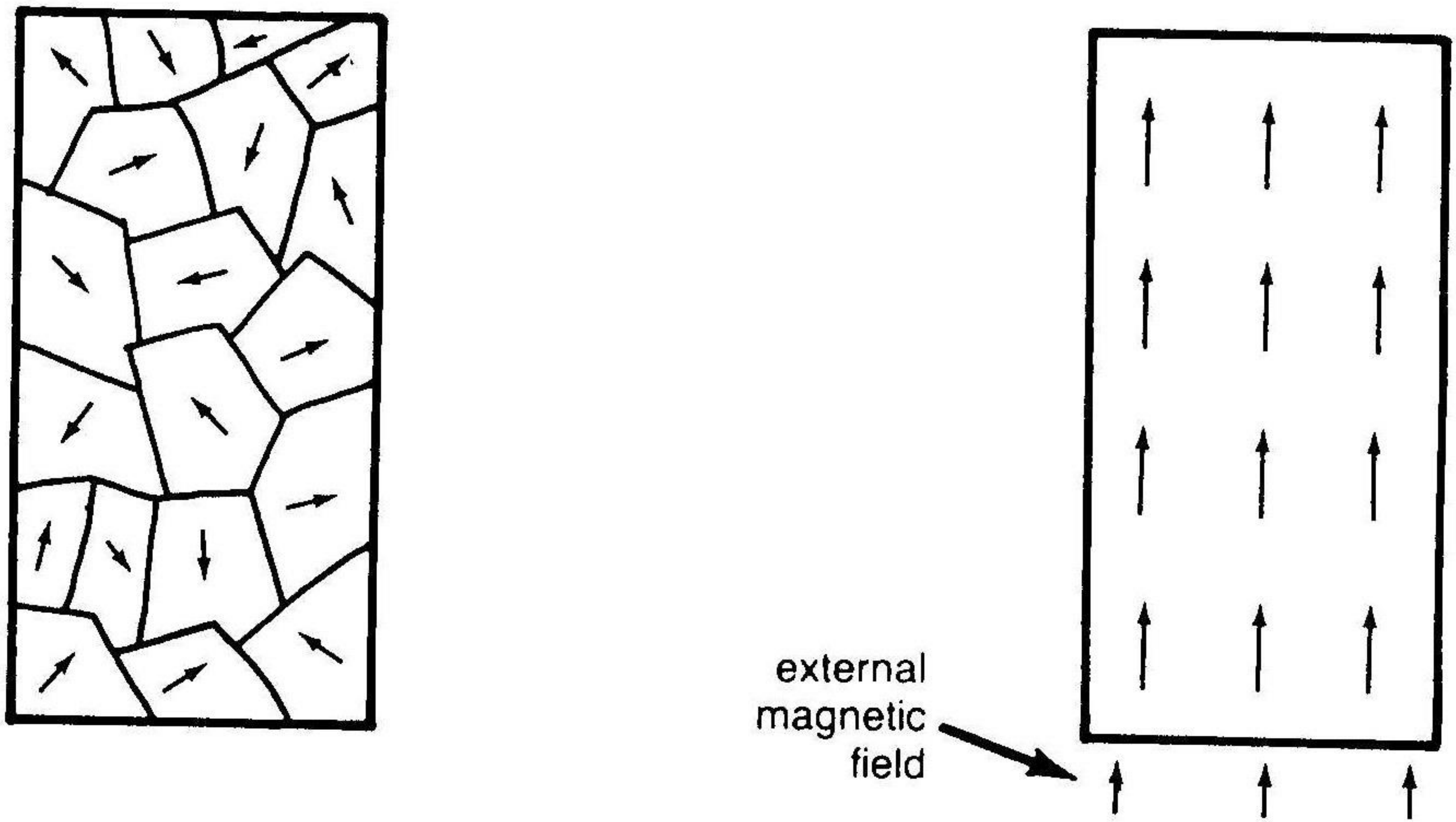
Only a few types of materials are attracted by magnets. These materials exhibit the property of "ferromagnetism" or "iron-like" magnetism.

