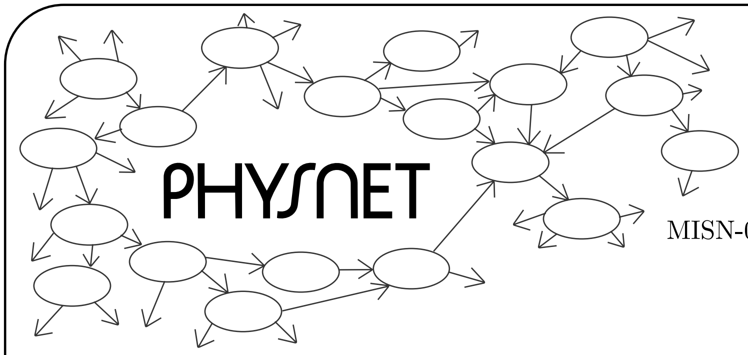
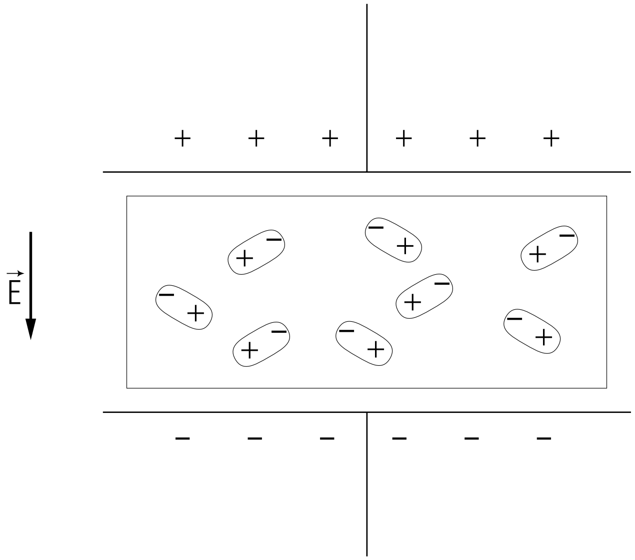


MISN-0-421

ELECTRIC PROPERTIES OF MATERIALS



Project PHYSNET Physics Bldg. Michigan State University East Lansing, MI

ELECTRIC PROPERTIES OF MATERIALS

by

F. Reif, G. Brackett and J. Larkin

CONTENTS

Title: **Electric Properties of Materials**

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Input Skills:

1. Vocabulary: electric potential, potential drop, equipotential surface (MISN-0-420).

Output Skills (Knowledge):

K1. Vocabulary: conductor, dielectric, dielectric constant, electric dipole moment, potential difference.
K2. Describe the electric field and potential inside a conductor.
K3. Describe the electric field inside a dielectric slab.
K4. State examples of conductors and dielectrics.

Output Skills (Rule Application):

R1. Given the electric field inside and outside a dielectric slab, calculate the dielectric constant of the material.

Output Skills (Problem Solving):

S1. Given a conducting or dielectric object in equilibrium in an externally produced electric field, qualitatively determine: (a) the charge distribution; (b) the electric field and potential inside or at the surface.
S2. Determine the electric field due to charged conductors: (a) quantitatively, by relating the electric field between two parallel metal plates to the potential of the plates or to the potential difference between them; (b) qualitatively, by comparing the magnitude of this field at various points near a conductor.
S3. Qualitatively determine the force on a dipole due to the electric field produced by external particles.
S4. Qualitatively determine the electric force on an uncharged object, given information about nearby charged particles or the electric field due to them.

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MISN-0-421

ELECTRIC PROPERTIES OF MATERIALS

Abstract:
Electric field and potential (Chs. 19 and 20)

All materials (whether solids, liquids, or gases) consist of charged atomic particles, i.e., of atomic nuclei and electrons. Hence all materials give rise to electric effects which are readily observable and useful in any practical applications. We shall use the present unit to discuss some of these important electric effects.

SECT.

A DIELECTRICS AND CONDUCTORS

► *Charged particles in materials*

Every material consists of positively and negatively charged particles, the atomic nuclei and electrons which form the atoms and molecules in the material. These charged particles are bound together by atomic forces (ultimately due to Coulomb forces) which keep the particles associated so as to form the material. Because of the mutual attraction between positively and negatively charged particles, every positively charged particle is very near to negatively charged particles. As a result, any small region of the material contains almost the same amount of positive and negative charge, so that the *total* charge in any small region of the material is ordinarily zero.

If a material is placed in an electric field due to external charged objects, the positively charged particles in the material experience electric forces *along* the direction of this field and the negatively charged particles experience electric forces *opposite* to the direction of this field. Thus the forces due to the applied electric field tend to separate the positively and negatively charged particles from each other. How much separation occurs depends crucially on the magnitude of the atomic forces which hold these charged particles together in the material. Thus the applied electric field produces only a very small separation of the charged particles if these are bound together by strong atomic forces. But the same field produces a larger separation of the charged particles if these are bound together by weaker atomic forces.

► *Dielectrics*

In most materials, every negatively charged particle is strongly bound to some positively charged nearby particle. If an electric field is applied, these charged particles then move only slightly away from their normal positions in the material. Such materials are called “dielectrics” or “electric insulators” in accordance with this definition (already encountered in text section H of Unit 411):

Def. | **Dielectric**: A material in which charged particles can only move slightly away from their normal positions. | (A-1)

Examples of dielectrics are materials such as glass, plastics, rubber, oil, and dry air.

► *Conductors*

By contrast, there are materials in which some of the charged atomic particles are bound so weakly by atomic forces that they are free to move throughout the entire material. Such materials are called "electric conductors" in accordance with this definition:

Def.	**Conductor**: A material containing charged atomic particles which can move throughout the entire material.	(A-2)

For example, metals (such as copper or aluminum) are electric conductors because some of their electrons are "mobile," i.e., are free to move throughout the entire metal. Similarly, ionic solutions such as solutions of sodium chloride in water are electric conductors because they contain positively and negatively charged ions (e.g , Na^+ and Cl^- ions) which are free to move throughout the entire solution.

Although the mobile electrons in a metal are free to move throughout the entire metal, the atomic forces on them are ordinarily strong enough to keep them within the metal. Thus the mobile electrons remain ordinarily within the metal unless this metal is in contact with another conductor, in which case the electrons can pass freely between the two conductors.

There is no sharp distinction between materials which are dielectrics or conductors. Nevertheless, most materials differ so much in their electric properties that their classification into dielectrics and conductors is clear and useful.

In the remaining sections of this unit we shall first discuss the properties and practical applications of electric conductors, and then those of dielectrics.

Knowing About Conductors and Dielectrics

A-1 Which are conductors and which are dielectrics: (a) A solution of CuSO_4 in which both positively and negatively charged ions (Cu and SO_4) are free to move throughout the substance. (b) A solution of sugar in which positively and negatively charged particles are closely bound to each other and do not move separately. (c) Mineral oil. (d) Aluminum wire. (e) Sea water. (f) Glass? *(Answer: 3)*

SECT.

B CONDUCTORS IN EQUILIBRIUM

► *Approach to equilibrium*

Suppose that one or more charged objects are brought to some fixed positions near a conductor (such as a piece of metal) at rest relative to the laboratory. Then the mobile charged particles in the conductor move initially because of the electric forces due to the charged objects. (For example, in Fig. B-1 the electrons in the metallic conductor, being attracted toward the positively charged object, move toward the side of the conductor closer to the object. Hence this side becomes negatively charged, leaving the other side of the conductor positively charged because of a deficiency of electrons.) But the motion of the mobile charged particles lasts only for a short time because these particles interact with all the other charged particles and with all the atoms in the conductor (thus losing their energy to increase the random internal energy of the conductor). Thus the conductor quickly reaches the "equilibrium" situation where the average velocity of every mobile charged particle is zero (i.e., where every such particle remains at rest).*

* Of course, the mobile charged particles still move about rapidly in random directions, although their *average* velocity along any particular direction is zero.

In this equilibrium situation the mobile charged particles must then have rearranged themselves throughout the conductor in such a way that the average electric force on every mobile charged particle, due to all the other charged particles, is *zero* (since the average velocity of the mobile charged particle would otherwise not remain equal to zero).

PROPERTIES OF CONDUCTORS IN EQUILIBRIUM

► $\vec{E} = 0$

Suppose that a conductor is in equilibrium so that each of its mobile charged particles has zero average velocity. Since the average electric force on each mobile charged particle in the conductor must then be zero, the electric field $\vec{E}$ at any point in the conductor must also be zero. (Otherwise there would be an average electric force accelerating some mobile charged particles in the conductor and the conductor would not be in equilibrium.)

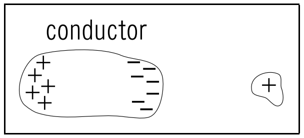


Fig. B-1: Metal conductor near a charged object.

Thus we arrive at this important conclusion:

$$\boxed{\text{At every point in a conductor in equilibrium, } \vec{E} = 0.} \qquad \text{(B-1)}$$

► *V = constant*

Since the electric field is zero throughout a conductor in equilibrium, no work is done on a charged particle moving from one point to another point within the conductor. Hence the potential drop between any two such points is zero. Correspondingly, the potential V must then be the *same* at any two such points within the conductor. Thus Rule (B-1) implies this conclusion:

$$\boxed{\text{Throughout a conductor in equilibrium, } V = \text{constant.}} \qquad \text{(B-2)}$$

► *$\vec{E}$ outside ⊥ to surface*

In particular, all points on the surface of the conductor must then be also at the same potential, i.e., *the surface of a conductor in equilibrium must be an equipotential surface.* But we already know from text section D of Unit 420 that the electric field is everywhere perpendicular to an equipotential surface. Hence we can conclude that the *electric field immediately outside the surface of a conductor in equilibrium must be everywhere perpendicular to this surface.* (See Fig. B-2.)

► *Charge on conductor surface*

How can the electric field immediately outside a conductor in equilibrium be different from zero, although the electric field everywhere inside this conductor is zero? The reason is that, after equilibrium has been reached, charged particles are arranged in a thin boundary layer just inside the surface of the conductor in such a way that they produce zero electric field everywhere inside the conductor, but produce a net non-zero field outside the conductor. *

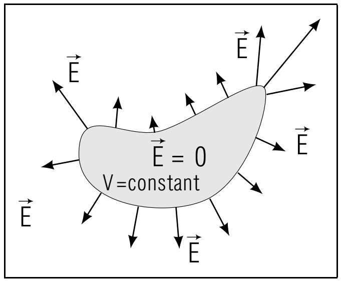


Fig. B-2: Conductor in equilibrium.

> * In fact, it can be shown that there is zero net charge in any region *within* a conductor in equilibrium. Hence any net charge in the conductor is located in a thin boundary layer just inside the *surface* of the conductor.

The following example illustrates this conclusion in a simple case.

Example B-1: CONDUCTING SLAB IN A UNIFORM EXTERNAL FIELD

Suppose an uncharged metal slab is placed into a uniform electric field $\vec{E}_0$ produced by fixed external charged particles. (As indicated in Fig. B-3, we assume that the large parallel surfaces of the slab are perpendicular to the field $\vec{E}_0$ which points to the right.) What then happens to the mobile charged particles in the metal slab and to the electric field at points inside and outside the slab?

► *Effects of electron motion*

Immediately after the slab is placed in the external field $\vec{E}_0$ (before any of the mobile electrons in the metal slab have had a chance to move), the electric field $\vec{E}$ inside the slab is just equal to the external field $\vec{E}_0$.

