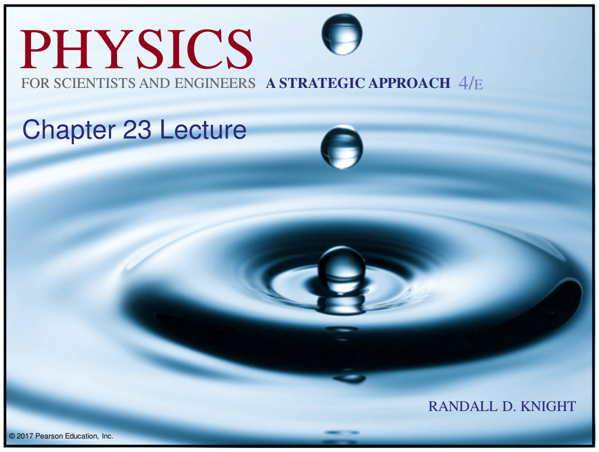
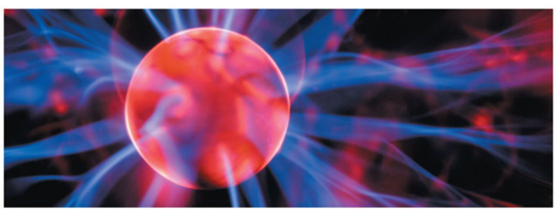


Chapter 23 The Electric Field



IN THIS CHAPTER, you will learn how to calculate and use the electric field.

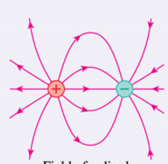
 Slide 23-2

Chapter 23 Preview

Where do electric fields come from?

Electric fields are created by charges.

- Electric fields add. The field due to several point charges is the sum of the fields due to each charge.
- Electric fields are *vectors*. Summing electric fields is vector addition.
- Two equal but opposite charges form an electric dipole.
- Electric fields can be represented by electric field vectors or electric field lines.



Field of a dipole

« LOOKING BACK Section 22.5 The electric field of a point charge

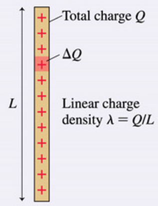
 Slide 23-3

Chapter 23 Preview

What if the charge is continuous?

For macroscopic charged objects, like rods or disks, we can think of the charge as having a continuous distribution.

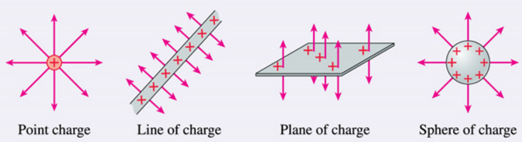
- A charged object is characterized by its charge density—the charge per length, area, or volume.
- We'll divide objects into small point charge-like pieces ΔQ.
- The summation of their electric fields will become an integral.
- We'll calculate the electric fields of charged rods, loops, disks, and planes.



Chapter 23 Preview

What fields are especially important?

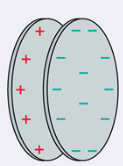
We will develop and use four important electric field models.



Chapter 23 Preview

What is a parallel-plate capacitor?

Two parallel conducting plates with equal but opposite charges form a parallel-plate capacitor. You'll learn that the electric field between the plates is a uniform electric field, the same at every point. Capacitors are also important elements of circuits, as you'll see in Chapter 26.



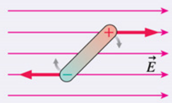
Chapter 23 Preview

How do charges respond to fields?

Electric fields exert forces on charges.

- Charged particles *accelerate*. Acceleration depends on the charge-to-mass ratio.
- A charged particle in a uniform field follows a parabolic trajectory.
- A dipole in an electric field feels a torque that aligns the dipole with the field.

« LOOKING BACK Section 4.2 Projectiles



 Slide 23-7

Chapter 23 Reading Questions

 Slide 23-8

Reading Question 23.1

What device provides a practical way to produce a uniform electric field?