The only common materials which exhibit ferromagnetism are iron, nickel, cobalt, and some alloys.

Ferromagnetism occurs as a result of long-range ordering of the atoms of a solid such as iron into small ordered regions called "domains." The orientation of the atoms in these domains is such that the domain as a whole acts like a tiny magnet.

A piece of unmagnetized iron will have many such domains of random orientations so that the magnetic fields cancel and the bulk material produces no magnetic field.

If the material is subjected to an external magnetic field, the tiny domains tend to line up with the field. The material then yields a net magnetic field and is said to be "magnetized ".



(a) unmagnetized

(b) magnetized

If the north pole of the magnet is brought close to the iron, the domains are aligned with their fields pointing away from the magnet so that the surface of the iron represents a south pole and is attracted. When the south pole of a magnet is brought close, the domains align so that the surface of the material constitutes a north pole and attraction again occurs.

When the external magnetic field is removed, the domains do not immediately resume their random orientations, so the material retains part of its magnetization for a time. Certain iron alloys retain their magnetization for long periods , the so-called "permanent magnets.”

The thermal agitation of the molecules of the material tends to randomize the orientations of the domains and thus demagnetize the material.

Heating a magnet above a certain temperature will destroy the magnetic ordering and the material no longer exhibits the ferromagnetic property.

A magnet will not pick up a red-hot piece of iron, since iron does not exhibit ferromagnetism at that temperature. Most common materials can be classified magnetically as either ferromagnetic, paramagnetic, or diamagnetic.

ELECTROMAGNETS

If an electric current I flows through a straight wire, a magnetic field will be generated by that current. The magnetic field is represented by a letter *B*. The field will circle the current-carrying wire.

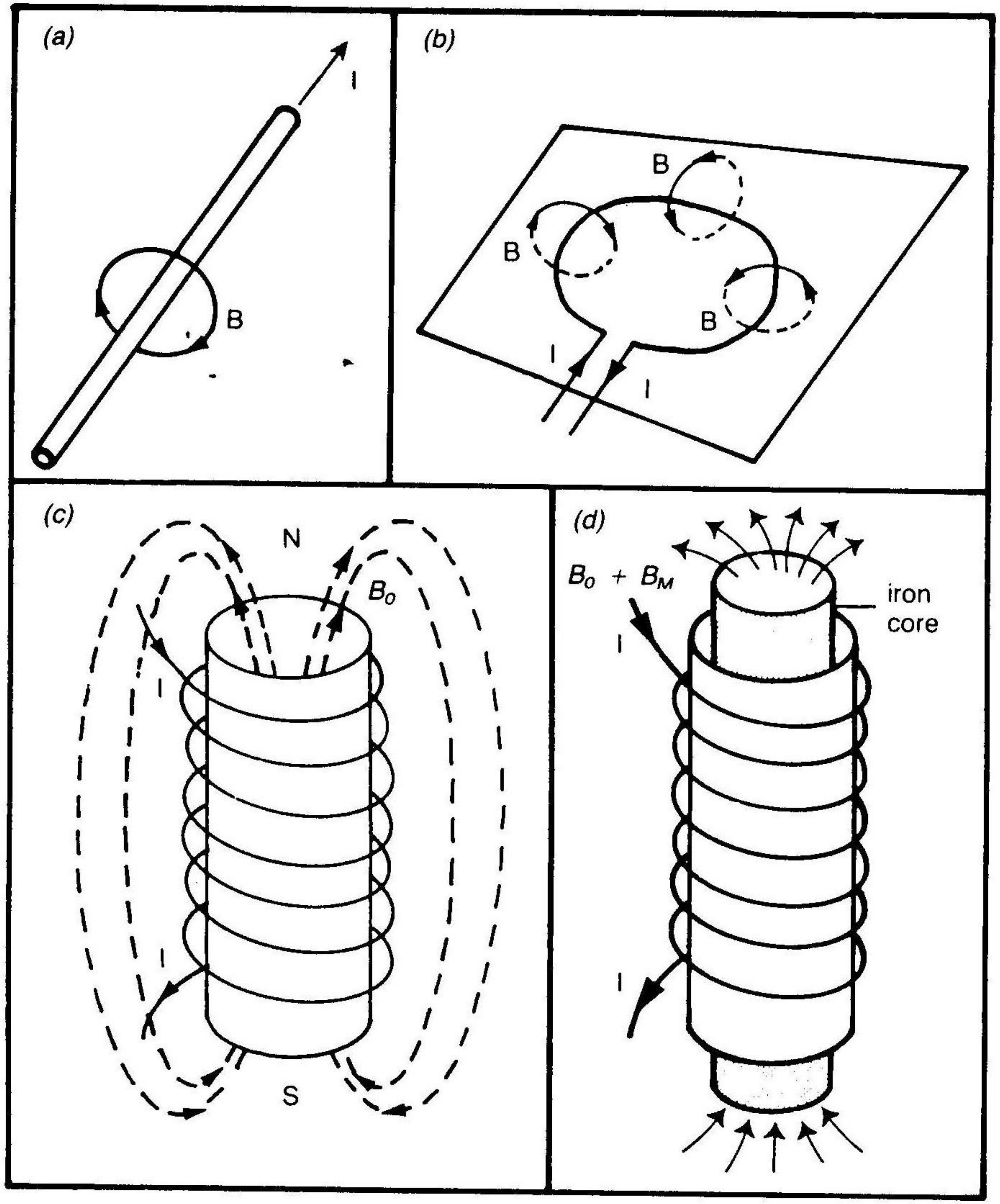
The direction of the magnetic field associated with any current may be determined by the "right-hand rule." Point the thumb of the right hand in the direction of the current, and curl the index finger around the wire. The direction of the index finger gives the direction of the magnetic field.