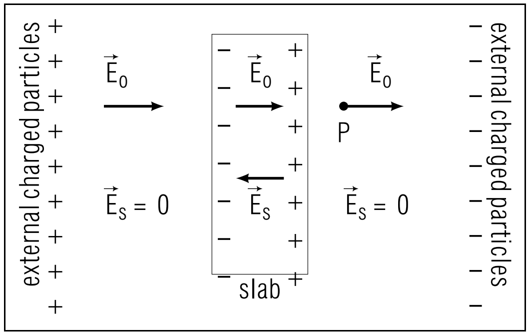


Fig. B-3: Metal slab in a uniform electric field $\vec{E}_0$ produced by external charged particles.

This field then exerts on the negatively charged mobile electrons in the slab a force to the left. Hence these electrons move to the left surface of the slab and leave the right surface with a deficiency of electrons. Thus the left surface of the slab acquires some net negative charge $-Q$ and the right surface is left with some net positive charge $+Q$.

The negative charge $-Q$ on the left surface of the slab then produces at any point inside the slab an electric field *toward* this surface (i.e., toward the left). Similarly, the positive charge $+Q$ on the right surface of the slab produces inside the slab an electric field *away* from this surface (i.e., also toward the left). Both these fields thus have the same direction toward the *left* (and also have the same magnitude, irrespective of the distance of the point from the large uniformly charged surfaces).*

* Recall the discussion of text section E of Unit 419.

Thus the field $\vec{E}_s$ due to the accumulated charges on *both* surfaces of the slab has a direction to the left, *opposite* to the direction of the external electric field $\vec{E}_0$. Because of the rearrangement of mobile electrons in the metal slab, the total electric field $\vec{E} = \vec{E}_0 + \vec{E}_s$ inside the slab is then *smaller* than the original electric field $\vec{E}_0$ at the position of the slab.

► *Final field inside slab*

This remaining electric field $\vec{E}$ still exerts forces toward the left on the mobile electrons in the metal. Thus the motion of these electrons continues until the charges $-Q$ and $+Q$ accumulated on the surfaces of the slab have become large enough so that the electric field $\vec{E}_s$ produced by them inside the metal is precisely equal in magnitude, and opposite in direction, to the external field $\vec{E}_0$. Then the total electric field $\vec{E} = \vec{E}_0 + \vec{E}_s$ inside the metal slab is zero, there is no longer a net force on the mobile electron inside the slab, and the slab has attained the equilibrium situation where the average velocity of the mobile electrons remains equal to zero.

► *Final field outside slab*

What then is the electric field at a point *outside* the slab, such as the point P in Fig. B-3? The negative charge $-Q$ on the left surface of the slab produces at P a field *toward* this surface (i.e., toward the left), The positive charge $+Q$ on the right surface of the slab produces at P a field *away* from this surface (i.e., toward the right). Thus these fields have *opposite* directions, but the same magnitude (since these fields do not depend on the distance of P from the large uniformly charged surfaces). The field $\vec{E}_s$ at P due to *both* charged surfaces is then *zero*. Hence the total field $\vec{E} = \vec{E}_0 + \vec{E}_s$ at P is just equal to the external field $\vec{E}_0$ and is thus *not* equal to zero.

Describing Potential, Field, and Charge Distribution (Cap. 1)

B-1 A cast-iron (conducting) weather vane in the shape of a rooster is in a uniform upward electric field due to a storm-cloud overhead. (a) Does the rooster's head have a potential which is larger, smaller, or the same as the potential of its feet? (b) What is the direction of the electric field at a point inside the iron rooster? (c) If the total charge of the rooster is zero, is the charge of its head positive or negative? *(Answer: 6) (Suggestion: [s-7])*

B-2 An uncharged metal sphere on an insulating support is placed in the initially horizontal uniform electric field produced by two uniformly charged vertical plates. (See Fig. B-4a.) (a) Is the right side of the sphere positively or negatively charged? What is the sign of the net charge of the left side of the sphere? (b) Describe the direction of the electric field (due to the sphere and to the charged plates) at a point inside the sphere and at a point just outside the sphere's surface. (c) What is the potential drop V from the point A to the point B shown in Fig. B-4a? (d) Which of the field-line drawings (b or c) best indicates the total electric field due to the charged plates and the metal sphere? *(Answer: 1) (Suggestion: [s-7])*

B-3 In a lamp connected to a wall socket, electrons continually move from the socket and through a copper wire connected to the light bulb. (a) Must the electric field inside the wire equal zero? (b) Very shortly after the wire is disconnected from the wall socket, all the electrons in the wire come to rest (on the average). Under these conditions, must the electric field inside the wire equal zero? Why or why not? *(Answer: 9)*

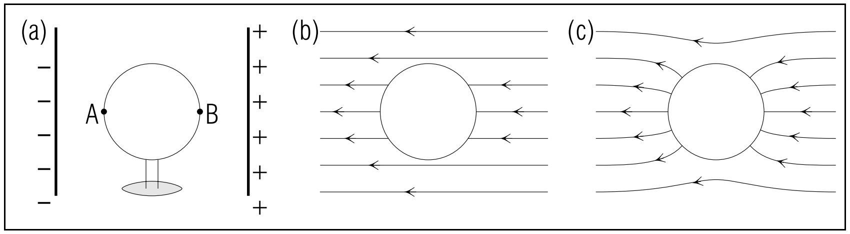


Fig. B-4.

SECT.

C APPLICATIONS OF CONDUCTORS IN EQUILIBRIUM

Conductors in equilibrium occur very commonly and are used in many practical applications. We shall discuss several such applications.

MEASUREMENT OF POTENTIAL DIFFERENCE

► *Voltmeter*

One of the most easily measured electric quantities is the "potential difference" (i.e., the difference of the potentials) between two points. *

> * The potential difference between two points A and B can denote either the potential drop $V_A - V_B$ or the potential change $V_B - V_A$.

An instrument designed to measure potential differences is called a "voltmeter." Although there exist many different kinds of voltmeters, any voltmeter consists basically of a dial (or other display) which indicates the potential difference between two special points called the "terminals" of the voltmeter. (We shall discuss one particular kind of voltmeter later in this section.)

► *Wire connections*

How can one use a voltmeter, with terminals A and B, to measure the potential difference between any two points A' and B'? For example, in order to obtain an electrocardiogram, one may want to measure the potential difference between a point A' on a person's chest and a point B' on his left ankle, as indicated in Fig. C-1. It is then clearly difficult, if not impossible, to put these points A' and B' on the person's body in direct contact with the terminals of the voltmeter.

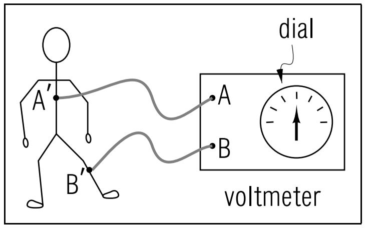


Fig. C-1: Use of a voltmeter to measure the potential difference between two points on a person's body.

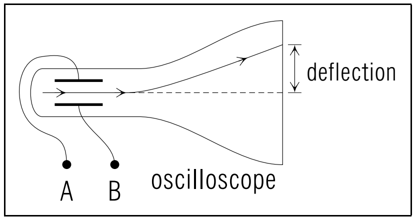


Fig. C-2: Oscilloscope used as a voltmeter.

This problem is easily solved by merely using a metal wire (of any convenient length) to connect the point A' to the terminal A of the voltmeter, and using another metal wire to connect the point B' to the other terminal B of the voltmeter. Indeed, in *equilibrium,* all points of each of these wires are at the same potential. Hence the potential V_A of the terminal A is then the same as the potential V'_A of the point A'; similarly, the potential V_B of the terminal B is the same as the potential V'_B of the point B'. Hence the wire connections assure that the potential difference $V_A - V_B$ measured by the voltmeter is equal to the potential difference $V'_A - V'_B$ between the two points A' and B' of interest.

► *Oscilloscope as voltmeter*

An oscilloscope (described in text section F of Unit 411) can be used as a voltmeter. Indeed, suppose that two points A and B on the oscilloscope (its "terminals") are connected by metal wires to the deflecting plates in the oscilloscope. (See Fig. C-2.) In equilibrium, the potential difference $V_A - V_B$ between the terminals is then equal to the potential difference between these deflecting plates. If the plates are separated by a distance D, the electric field between the plates has then a magnitude E such that $ED = V_A - V_B$. A larger potential difference corresponds thus to a larger field between the plates, and hence to a larger deflection of the electron beam passing between the plates. The deflection of this beam (or the corresponding position of the spot on the oscilloscope screen) can then be measured and used to indicate the potential difference between the terminals A and B.

FIELD MAGNITUDE AND CONDUCTOR SEPARATION

As discussed in the preceding section, the surface of a conductor in equilibrium is always an equipotential surface. By changing the separation between two conductors in equilibrium, one can then change the separation between two equipotential surfaces and correspondingly affect the electric field between them. In this way one can use a fixed potential difference, such as that produced by a battery, to produce electric fields of various magnitudes.

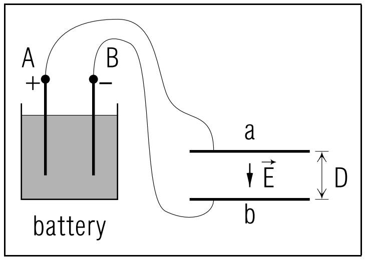


Fig. C-3: Battery connected to two metal plates.

► *Field betweenmetal plates*

For example, consider a battery which maintains between its terminals A and B a fixed potential difference $V = V_A - V_B$. Suppose that these terminals are connected by metal wires to two parallel metal plates a and b, as indicated in Fig. C-3. In equilibrium, the entire metal plate a is then at the potential V_A, and the entire metal plate b is at the potential V_B. Hence the potential difference between the metal plates is always equal to the fixed potential difference V between the terminals of the battery, irrespective of the separation D between the plates. Correspondingly, the magnitude E of the electric field between the plates must be such that $ED = V$ or

$$E = \frac{V}{D} \qquad \text{(C-1)}$$

If the separation D between the metal plates is decreased while the battery maintains the potential difference between them fixed, the magnitude E of the electric field between the plates must then correspondingly increase. In this way it is possible to produce large electric fields with modest potential differences.

Example C-1: Electric field in a nerve membrane

The thickness of a nerve membrane is about 50 Å (i.e., 5×10^{-9} m). Such a nerve membrane separates the ionic solution on the inside of a nerve cell from the ionic solution on the outside of the nerve cell. Biochemical processes in a "resting" nerve cell produce in these ionic solutions differing charge concentrations so as to maintain between these solutions a potential difference of about 0.1 volt. What then is the electric field inside the nerve membrane?

As indicated in Fig. C-4, the two ionic solutions are conductors separated by the very small distance $D = 5 \times 10^{-9}$ meter. According to Eq. (C-

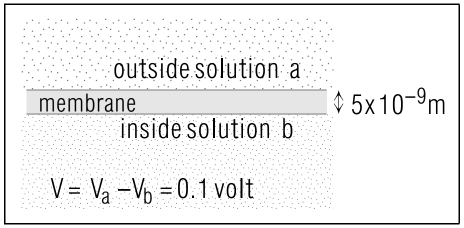


Fig. C-4: Nerve membrane separating two ionic solutions.

1), the small potential difference of 0.1 volt produces then in the nerve membrane an electric field of magnitude $E = (0.1\,\text{volt})/(5\times10^{-9}\,\text{meter}) = 2 \times 10^{7}\,\text{volt/meter}$, a field much larger than the electric breakdown strength of air!