If the current-carrying wire is bent into a loop, the magnetic fields add together inside the loop to give a stronger magnetic field.

A further strengthening of the magnetic field can be obtained by winding a long coil of wire, often referred to as a "solenoid." The magnetic field configuration is like that of the bar magnet.

The solenoid can be called an "electromagnet" and could be used for the same functions as a bar magnet. The principal disadvantage of the solenoid is that very large currents are required to produce useful magnetic fields.

Practical electromagnets are made by adding an iron core to the solenoid. The small magnetic field produced by the current causes the domains of the ferromagnetic core to line up and produce an additional magnetic field, B_m.



I = electric current

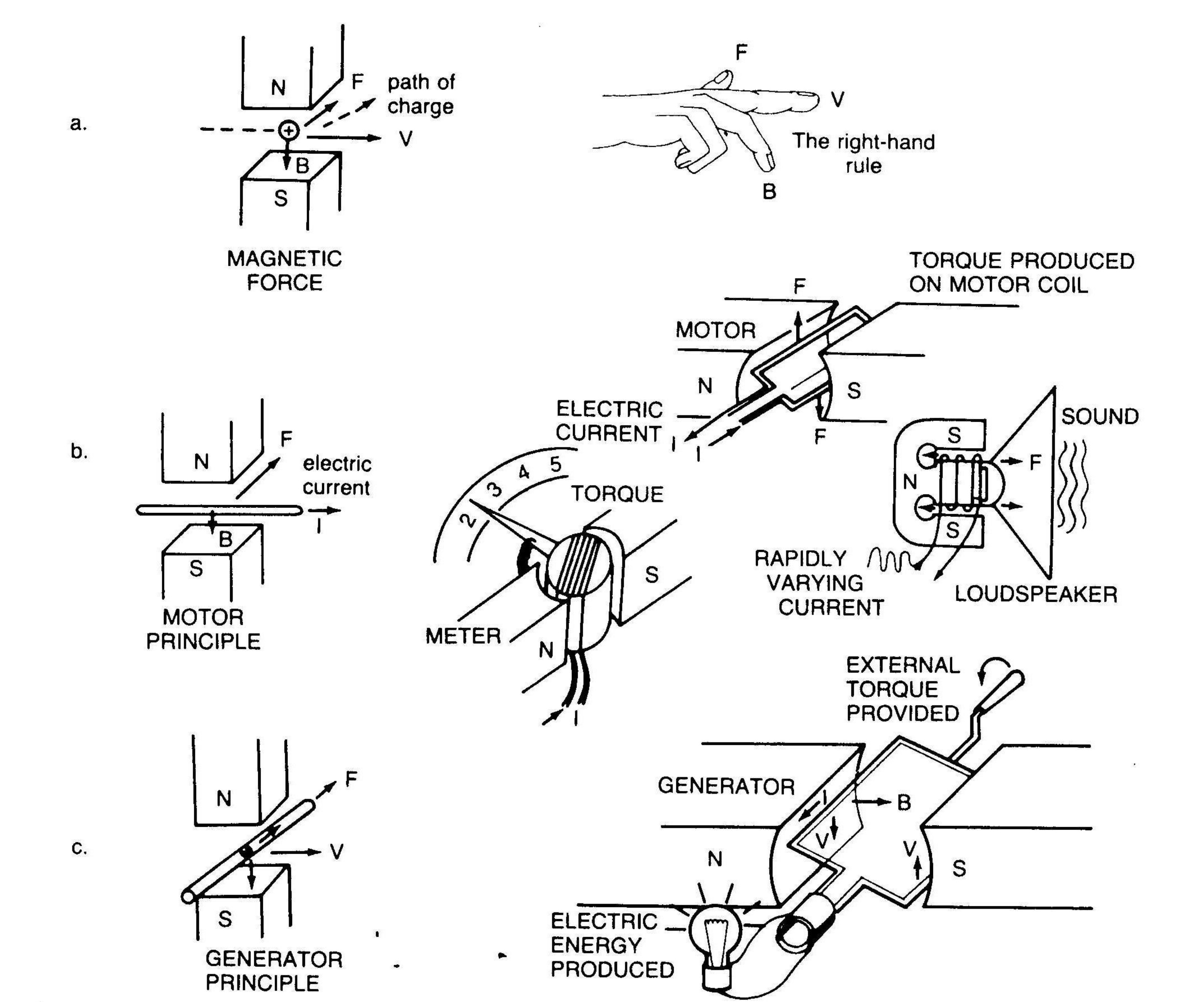
B = magnetic field

THE INTERACTION BETWEEN ELECTRICITY AND MAGNETISM

Electricity and magnetism are manifestations of the same basic force, the electromagnetic force.

Many physical phenomena and the operating principles for many devices involve the interaction between electricity and magnetism.

The first-phenomenon to be examined is the force exerted upon an electric charge by a magnetic field. If a positive charge q moves into the field B of a magnet with velocity v, it will experience a force that is perpendicular both to the velocity and to the magnetic field.


a.
N
F
path of
charge
V
B
S
MAGNETIC
FORCE
F
V
The right-hand
rule
B
TORQUE PRODUCED
ON MOTOR COIL
F
MOTOR
N
S
ELECTRIC
CURRENT
I
I
F
b.
N
F
electric
current
I
B
S
MOTOR
PRINCIPLE
2
3
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5
TORQUE
S
METER
N
I
SOUND
S
F
N
S
RAPIDLY
VARYING
CURRENT
LOUDSPEAKER
EXTERNAL
TORQUE
PROVIDED
c.
N
F
V
S
GENERATOR
PRINCIPLE
GENERATOR
I
B
V
N
V
S
ELECTRIC
ENERGY
PRODUCED

$F=qvB_{\perp}$

A magnetic field exerts no force on a charge at rest or on a charge that is moving exactly parallel to the magnetic field.

The direction of the force is given by the "right hand rule”. If the magnetic field area is small and the charge passes through it, the effect is to deflect the charge from its original path.

If the magnetic field area is large enough to trap the charge, it will move the charge in a circular path. In other words, the magnetic force provides the centripetal force necessary to move the charge in a circle.

Any current-carrying wire in a magnetic field will experience a force perpendicular to the wire. This is sometimes called the electric motor principle.

An electric motor can be thought of as a collection of wire loops arranged on a rotor, suspended in a magnetic field in such a way that they can spin freely. If an electric current flows through the loops, a force will be produced perpendicular to each section of the wire.