FIELD MAGNITUDE AND CONDUCTOR SHAPE

The electric field can also be affected by modifying the *shape* of a conductor (even if the separation between conductors remains essentially unchanged) since one can thus modify the spacing between adjacent equipotential surfaces.

► *Field near a bump*

To illustrate the effects of the shape of a conductor, let us consider the metal piece in Fig. C-5b which differs from the metal piece in Fig. C-5a merely by having a bump projecting from its surface. Both conductors are in equilibrium and at the same potential V_a, while the potential far from these conductors is also the same. Then the equipotential surfaces far from the bump in Fig. C-5b must also be the same in both figures. However, the particular equipotential surface corresponding to the potential V_a of the metal surface is different since it has the bump shown in Fig. C-5b. Correspondingly, the equipotential surfaces near this bump are correspondingly modified, being crowded more closely together because of the protruding bump. But, as we know from text section D of Unit 420, the magnitude of the electric field is larger where the separation between two equipotential surfaces is smaller. Thus the closer separation of the equipotential surfaces near the bump of the metal leads to an increased electric field just outside this bump.

► *Large fields near needles*

If the bump is so pronounced as to resemble a sharp needle, the local crowding together of the equipotential surfaces just outside this needle can lead to very large electric fields. Such large fields are used in various practical applications. For example, the large electric field near a metal needle can ionize the surrounding air. Small particles (such as grains of dust or liquid droplets) passing through the air then become charged because ions become attached to the particles. These charged particles can then be moved at will by suitably applied electric fields. For instance, in "electrostatic spray painting" small droplets of paint charged in this way are thus guided by electric fields to produce uniform coats of paint on metal furniture. Similarly, in "electrostatic precipitators" dust or pollen grains in the air entering a room are charged and then removed by electric forces, thus resulting in the purification of the air.

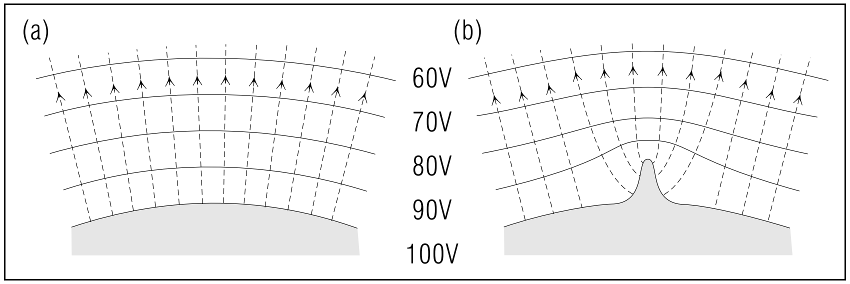


Fig. C-5: Comparison of equipotential surfaces near two pieces of metal of different shape. (a) Smooth piece of metal. (b) Same piece of metal with a bump. (The electric field lines are indicated as dotted lines perpendicular to the equipotential surfaces.)

The electric field near a very sharp metal needle can become so large that electrons are torn out of the metal. (This phenomenon is called "field emission"). For instance, the field emission of electrons from a sharp needle is used as a localized intense source of electrons in some modern scanning electron microscopes.

► *Avoiding large fields*

Some electrical equipment, such as X-ray machines, produce large potential differences. In designing such equipment, it is then important to avoid producing large electric fields which might lead to troublesome ionization of the air in the equipment. Accordingly, great care is taken to keep all metallic pieces in the equipment free from any bumps (such as protruding screws or sharp corners).

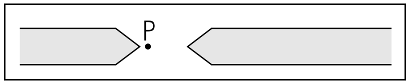


Fig. C-6.

Relating Field and Potential due to Metal Plates (Cap. 2a)

C-1 Two parallel metal plates, separated by 0.5 cm, are connected to the terminals of a flashlight battery so that the potentials of the two plates always differ by 1.5 volt. What is the magnitude of the electric field between the plates? Which of the following actions would make this electric field larger? (a) Moving the plates closer together; (b) Replacing the 1.5 V battery with a 12 V automobile battery; (c) Replacing each metal plate with a plate of larger area. *(Answer: 5) (Suggestion: [s-14])*

C-2 Between two metal plates connected to a 12 V automobile battery the electric field has a magnitude of 3×10^6 V/m (large enough to cause breakdown of air), what is the distance between the plates? *(Answer: 8)*

Knowing About Producing Large Fields

C-3 The tips of two wires attached to the terminals of a 6 V battery are shown in Fig. C-6. Which of the following will result in increasing the magnitude of the electric field at the point P shown? (a) Filing the tips of the wires to sharper points; (b) Filing these tips to a rounder shape; (c) Moving the wires closer together (so as to increase the density of equipotential lines near P)? *(Answer: 2)*

Comparing Fields near a Charged Conductor (Cap. 2b)

C-4 During an electrical storm, the air "breaks down" and becomes conducting in places where the electric field is very large. When charged particles flow rapidly through this conducting air, the associated production of large amounts of light and heat is called "lightning." Fig. C-7 shows the conducting surface of a wet farm yard and nearby hill in the presence of an electric field due to a charged thunder-cloud overhead. (a) At which of the labeled points is the electric field largest? (b) Suppose the farmer installs a "lightning rod," a pointed, conducting rod sunk in the ground and reaching to the point A. At what point then is the electric field largest? Why do farmers install such lightning rods? (c) Why is it dangerous to observe a thunder-storm from a hillside as the boy in Fig. C-7 is doing? (d) If you were on such a hillside during a storm, would it be safer to stand up or to lie down? *(Answer: 11)*

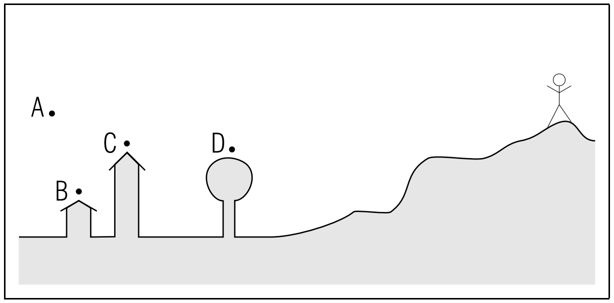


Fig. C-7.

C-5 Suppose a charged conducting surface is initially smooth, but is then dented. According to the reasoning applied to the bump-like extension shown in Fig. C-5b, is the electric field at a point near this dent smaller or larger in magnitude than the field at this same point before the dent was made? *(Answer: 13) (Suggestion: [s-11]) (Practice: [p-1])*

SECT.

D MOLECULAR DIPOLE MOMENTS

After the preceding discussion of electric conductors, let us consider some of the electric properties of molecules and the resulting electric properties of dielectrics.

ELECTRIC DIPOLES

A molecule (whether consisting of one or more atoms) has ordinarily zero total charge. However, the average position of the positively charged atomic nuclei in the molecule may be different from the average position of the negatively charged electrons in the molecule. The molecule interacts thus electrically with its environment nearly in the same way as if the positively and the negatively charged particles in the molecule were localized at their average positions (i.e., as if the molecule consisted of one particle with positive charge $+q$ and of another particle with negative charge $-q$, these particles being separated by some distance d). Such a system of two oppositely charged particles is called an "electric dipole" and is illustrated in Fig. D-1.

► *Definition of dipole moment*

The relative position of the particles in a dipole moment can conveniently be specified by the position vector $\vec{d}$ of the positively charged particle relative to the negatively charged particle (i.e., by the vector $\vec{d}$ having a length equal to the distance d between the particles and having a direction pointing from the negatively charged to the positively charged particle). It is then conventional to describe the electric dipole by its "electric dipole moment" (denoted by the symbol $\vec{p}$) defined as the following vector directed along $\vec{d}$:

Def. | **Electric dipole moment**: $\vec{p} = q\vec{d}$ | (D-1)

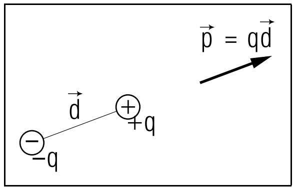


Fig. D-1: Electric dipole and corresponding electric dipole moment $\vec{p}$.

ELECTRIC FORCES ON A DIPOLE

As we have discussed, a molecule interacts electrically with its environment like an electric dipole and may thus be characterized by an electric dipole moment. Although the *total* charge of such a dipole is zero, the dipole can nevertheless be affected by externally produced electric fields.

► *Force on dipole*

Consider an electric dipole in the presence of some external charged particles. These external particles produce then some electric field $\vec{E}_+$ at the position of the positively charged particle of the dipole, and produce some electric field $\vec{E}_-$ at the position of the negatively charged particle of the dipole. (See Fig. D-2a.) Correspondingly, the electric force $\vec{F}_+$ exerted by the external particles on the positively charged particle, with charge $+q$ is $\vec{F}_+ = q\vec{E}_+$; similarly, the electric force $\vec{F}_-$ exerted by the external particles on the negatively charged particle, with charge $-q$, is $\vec{F}_- = -q\vec{E}_-$. (See Fig. D-2b.) The total external force $\vec{F}_{\rm tot}$ exerted on the dipole by the external particles is then

$$\vec{F}_{\rm tot} = \vec{F}_+ + \vec{F}_- = q\vec{E}_+ - q\vec{E}_- = q(\vec{E}_+ - \vec{E}_-) \qquad \text{(D-2)}$$

► *Total force on dipole*

Since the two particles in the dipole are located at different positions, the electric fields $\vec{E}_+$ and $\vec{E}_-$ at these positions are ordinarily not the same. Correspondingly Eq. (D-2) shows that the total external force on the dipole is ordinarily not zero (so that the center of mass of the dipole is accelerated). But if the electric fields at the positions of the two particles of the dipole are the same (e.g., because the externally produced electric field is uniform), the electric forces on these particles have the same magnitude but opposite directions, so that the total electric force on the dipole is zero.

► *Rotation of dipole*

Even in the case where the total force on the dipole is zero, the electric forces on the individual particles of the dipole have observable effects. For example, in Fig. D-2b the force on the positively charged particle is then to the right, and the force on the negatively charged particle is of the same magnitude but to the left. These two forces then tend to rotate the dipole (or to produce a "torque" on it) in such a sense that its electric dipole moment becomes aligned along the direction of the electric field.

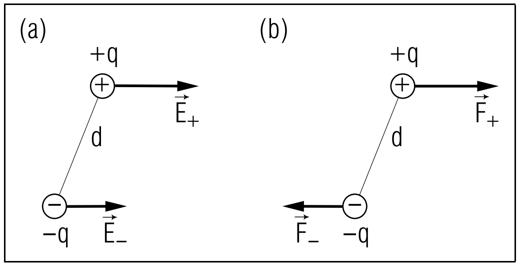


Fig. D-2: Electric forces on a dipole due to external electric fields.

AVERAGE DIPOLE MOMENT PRODUCED BY AN ELECTRIC FIELD

A collection of molecules that have non-zero *average* dipole moments (averaged over all the molecules) in the presence of an electric field can individually have, in the absence of an electric field, either zero or non-zero dipole moments.

► *Permanent dipole moments*

Some molecules have "permanent" dipole moments, i.e., dipole moments which exist even in the absence of an externally produced electric field. [For example, the hydrogen chloride (HCl) molecule possesses such a permanent dipole moment because the H atom in the molecule has a net positive charge, while the Cl atom has a net negative charge.] But, in the absence of an externally produced electric field, the *average* electric dipole moment of a molecule in a collection of such molecules is equal to zero because the molecules rotate around in random ways so that their dipole moments point as often in one direction as in the opposite direction. (See Fig. D-3a.) On the other hand, in the presence of an externally produced electric field $\vec{E}$, the electric forces exerted by this field on the charged particles in a dipole tend to rotate these dipoles so that they become more nearly aligned along the field. Hence a collection of randomly rotating molecules contains somewhat more molecules with dipole moments pointing along the electric field $\vec{E}$ than along the opposite direction. As a result of the external electric field, a molecule in such a collection thus acquires an *average* electric dipole moment in the direction of the electric field.

► *Induced dipole moments*

In the absence of an externally produced electric field, most molecules [such as hydrogen (H_2) or nitrogen (N_2)] have *no* electric dipole moment because the average positions of the positively and negatively charged particles in the molecule are the same. But, in the presence of an externally produced electric field $\vec{E}$, a positively charged particle in such a molecule experiences an electric force along $\vec{E}$ while a negatively charged particle experiences a force opposite to $\vec{E}$. Thus these charged particles become slightly separated from each other (by a larger amount if $\vec{E}$ is made larger). As indicated in Fig. D-3b, the molecule then acquires electric dipole moment along the direction of the external electric field. Such a dipole moment is said to be "induced" by the electric field since it results from a charge separation produced by the electric field.

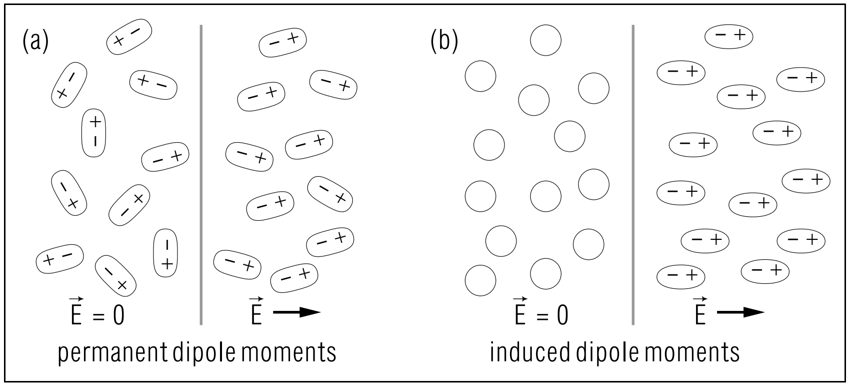


Fig. D-3: Average molecular electric dipole moments produced by an external electric field.

► *Summary*

Consider any collection of molecules, irrespective of whether these have permanent dipole moments or not. The following comments then summarize how the molecules in such a collection become "electrically polarized," i.e., how they acquire an average electric dipole moment: In the absence of an external electric field, the average electric dipole moment of a molecule is equal to zero. But, in the presence of an external electric field, a molecule acquires an average electric dipole moment along the direction of this field. (As long as the electric field is not too large, this average dipole moment is simply proportional to the field.)

Knowing About Dipole Moments

D-1 The electric properties of a cesium iodide (CsI) molecule are almost identical to the properties of the simple system of two charges shown in Fig. D-4. What is the dipole moment of a CsI molecule?

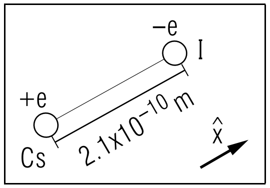


Fig. D-4.

(Answer: 14)

Note: Tutorial section D discusses the description of dipole moments in chemistry.

Describing Electric Effects on a Dipole (Cap. 1a)

D-2 *Dipole in a uniform field:* A dipole made of two charged plastic balls is hung in the uniform electric field $\vec{E}$ between two charged metal plates (Fig. D-5a). (a) What is the direction (right or left) of the electric force on this dipole due to the plates? (b) If the dipole is initially at rest as shown in Fig. D-5a, in what sense (clockwise or counterclockwise) will it begin to rotate? *(Answer: 4) (Suggestion: [s-3])*

D-3 *Dipole in a non-uniform field:* Suppose the dipole described in problem D-2 is hung just to the left of a positively charged metal sphere (Fig. D-5b). What then is the direction of the force on the dipole due to the sphere? *(Answer: 7) (Suggestion: [s-4]) (Practice: [p-2])*

Knowing About Polarization

D-4 (a) Fig. D-6a shows four typical hydrogen chloride molecules in a sample of HCl gas. Is the electric field acting on this gas directed roughly along $\hat{y}$ or opposite to $\hat{y}$? (b) Fig. D-6b shows the same four HCl molecules in the presence of an electric field which has the same direction but a different magnitude. Is this field larger, smaller, or the same in magnitude than the field present in Fig. D-6a? *(Answer: 12) (Suggestion: [s-13])*

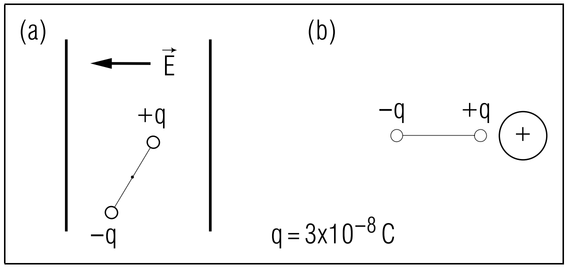


Fig. D-5.

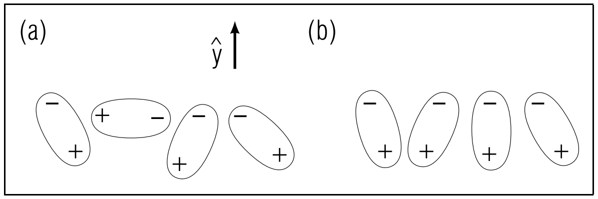


Fig. D-6.

SECT.

E DIELECTRICS IN EQUILIBRIUM

► *Slab in electric field*

To investigate the electric effects produced by dielectric materials, let us consider the simple case of a homogeneous dielectric slab located in a uniform externally produced electric field $\vec{E}_0$ perpendicular to the large parallel surfaces of the slab. (See Fig. E-1.) As discussed in the preceding section, the many molecules in the dielectric have become polarized so their average electric dipole moments are all oriented along the direction of the field $\vec{E}_0$. What then are the large-scale observable effects of all these many dipole moments?

► *Regions of the slab*

To answer this question, let us examine separately the effects produced by molecules close to the surfaces of the slab and molecules in the interior of the slab. To do this, we consider two imaginary surfaces (indicated by the dashed lines in Fig. E-1) very close to the actual surfaces of the slab.*

> * For example, each such imaginary surface might be at a distance 10 meter from the surface of the slab, i.e., at a distance which is very small from a macroscopic point of view, although still quite large compared to molecular sizes.

Then we can regard the slab as consisting of a right surface region (between the actual right surface and the right imaginary surface), of a left surface region (between the actual left surface and the left imaginary surface), and of an interior region (between the two imaginary surfaces). What then is the net charge located in each of these regions as a result of the dipole moments of the molecules in the dielectric?

► *Surface charges*

As is seen from Fig. E-1a, all molecules which are located entirely within the right surface region of the slab contribute no net charge to this region (since each such molecule contributes as much positive as negative charge to this region). But all molecules located so that they are "cut" by the right imaginary plane contribute positive charge to the right surface region (while contributing negative charge to the interior region). Thus the right surface region of the slab acquires a net positive charge. *

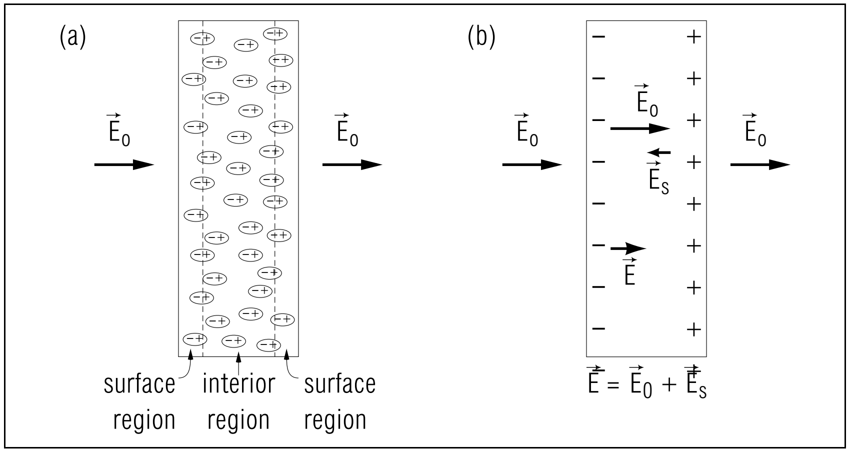


Fig. E-1: Electrically polarized molecules in a dielectric slab. (a) Net charges in various regions. (b) Electric fields inside the dielectric slab.

> * Note that the positive charge in the right surface region is larger if the charge separation in the polarized molecules is larger, since more molecules are then cut by the imaginary right plane.

Similarly, all molecules located so that they are cut by the left imaginary plane contribute a net negative charge to the left surface region. On the other hand, the interior region acquires *no* net charge since it acquires as much negative charge from the molecules cut by the right imaginary plane as it acquires positive charge from the molecules cut by the left imaginary plane. In summary, the effect of all the electrically polarized molecules in the dielectric slab is thus simply to produce a net positive charge on the right surface of the dielectric slab and a net negative charge of the same magnitude on the left surface of the slab (as indicated in Fig. E-1b).

► *Field inside slab*

The surface charges due to the polarized molecules in the dielectric then produce inside the slab an electric field $\vec{E}_s$ to the left (i.e., away from the positive charge on the right surface and toward the negative charge on the left surface). This field $\vec{E}_s$ has thus a direction *opposite* the externally produced field $\vec{E}_0$. Hence the total field $\vec{E} = \vec{E}_0 + \vec{E}_s$ in the dielectric is *smaller* than the externally produced field $\vec{E}_0$ (i.e., smaller than the field which would exist if the dielectric were not there or if its molecules were not polarized).

DIELECTRIC CONSTANT

To compare the magnitude E of the actual electric field in the dielectric with the magnitude E_0 of the externally produced electric field, it is conventional to introduce this definition:

Def. **Dielectric constant**: $K = \dfrac{E_0}{E}$ (E-1)

According to this definition, the dielectric constant K is larger than 1 since E is always smaller than E_0 . Furthermore, the dielectric constant K does not depend on the particular value of the external field E_0, but only on the properties of the dielectric material. (The reason is that, if the external electric field E_0 were 3 times as large, the net field E inside the slab would also be 3 times as large, so that the ratio $K = E_0/E$ would remain unchanged.) *

> * If E_0 is 3 times as large, the electric dipole moments of the molecules are 3 times as large, and thus the surface charges contributed by these molecules are also 3 times as large. Hence the electric field $\vec{E}_s$ produced by these charges inside the dielectric is 3 times as large. Consequently, the total electric field $\vec{E} = \vec{E}_0 + \vec{E}_s$ is also 3 times as large.

Table E-1 lists the dielectric constants of several common materials.

Material	K
vacuum	1.0000
air (standard conditions)	1.0006
polyethylene	2.3
nylon	3.5
paper	3.5
mica	4.2
pyrex glass	4.5
pyranol oil	4.5
cell membrane (lipid)	6
water (room temperature)	77
titanium dioxide	100

Table E-1: Dielectric constants of some common materials.