Looking at the coil from one end, the magnetic force will be up on one side of the coil and down on the other, producing a torque to rotate the motor.

This same principle is used to produce one of the common types of electric current meters, the moving-coil meter. A coil of wire is placed so that it can rotate in the field of a magnet.

When I flows through the wires, the magnetic force on the coil sides and the torque on the coil are proportional to the amount of current flowing in the coil. An indicator needle is attached to the coil, and its movement is resisted by a calibrated spring.

The amount of the needle's deflection is proportional to the torque and hence proportional to the electric current.

Many devices exist to produce an electric current proportional to some physiologically significant measurement.

Another operational principle that arises out of the basic magnetic force law is the generator principle.

When a wire is forced to move through a magnetic field in a direction perpendicular to the wire, the magnetic force on the mobile charges in the wire is directed along the wire. This tends to move the charges down the wire in the same way that a battery would act to move them. It can be said that moving a wire sideways through a magnetic field generates a voltage in the wire.

The motor principle and the generator principle demonstrate the reversible nature of the interaction between electricity and magnetism. The electric motor and the electric generator can in fact be the same device.

- If electric current is forced to flow through the coil by an external electric source, the resulting magnetic force will cause the coil to rotate as a motor.
- If the coil is forced to rotate by some external source of mechanical energy, the magnetic force will generate a voltage in the coil.

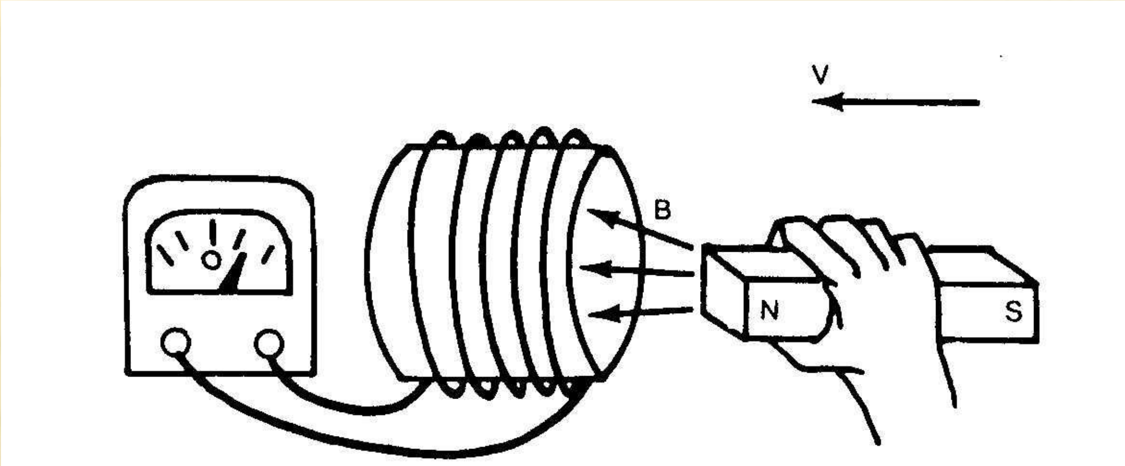
If a magnet is moved into a coil of wire, it will generate a voltage in the coil. The magnitude of the generated voltage depends 1) on the area covered by the magnetic field in the coil, 2) the number of turns in the coil, 3) the strength of the magnet, and 4) the speed with which the magnet is brought into the coil.

The product of the magnetic field and the area is defined as the magnetic flux: $\Phi = BA$

Then the voltage generated in the coil can be determined by the rate of change of the magnetic flux times the number of turns in the coil:

$$\boxed{V = -N \frac{\Delta \Phi}{\Delta t}}$$

Faraday's law



The negative sign in Faraday's law indicates that the induced magnetic field always opposes the change that created it.

Many types of remote sensors used in diagnostic procedures make use of Faraday's law and the generator principle to induce an electrical signal in a receiving coil or antenna. Examples are ultrasound scans, Doppler pulse detection, and NMR imaging.