► *Field reduced by K*

According to the definition of the dielectric constant K, Def. (E-1), the actual field $\vec{E}$ inside a dielectric is related to the externally produced field $\vec{E}_0$ so that

$$E = \frac{E_0}{K} \tag{E-2}$$

For example, if the dielectric slab in Fig. E-1 were a glass plate having a dielectric constant $K = 4$ and the external field had a magnitude $E_0 =$ 1000 volt/meter, the magnitude E of the actual electric field inside the glass plate would be only 250 volt/meter.

► *K in special cases*

If the slab in Fig. E-1 contained no molecules, i.e., if it were just a vacuum, $\vec{E}$ would be the same as $\vec{E}_0$. Thus the dielectric constant of a vacuum is $K = 1$. Suppose, however, that a given volume of the dielectric contains many molecules and that these are readily polarized (i.e., that an average dipole moment is readily produced by an external electric field). Then the dielectric constant K is appreciably larger than 1. Finally, if the slab in Fig. E-1 were a conductor in equilibrium, the net electric field $\vec{E}$ inside the conductor would be zero. Hence a conductor can be regarded as the extreme case of a material with dielectric constant $K = E_0/E$ which is infinitely large. (Indeed, a conductor can be viewed as enormously polarizable since the mobile charged particles in it can move throughout the *entire* material as a result of an external electric field.)

APPLICATIONS

Suppose that one knows the dielectric constant K of a material. Then one can use the relation $\vec{E} = \vec{E}_0/K$ to find the electric field inside this material from information about the external electric field produced by charged particles outside this material.

A knowledge of the dielectric constant of a material can also provide valuable information about the molecules in the material. For example, if a material has a large dielectric constant due to induced molecular dipole moments, one can infer that the charged particles in the molecules are sufficiently weakly bound to each other so that they are easily separated by an electric field.

► *Measurement of K*

How can one actually measure the dielectric constant of a material? As indicated in Fig. E-2, one need only introduce this material so that it

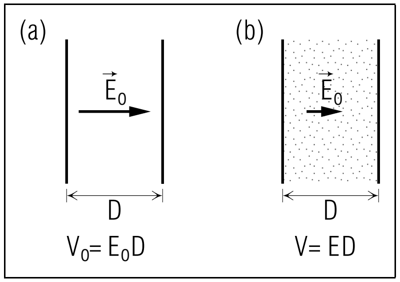


Fig. E-2: Electric field between charged parallel metal plates. (a) Region between plates empty. (b) Region filled with dielectric.

fills the entire region between two charged parallel metal plates. The dielectric constant K of the material is then equal to the ratio E_0/E, where E_0 is the magnitude of the initial electric field between the metal plates (i.e., of the field due only to the charged plates) and where E is the magnitude of the final electric field inside the dielectric filling the region between the plates.

If the plates are separated by a distance D, the initial potential difference between them is $V_0 = E_0 D$ and the final potential difference between them is $V = ED$. Thus the dielectric constant K is simply equal to $K = V_0/V$, the ratio of the easily measured initial and final potential differences between the plates.

Describing Potential, Field, and Charge Distribution (Cap. 2)

E-1 Consider a rectangular (box-shaped) region in a vacuum with sides parallel to an initially uniform electric field $\vec{E}_0 = (200\,\mathrm{V/m})\hat{y}$ (Fig. E-3). (a) If this region contains nothing (just vacuum), what is the electric field at the point P, and what is the potential drop from A to B (across the region). (b) If the region is filled with a metal, what is the electric field at the point P, and what is the potential drop from A to B? Describe the charge distribution of the region by stating the sign of any net charge on the top and on the bottom faces of the metal in the region. (c) Now suppose the region is filled with a dielectric. Is the net charge of the top face larger, smaller, or the same in magnitude compared with the top face of the metal? Qualitatively describe the electric field at P and the potential drop from A to B by stating whether these quantities are larger or smaller in magnitude than the corresponding quantities described in parts (a) and (b) of this question. *(Answer: 18)*

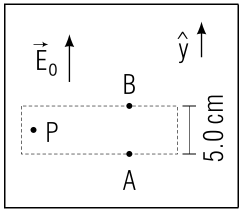


Fig. E-3.

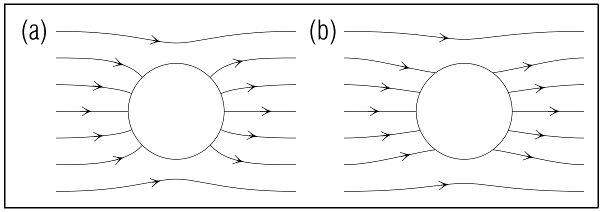


Fig. E-4.

E-2 Suppose an uncharged sphere (supported by an insulating handle) is inserted into the initially uniform electric field between two uniformly charged plates. Which of the diagrams in Fig. E-4 best indicates the field near the sphere if this sphere is made of dielectric material and if it is made of conducting material? *(Answer: 15) (Suggestion: [s-1]) (Practice: [p-3])*

Relating Field, Potential and the Dielectric Constant (Cap. 4)

E-3 Consider again the rectangular region in the presence of an initially uniform field $\vec{E}_0 = (200\,\mathrm{V/m})\hat{y}$ in a vacuum (Fig. E-3). When the rectangular region is empty, the electric field at P is just $\vec{E}_0$, and the potential drop from A to B is $V_0 = 10\,V$. When this region is filled with a substance of dielectric constant K, the electric field at P is $\vec{E}$ and the potential drop from A to B is V. (a) Express K in terms of the magnitudes of the electric fields $\vec{E}$ and $\vec{E}_0$ and in terms of the potential drops V and V_0. (b) If the region is filled with pure water, what are the values of $\vec{E}$ and V? (See Table E-1.) *(Answer: 24)*

E-4 Suppose the rectangular region in Fig. E-3 is filled with a plastic of dielectric constant 2. (a) If $\vec{E}_0 = (200\,\mathrm{volt/m})\hat{y}$, what is the electric field $\vec{E}$ inside the plastic? What is the potential drop V from A to B? What are the ratios E_0/E and V_0/V (where V_0 is the potential drop from A to B if the region is empty)? (b) Suppose the field $\vec{E}_0$ is made three times as large [i.e., $\vec{E}_0 = (600\,\mathrm{volt/m})\hat{y}$]. Which of the following quantities have values different than the values found in part (a): $\vec{E}$, V, E_0/E, V_0/V? Find those values which are different from the values found in part (a). *(Answer: 10) (Practice: [p-4])*

SECT.

F FORCES ON CONDUCTORS AND DIELECTRICS

A net electric force can act on an object even if the total charge of this object is zero. As a specific illustration, let us discuss the electric force on an uncharged rod near a positively charged sphere, as shown in Fig. F-1.

► *Force on conductor*

What happens if the rod is a *metal* and thus an electric conductor? (1) The positively charged sphere attracts the mobile electrons in the metal rod and thus causes these electrons to move toward the sphere. (2) After the electron motion has stopped (i.e., in equilibrium, when the electric field in the rod is zero), the end of the rod nearer to the sphere has then a negative charge because of an accumulation of electrons, while the farther end of the rod is left with an opposite charge of the same magnitude because of a deficiency of electrons. (3) The attractive force exerted by the positively charged sphere on the negative charge on the nearer end of the rod has a larger magnitude than the repulsive force exerted by this sphere on the positive charge on the farther end of the rod. (4) The vector sum of these two forces, i.e., the total electric force $\vec{F}_{\text{tot}}$ on the rod, is then directed *toward* the sphere.

► *Force on dielectric*

Suppose that the rod consists of a *dielectric* material. Then the molecules in the rod become electrically polarized by the electric field due to the positively charged sphere. As discussed in the preceding section, the end of the rod nearer to the sphere acquires then a net negative charge while the farther end acquires a net positive charge (although these charges are smaller in magnitude than in the case of the conducting rod with its completely mobile electrons).

Thus the result is again a non-zero total electric force on the rod toward the sphere (although this force is smaller than in the case of the metal rod).

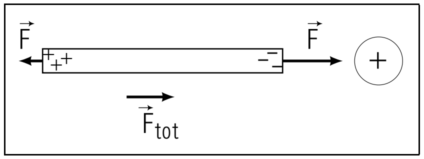


Fig. F-1: Electric forces on an uncharged rod.

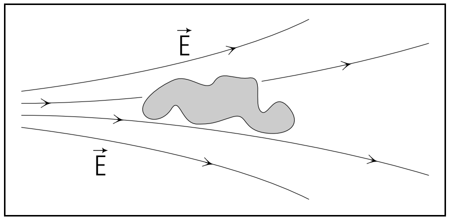


Fig. F-2.

Describing Electric Forces on Uncharged Objects (Cap. 5)

F-1 Suppose the ball in Fig. F-1 were negatively charged. Would the force due to the ball on the uncharged rod then be directed toward or away from the ball? *(Answer: 21) (Suggestion: [s-12])*

F-2 Figure F-2 shows a non-uniform externally produced electric field which is larger near the left end than near the right end of a conducting object placed in this field. (a) What is the direction of the electric force on this object? (b) Suppose the object in Fig. F-2 is made of a dielectric substance. Compared with the force described in part (a), does the electric force on this dielectric object have the same direction or a different direction? Is its magnitude larger or smaller? *(Answer: 17)*

F-3 In general, if an uncharged object is in the presence of a non-uniform electric field, is the electric force on this object directed from its center towards the region where the field is larger in magnitude or towards the region where this field is smaller in magnitude? *(Answer: 26)*

F-4 A negatively charged metal rod is placed just above a bit of metal foil. (a) What is the direction of the electric force on the foil due to the rod? (b) If the foil is touched by the rod, electrons from the rod spread out over the foil, giving it a negative charge. What is the direction of the electric force on the foil due to the rod after the two have been in contact? (c) When a negatively charged metal rod is held at rest just above a bit of foil, the foil initially moves quickly upward, striking the rod and sticking there for a very small time (less than half a second). Then the foil drops from the rod and remains at rest below it. Use your answers to parts (a) and (b) to explain why the foil behaves in this way. *(Answer: 27) More practice for this Capability: [p-5], [p-6]*

SECT.

G SUMMARY

DEFINITIONS

dielectric; Def. (A-1)

conductor; Def. (A-2)

electric dipole moment; Def. (D-1)

dielectric constant; Def. (E-1)

IMPORTANT RESULTS

Conductors in equilibrium: Rule (B-1), Rule (B-2)

Inside conductor, $\vec{E} = 0$, $V =$ constant

Field inside dielectric slab: Eq. (E-2)

$\vec{E} = \vec{E}_0/K$

USEFUL KNOWLEDGE

Common examples of conductors and dielectrics (Sec. A)

Production of large electric fields (Sec. C)

Polarization (Sects. D and E)

CAPABILITIES

Be able to:

(1) For a conducting or dielectric object in equilibrium in an externally produced electric field, qualitatively describe:
  (a) The charge distribution of the object,
  (b) The electric field and potential inside or at the surface of the object,
  (Sects. B and E, [p-3]).

(2) Describe the electric field due to charged conductors:
  (a) Quantitatively, by relating the electric field between two parallel metal plates to the potentials of the plates or to the potential difference between them (Sec. C),
  (b) Qualitatively, by comparing the magnitudes of this field at various points near a conductor (Sec. C, [p-1]).

(3) Qualitatively describe the force on a dipole (or its tendency to rotate) due to the electric field produced by external particles (Sec. D, [p-2]).

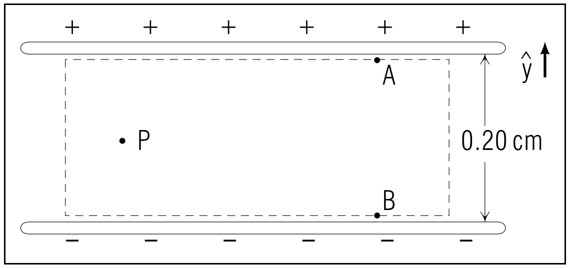


Fig. G-1.

(4) Relate the dielectric constant of a slab of material to the electric field or to potential differences inside and outside of this slab (which is oriented perpendicular to a uniform electric field) (Sec. E, [p-4]).

(5) Describe the electric force on an uncharged object from information about nearby charged particles or the electric field due to them (Sec. F, [p-5], [p-6]).

Study aids are available in:

Tutorial section D: Knowing about dipole moments in chemistry

Tutorial section H: Additional problems

Relating Electric Properties of Matter

G-1 Figure G-1 shows a rectangular region between two parallel metal plates connected to a 6.0 V battery. Thus the two plates are equipotential surfaces with potentials differing by 6.0 V and separated by a distance of 0.20 cm. (a) Find the electric field at the point P and the potential drop from A to B if the region is a vacuum, and if it is filled by a conducting substance, or by a substance with dielectric constant 5.0. (b) If the region is filled by a conductor or by a dielectric, is the top surface of the substance positively or negatively charged? Is the charge of this surface larger, smaller, or the same in magnitude as the charge of the upper metal plate? *(Answer: 25)*

G-2 Can a substance in equilibrium have a dielectric constant of less than 1? Use Fig. G-1 and the charge distributions you described in G-1 to explain this answer. *(Answer: 22) (Suggestion: [s-6])*

SECT.

H PROBLEMS

H-1 *Forces on an uncharged object:* An uncharged plastic ball suspended by a thread is attracted by both a positively charged rubber rod and by a negatively charged plastic rod. Explain these observations by describing the electric forces on various parts of the ball. *(Answer: 16)*

H-2 *Force on a dipole, and change in field:* Figure H-1 shows a dipole composed of two particles of charge $+q$ and $-q$ located in a non-uniform field which has values $\vec{E}_1$ at particle 1 and $\vec{E}_2$ at particle 2. (a) Use the symbols provided to write an expression for the total electric force on the dipole. (b) Express this force in terms of the change $\Delta\vec{E} = \vec{E}_2 - \vec{E}_1$ of the electric field between the positions of particles 1 and 2. (c) Suppose this change $\Delta\vec{E}$ were larger in magnitude. Would the electric force on the dipole then be larger, smaller, or the same in magnitude? (d) Suppose $\vec{E}_1$ and $\vec{E}_2$ were both larger in magnitude but that the change $\Delta\vec{E}$ were the same as in part (b). Is the force on the dipole then larger, smaller, or the same in magnitude as the force described in part (b)? *(Answer: 20)*

Field, Potential, and Conductor Size

H-3 Figure H-2a shows two conducting spheres of unequal size which are connected by a conducting wire. (a) Which sphere has at its surface a larger potential (or are both potentials equal)? (b) Use the charges Q_A and Q_B and the radii R_A and R_B of each sphere to express the magnitudes of the electric potential and field at the surface of that sphere. Then for the surface of each sphere, express the magnitude of the electric field in terms of the magnitude of the electric potential. (c) Which sphere produces at its surface the larger electric field? (d) Consider the case in which R_B is very small so that sphere B is simply a spherical tip of the conducting wire (Fig. H-2b). If the potential of sphere A is the same as in part (c), is the electric field at the surface of this tip larger or smaller in magnitude than the field at the surface of the sphere B shown in Fig. H-2a? is your answer consistent with what you know about the field produced by needles? *(Answer: 23)*

H-4 Use the results of problem H-3 to answer these questions: (a) The conducting needle in a field emission microscope has a potential of 10,000 V and the radius of its spherical tip is 1×10^{-7} meter. What is the magnitude of the electric field at the surface of this tip? (b) Airplane wings often have conducting-wire "trailers" with tips of radius about 1×10^{-5} meter. If the maximum field which can exist at the surface of these tips has a magnitude of 3×10^6 V/m (the breakdown strength of air), what is the corresponding maximum magnitude of the potential of the metal airplane? [Thus these wire "trailers" prevent the airplane from acquiring a dangerously large potential.] *(Answer: 19)*

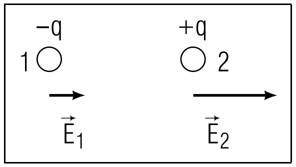


Fig. H-1.

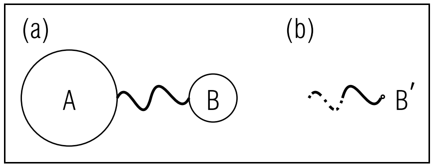


Fig. H-2.

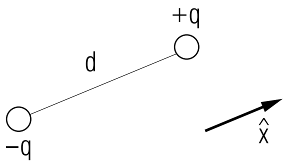
Note: Tutorial section H contains further problems.

TUTORIAL FOR D

KNOWING ABOUT DIPOLE MOMENTS IN CHEMISTRY

Unfortunately the definition of dipole moment sometimes used in chemistry is different than the one used in physics (and discussed in Sec. 21D). Further, chemists use different units for dipole moment. The following frames should help you to relate these differing definitions and units.

d-1 *ANOTHER DEFINITION OF DIPOLE MOMENT:* The following diagram shows a dipole, composed of particles separated by a distance d and having charges of magnitude q.



According to the definition given in Sec. D (which we shall use throughout this book), what is the dipole moment p of the dipole in the preceding diagram?

► $\vec{p} =$ ____________________

In chemistry, the dipole moment of the dipole in the preceding diagram is sometimes defined in this way: The dipole moment $\vec{\mu}$ is a vector with magnitude qd and direction from the positive charge towards the negative charge. (μ is the Greek letter "mu.")

According to this definition, what is the dipole moment $\vec{\mu}$ of the dipole in the preceding diagram?

► $\vec{\mu} =$ ____________________

(Answer: 67)

d-2 *UNITS FOR DIPOLE MOMENT:* In this book we shall ordinarily express dipole moments in terms of the SI unit "coulomb meter" (see, for example, text problem D-1). However, for the purpose of describing molecules, this is an enormous unit. Therefore, in chemistry it is common to express dipole moments in terms of the unit

$$\text{debye } = (\text{ charge of the electron})(1\,\text{angstrom}) = 1.6 \times 10^{-29}\,\text{C m}$$

Express your answer to text problem D-1 in terms of the unit debye.

► $(-3.4 \times 10^{-29}\,\text{C m})\,\hat{x} = ($____________$)$ debye $\hat{x}$

The dipole moment of a hydrogen bromide (HBr) molecule is 0.78 debye. What is this magnitude in terms of SI units?

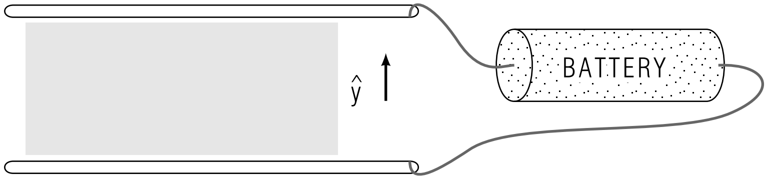
► 0.78 debye = ____________________

(Answer: 64)

TUTORIAL FOR H

ADDITIONAL PROBLEMS

h-1 *ELECTRIC FIELD INSIDE A DIELECTRIC:* A slab of material of dielectric constant 5.0 is located inside two metal plates separated by 1.0 cm (as indicated in the following diagram).

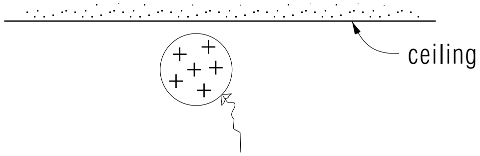


If the two metal plates are connected by conducting wires to a 6.0 V battery, so that the lower plate has a higher potential, what is the electric field inside the dielectric slab? *(Answer: 63) (Suggestion: s-2)*

h-2 *STORING CHARGE ON PARALLEL PLATES:* Two parallel metal plates have area A, are separated by a distance D, and are connected to the terminals of a battery. The plates therefore have charges of equal magnitude, and their potentials differ by V_0. (a) What is the magnitude E of the electric field between these plates? What is the magnitude σ of the charge density of each plate? What is the magnitude Q of the charge of each plate? (b) Suppose we replace the two plates by new ones which have the same separation but which have areas 4 times as large as the original plates. Which of the following quantities then have values different from those in the situation described in part (a): V_0, E, σ, Q? For each different value, write an expression in terms of the original charge Q_0. (c) If other quantities remain the same, does increasing the area of plates increase the field between them? Does increasing the area increase the amount of charge stored on each plate? *(Answer: 57) (Suggestion: s-5)*

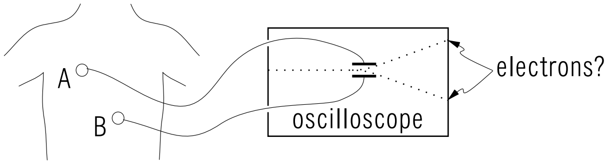
h-3 *MAKING AN ELECTRIC FIELD VISIBLE:* If long thin grass seeds are placed on a smooth glass plate near a highly charged object, the seeds turn so that they are parallel to the electric field, making a visible pattern. Why do the seeds turn in this way? *(Answer: 54)*

h-4 *ELECTRIC FORCE DUE TO AN UNCHARGED CEILING:* The following diagram shows an air-filled rubber balloon positively charged (by rubbing on a carpet). It is near an uncharged ceiling (made of dielectric plaster). Draw + and − signs on the following diagram to indicate roughly the charge distribution of the ceiling.



What is the direction of the electric force on the balloon due to the ceiling (which has a total charge of zero)? *(Answer: 60)*

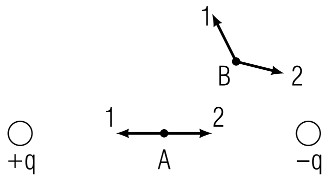
h-5 *USE OF AN OSCILLOSCOPE AS A VOLTMETER:* The following diagram shows two conducting wires connected to points A and B on a person's chest and leading to the horizontal deflecting plates of an oscilloscope.



If the potential at A is higher than the potential at B, are the negatively charged electrons passing through the plates deflected upward or downward? *(Answer: 66)*

h-6 *DESCRIBING ELECTRIC EFFECTS DUE TO A DIPOLE:* As discussed in this chapter, a dipole can rotate or move due to interaction with the electric field of external particles. However, a dipole also *produces* an electric field which affects the motion of external particles.

At each of the two points A and B near the dipole shown in the following diagrams, which of the labeled arrows best indicates the direction of the electric field at that point due to the dipole?



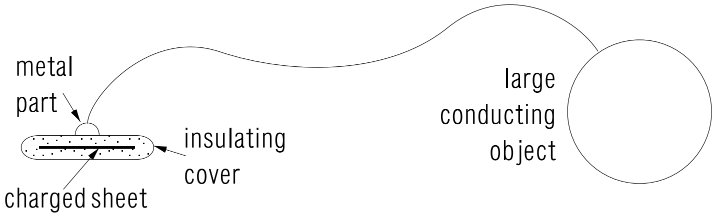
Briefly explain why the following statement is *not* correct: If a system of charged particles has a total charge of zero, then this system produces everywhere an electric field equal to zero. *(Answer: 61) (Suggestion: [s-9]) (Practice: [p-7])*

h-7 *PARALLEL PLATES PARTIALLY FILLED BY A DIELECTRIC:* If a tank for storing dielectric fluid (e.g., oil or gasoline) is made with top and bottom which are parallel conducting plates insulated from other objects, then the fraction f of fluid in the tank can be determined in the usual way:

Suppose the top and bottom plates have a uniform charge distribution and are separated by a distance d. Then if the region between these plates is empty, the potentials of these plates differ by V_0. Now suppose the region between the plates is partially filled by a layer of fluid having dielectric constant K and thickness fd (where f is a fraction less than 1).

What is the difference in the potentials of the two plates when partially filled by the dielectric? Express your answer in terms of the symbols provided. *(Answer: 65) (Suggestion: [s-8])*

h-8 *AN ELECTRIC "CLAMP":* An electric "clamp" (used in industry to hold metal parts) consists simply of a metal sheet which can be given a large charge and which has an insulating cover, so that during operation no charge can be transferred onto or off of this sheet. The metal part is placed on the sheet's insulating cover, and connected with a conducting wire to some large conducting object which is far away (e.g., the pipes of a building, or the earth).



(a) If the sheet is negatively charged, what is the direction of the electric force on a part placed on top of the sheet? (b) What is the direction of this force if the sheet is positively charged? *(Answer: 62) (Suggestion: [s-10])*

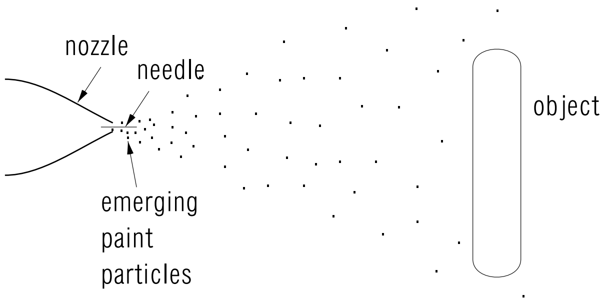
PRACTICE PROBLEMS

p-1 *COMPARING FIELDS DUE TO A CHARGED CONDUCTOR (CAP. 2B):* "Corona discharge" is a process by which a large electric field causes breakdown of air into electrons and positively charged ions. The electrons can then become attached to various particles (e.g., paint droplets or pollutant particles) giving these particles a negative charge which allows them to be moved by electric forces to any desired location.

The following diagram shows a negatively charged metal spray gun (used for painting) and a positively charged object to be painted. The paint particles become negatively charged through corona discharge and are then attracted to the positively charged object.

Circle on the following diagram the region in which the electric field is largest and in which the corona discharge therefore occurs.

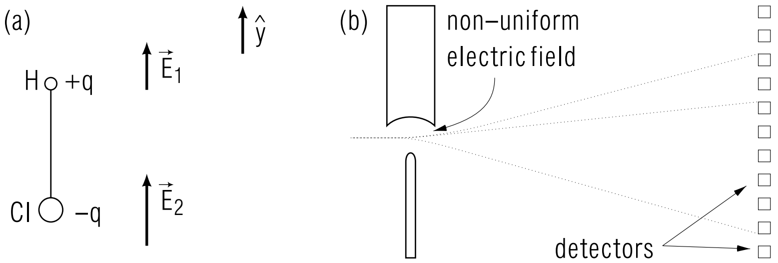
►



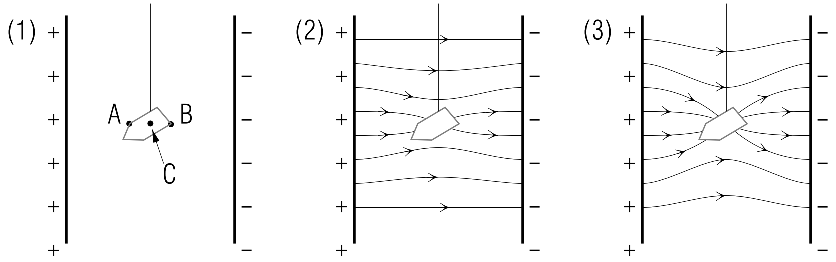
(Answer: 51) (Suggestion: Review text problems C-4 and C-5.)

p-2 *DESCRIBING ELECTRIC EFFECTS ON A DIPOLE (CAP. 3):* Many "polar" molecules (e.g., the hydrogen chloride molecule shown in the following diagram) can be considered as two ions, particles with charges of equal magnitude q and opposite sign. To measure q, the molecules are shot through a non-uniform electric field. Any force on the molecules due this field causes a deflection which can be observed by detectors [see diagram (b)].

Consider the HCl molecule in a non-uniform electric field shown in part (a) of the following diagram. The positively charged hydrogen ion (H) is acted on by an electric field $\vec{E}_1$ which is smaller in magnitude than the field $\vec{E}_2$ acting on the chlorine ion (Cl). (a) What are the directions of the external electric forces on the hydrogen ion and on the chlorine ion? (b) Which of these forces is larger in magnitude? (c) What is the direction of the external electric force $\vec{F}$ on the molecule? (d) If the magnitude q were larger, would this force be larger or smaller? Would the resulting deflection be larger or smaller? *(Answer: 55) (Suggestion: Review text problem D-2 and D-3.)*

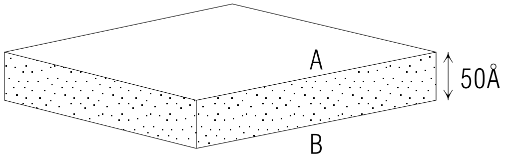


p-3 *DESCRIBING POTENTIAL, FIELD, AND CHARGE DISTRIBUTION (CAP. 1):* A bit of metal foil and a comparably-sized bit of paper can each be suspended by insulating threads in the region between two uniformly charged plates (as indicated in part 1 of the following drawing. Answer each of these questions for both the foil and the paper. (a) What is the sign of the charge of a small region near the point A? (b) Is the potential at the point A equal to the potential at the point B?

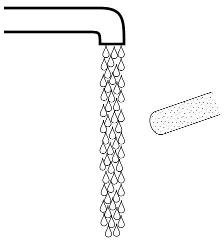


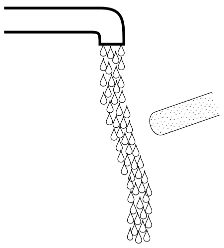
(c) Is the electric field at the point C equal to zero? (d) Which of the drawings 2 and 3 best indicates the electric field between the plates? *(Answer: 56) (Suggestion: Review text problems E-1 and E-2.)*

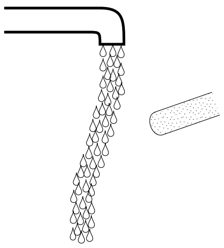
p-4 *RELATING FIELD, POTENTIAL, AND DIELECTRIC CONSTANT (CAP. 4):* A small flat piece of nerve membrane consists of a dielectric lipid material with a uniform charge distribution at each surface. In a vacuum, these charge distributions would produce an electric field of magnitude 1.2×10^8 V/m. (a) What is the actual magnitude of the electric field inside the lipid? (Refer to Table E-1.) (b) The surfaces of the membrane are separated by its thickness, $50\,\text{Å} = 5 \times 10^{-9}$ m. What is the difference in the potentials of a point A on one surface and a point B on the other surface? *(Answer: 53) (Suggestion: Review text problems E-3 and E-4.)*



p-5 *ELECTRIC FORCES ON INDUCED CHARGE DISTRIBUTIONS (CAP. 5):* A charged rubber rod is brought near the uncharged droplets in a stream of water from a faucet. (a) Is there an electric force on a water droplet due to the rubber rod? Is this force directed towards the rod or away from it? (b) Which of the following sketches best shows the appearance of the water stream near the charged rod? (c) How will the appearance of the water stream change if the rod is replaced by a rod of opposite charge? *(Answer: 59) (Suggestion: Review text problems F-1, F-2, and F-3.)*

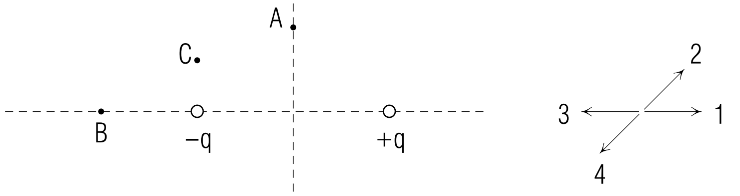
(1)


(2)


(3)


p-6 *ELECTRIC FORCES ON INDUCED CHARGE DISTRIBUTIONS (CAP. 5):* Dielectrophoresis is a process for exerting an electric force on small, uncharged objects (e.g., large molecules or other very small objects) suspended in a fluid. Suppose a fluid containing such small objects is placed in an electric field directed towards the left. (a) What is the direction of the electric force (due to this field) on the electrons in each small object? (b) Describe the induced charge distribution of each small object by stating the sign of the charge of the right and left end of each object. (c) If the electric field at the right end of each object is larger in magnitude than the field at the left end of the object, what is the direction of the electric force on each small object? (d) Towards which side of the container will these objects move? *(Answer: 52) (Suggestion: Review text problems F-1, F-2, and F-3.)*

p-7 *DESCRIBING ELECTRIC EFFECTS DUE TO A DIPOLE (CAP. 1B):* At each of the points A, B, and C near the dipole shown in the following diagram, first sketch an arrow indicating roughly the direction of the field at this point due to the dipole. Then state which of the four labeled arrows best indicates the direction of this field at each labeled point. *(Answer: 58) (Suggestion: Review tutorial frame [h-6].)*



SUGGESTIONS

s-1 *(Text problem E-2):* The electric field near the surface of a conductor is perpendicular to that surface.

s-2 *(Tutorial frame [h-1]):* First find the magnitude of the field in a vacuum between the plates. Then use the dielectric constant to find the field inside the slab.

Recall that the electric field is directed from points with higher potential towards points with lower potential.

s-3 *(Text problem D-2):* The forces on the two particles in the dipole are: qE towards the right and qE towards the left. Thus the *total* force on the dipole is zero, and its *center of mass* will not move. However, there is a non-zero force on each of the particles making up the dipole. These forces can cause it to rotate.

s-4 *(Text problem D-3):* Consider separately the forces on the two particles. The force on the positively charged particle is directed towards the left, away from the sphere. The force on the negatively charged particle is directed towards the right, towards the sphere.

Because the positively charged particle is nearer to the sphere, the force exerted on this particle is larger in magnitude than the force exerted on the negatively charged particle.

s-5 *(Tutorial frame [h-2]):* Remember that the charge density σ is the charge per unit area which is Q/A, if a charge Q is distributed uniformly over an area A. The magnitude E electric field between two plates with uniform charge densities σ and $-\sigma$ is given by:

$$E = 4\pi k_e \sigma$$

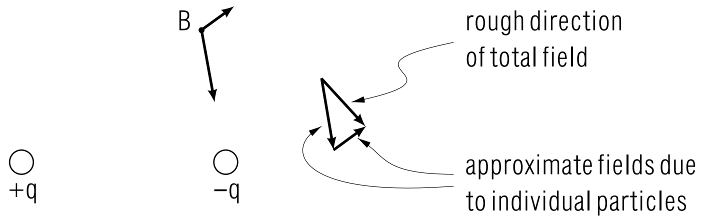
s-6 *(Text problem G-2):* You may find it helpful to review your work with problems F-1 and F-4. These problems involve details of the charge distributions, fields, and potentials describing electric effects on substances in an electric field.

s-7 *(Text problems B-1 and B-2):* Figure B-3 may help you to visualize the charge distribution, potential and field near a conductor in an externally produced electric field. Notice in particular that the total field (due to the charge distribution of the conductor and the externally produced field) is equal to zero inside the conductor, and is perpendicular to the conductor's surface.

s-8 *(Tutorial frame [h-7]):* Before the dielectric is present, the potential drop across the top part of the region is $(1-f)V_0$ and the potential part across the bottom part (where the slab will go is fV_0).

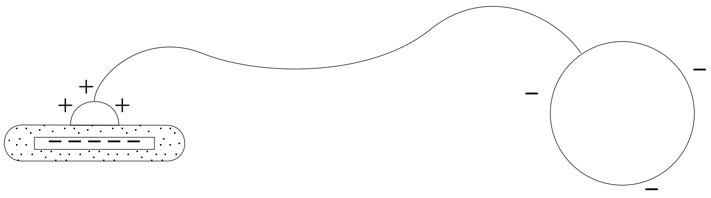
After the slab is inserted, the electric field in the top part of the region remains the same (see Fig. C-2 in the text) and so the potential drop remains $(1-f)V_0$. But in the bottom part of the region the potential drop is now $(1/K)$ times as large.

s-9 *(Tutorial frame [h-6]):* Roughly sketch arrows indicating the directions of the electric fields at the point of interest due to each individual particle. For example, at the point B these fields have the directions indicated in this drawing:

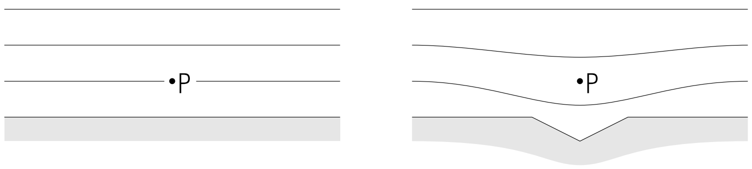


The sum of these two fields is the total field due to the dipole. (Remember that the electric field due to *one* particle is directed towards a negatively charged particle and away from a positively charged particle.)

s-10 *(Tutorial frame [h-8]):* If the sheet is negatively charged, mobile electrons in the metal part are acted on by a repulsive force due to the sheet. They therefore move from the part to the large conducting object. Thus the following sketch indicates the induced charge distribution of the metal part (and large conducting object).

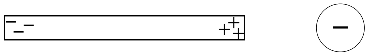


s-11 *(Text problem C-5):* The following diagrams show the metal surface and nearby equipotential surfaces before and after the dent is made. In both situations, the metal surface itself is an equipotential surface. In the second drawing, the equipotential surfaces far from the dent remain as they were in the first drawing, but the equipotential surfaces near the dent are now spread through a larger region.



To assess the effect of the dent on the electric field at a point P nearby, recall the relation between the magnitude of the electric field and the spacing of the equipotential surfaces.

s-12 *(Text problem F-1):* If the ball is negatively charged, it induces on the metal rod the charge distribution indicated in this diagram.



Thus the rod is acted on by a force (on the right end) directed towards the ball and by a force of smaller magnitude (on the left end) directed away from the ball.

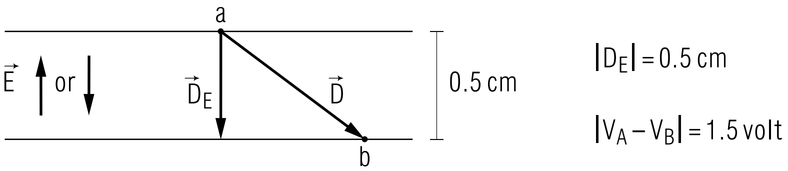
s-13 *(Text problem D-4):* As indicated in Fig. D-3a, the dipoles in an electric field tend to be aligned such that the electric field is directed roughly from the negative particles to the positive particles. The larger the magnitude of the field, the more complete is the alignment of the dipole molecules. (Because of their random internal energy, the dipoles are never completely aligned.)

s-14 *(Text problem C-1):* Recall that a constant field $\vec{E}$ (such as that produced between two parallel metal plates) is related to potential by:

$$ED_E = V_a - V_b$$

where V_a and V_b are the potentials at two points a and b and D_E is the component of the displacement $\vec{D}$ from a to b along the field $\vec{E}$.

If the points a and b each lie on one of the two metal plates, then we can use the preceding relation to find the magnitude of $\vec{E}$ as indicated by this drawing:



Because the electric field $\vec{E}$ is related to the difference $V_a - V_b$ in the potentials of the two plates and to the distance D_E between them, the only way to increase $\vec{E}$ is to change one of these two quantities.

In particular, plates of larger area have larger total charges, but it is spread out over a larger area. Thus they do not produce a larger field (unless the difference in potential or distance between the plates is also changed).

ANSWERS TO PROBLEMS

1. a. right, negative; left, positive
   b. inside, field is zero; near surface field is perpendicular to surface
   c. potential drop is zero (because potential inside is constant)
   d. (c)
2. (a) and (c)
3. conductors include (a), (d), (e); dielectrics include (b), (c), (f)
4. a. force is zero
   b. counterclockwise
5. $3 \times 10^2\,\mathrm{V/m} = 3 \times 10^2\,\mathrm{N/C}$, (a) and (b)
6. a. same
   b. electric field is zero
   c. positive
7. left, away from the sphere
8. 4×10^{-6} meter = 0.0004 cm
9. a. no; electrons moving along wire are not in equilibrium
   b. yes; in equilibrium, field must equal zero
10. a. $\vec{E} = (100\,\mathrm{V/m})\hat{y}$, $V = 5$ volt, 2, 2
    b. $\vec{E}$, V, $\vec{E} = (300\,\mathrm{V/m})\hat{y}$, $V = 15$ volt
11. a. C
    b. A. air is most likely to break down (i.e., lightning to strike) near the rod (rather than near the house, silo, or tree)
    c. field is largest (and lightning most likely to strike) near boy's head
    d. lie down
12. a. opposite to $\hat{y}$
    b. larger
13. smaller see [s-11]
14. $(-3.4 \times 10^{-29}$ coulomb meter$)\hat{x}$ (note direction)
15. dielectric b, conducting a

16. In both cases, the side of the ball nearer the rod is acted on by an attractive force larger in magnitude than the repulsive force acting on the side away from the rod.
17. a. left
    b. same, smaller
18. a. $\vec{E} = (200\,\mathrm{V/m})\hat{y}$, $V_{AB} = 10$ volt
    b. $\vec{E} = 0$, $V_{AB} = 0$, top positive, bottom negative
    c. net charge smaller in magnitude, E is smaller than 200 V/m, but larger than zero, V_{AB} is smaller than 10 volt, but larger than zero.
19. a. $1 \times 10^{11} unitV/m$
    b. 30 volt
20. a. $q\vec{E}_2 - q\vec{E}_1$
    b. $q\Delta\vec{E}$
    c. larger
    d. the same
21. towards
22. No, induced charges of the surfaces of the substance always makes the electric field $\vec{E}$ inside smaller than $\vec{E}_0$. Thus $E_0/E > 1$.
23. a. equal, say both are V_0
    b. $E_A = k_e Q_A/R_A^2$, $E_B = k_e Q_B/R_B^2$, $V_0 = k_e Q_A/R_A = k_e Q_B/R_B$, $E_A = V_0/R_A$, $E_B = V_0/R_B$
    c. sphere B
    d. larger, yes - needles produce large fields nearby
24. a. $K = E_0/E = V_0/V$
    b. $\vec{E} = (2.6\,\mathrm{V/m})\hat{y}$, $V = 0.13$ volt
25. a. vacuum, $(-3.0 \times 10^3\,\mathrm{V/m})\ \hat{y}$, 6.0 V; conductor, 0, 0; dielectric, $(-6.0 \times 10^2\,\mathrm{V/m})\ \hat{y}$, 1.2 V
    b. conductor, negative, same; dielectric, negative, smaller
26. towards the region where field is larger
27. a. up
    b. down

   c. Initially an upward force on the induced charge distribution causes the foil to move upward. After striking the rod, the foil is negatively charged and so is acted on by a downward force which causes it to fall downward.

51. region near the needle protruding from the nozzle
52. a. right
    b. right end negative, left end positive
    c. right
    d. right
53. a. $2 \times 10^7\,\mathrm{V/m}$
    b. $0.1\,\mathrm{V}$
54. The field induces a charge distribution in each seed, making it a dipole with one positive end and one negative end. There, electric forces rotate the seed until it is aligned with the field.
55. a. along $\hat{y}$, opposite to $\hat{y}$
    b. force on Cl
    c. opposite to $\hat{y}$
    d. larger, larger
56. a. negative for both
    b. equal for foil, not equal for paper
    c. yes for foil, no for paper
    d. foil, 3; paper 2
57. a. V_0/D, $\sigma = V_0/(4\pi k_e D)$, $Q = V_0 A/(4\pi k_e D)$
    b. V_0, E, σ are the same, $Q = V_0 A/(\pi k_e D) = 4Q_0$
    c. no, yes
58. A, 3; B, 1;C, 4
59. a. yes, towards
    b. 2
    c. no change
60. Ceiling is negatively charged near the balloon and positively charged farther away, having a total charge of zero. upward

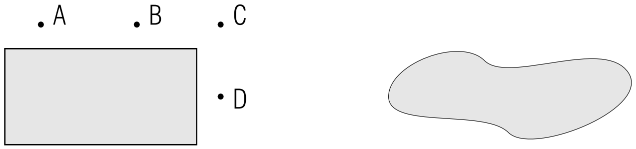
61. A, 2; B, 2; Field near system is sum of fields due to particles in the system. This sum is not necessarily zero, even if total charge of the system is zero.
62. a. down
    b. down
63. $(1.2 \times 10^2\,\mathrm{V/m})\hat{y}$
64. $(2.1\,\mathrm{debye})\hat{x}$, $1.2 \times 10^{-29}\,\mathrm{C\,m}$
65. $fV_0/K + (1-f)V_0$
66. upward
67. $\vec{p} = qd\,\hat{x}$; $\vec{\mu} = -qd\,\hat{x}$

MODEL EXAM

1. **Electrical breakdown in cellular material.** The lipid material making up a typical nerve cell wall has a thickness of 5×10^{-9} m, a dielectric constant K of 6, and a breakdown strength E_b of about 6×10^7 volt/m.

   What potential difference between the faces of a flat sheet of such material would lead to breakdown within the material? (Note that, in the body, typical potential differences across cell walls do not exceed about 0.1 V.)

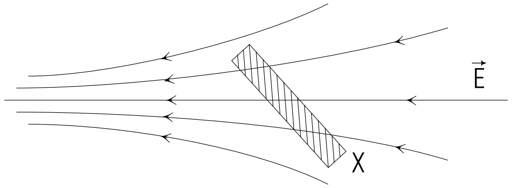
2. **Fields in and around charged conducting objects.** The figure shows a charged, conducting rectangular sheet.



   a. Write down the letter (A, B, C, or D) designating the point near the rectangle at which breakdown is *most* likely to occur.

   b. Describe the electric field just inside the surface of the positively charged, conducting object shown in the figure on the right above.

3. **Dielectric rod in an electric field.** The figure shows a dielectric rod in an externally-produced electric field. The field lines shown are those of the externally-produced field only.



   a. What is the sign of the charge of the end of the rod labeled "X" in the figure?

   b. Which answer below best describes the direction in which the rod will tend to rotate due to the torque exerted on it by the field?

(a) clockwise
(b) counterclockwise
(c) no rotation

Brief Answers:

1. 0.3 volt.
2. a. C.
   b. $E = 0$.
3. a. negative.
   b. (b)