A. A long thin resistor
B. A Faraday cage
C. A parallel-plate capacitor
D. A toroidal inductor
E. An electric field uniformizer

 Slide 23-9

Reading Question 23.1

What device provides a practical way to produce a uniform electric field?

A. A long thin resistor
B. A Faraday cage
✔**C. A parallel-plate capacitor**
D. A toroidal inductor
E. An electric field uniformizer

Slide 23-10

Reading Question 23.2

For charged particles, what is the quantity q/m called?

A. Linear charge density
B. Charge-to-mass ratio
C. Charged mass density
D. Massive electric dipole
E. Quadrupole moment

Slide 23-11

Reading Question 23.2

For charged particles, what is the quantity q/m called?

A. Linear charge density
✔**B. Charge-to-mass ratio**
C. Charged mass density
D. Massive electric dipole
E. Quadrupole moment

Slide 23-12

Reading Question 23.3

Which of these charge distributions did *not* have its electric field determined in Chapter 23?

A. A line of charge
B. A parallel-plate capacitor
C. A ring of charge
D. A plane of charge
E. They were *all* determined.

Reading Question 23.3

Which of these charge distributions did *not* have its electric field determined in Chapter 23?

A. A line of charge
B. A parallel-plate capacitor
C. A ring of charge
D. A plane of charge
✔**E. They were *all* determined.**

Reading Question 23.4

The worked examples of charged-particle motion are relevant to

A. A transistor.
B. A cathode ray tube.
C. Magnetic resonance imaging.
D. Cosmic rays.
E. Lasers.

Reading Question 23.4

The worked examples of charged-particle motion are relevant to

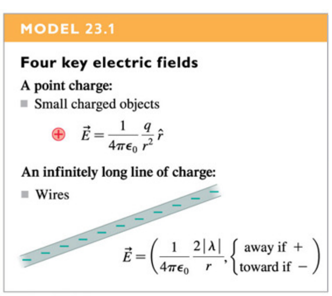
A. A transistor.
✔**B. A cathode ray tube.**
C. Magnetic resonance imaging.
D. Cosmic rays.
E. Lasers.

 Slide 23-16

Chapter 23 Content, Examples, and QuickCheck Questions

 Slide 23-17

Four Key Electric Fields: Slide 1 of 2



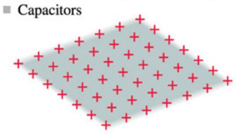
 Slide 23-18

Four Key Electric Fields: Slide 2 of 2

MODEL 23.1

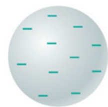
Four key electric fields

An infinitely wide plane of charge:
- Capacitors



$$\vec{E} = \left(\frac{\eta}{2\epsilon_0}, \begin{cases} \text{away if } + \\ \text{toward if } - \end{cases}\right)$$

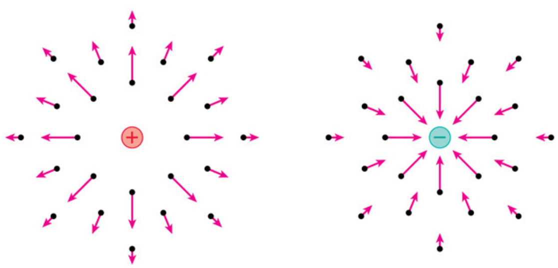
A sphere of charge:
- Electrodes



$$\vec{E} = \frac{1}{4\pi\epsilon_0}\frac{Q}{r^2}\hat{r} \text{ for } r > R$$

Electric Field of a Point Charge

$$\vec{E} = \frac{1}{4\pi\epsilon_0}\frac{q}{r^2}\hat{r} \qquad \text{(electric field of a point charge)}$$



The Electric Field

- The electric field was defined as
  $\vec{E} = \vec{F}_{\text{on } q} / q$
  where $\vec{F}_{\text{on } q}$ is the electric force on test charge q.
- The SI units of electric field are therefore Newtons per Coulomb (N/C).

TABLE 23.1 Typical electric field strengths

Field location	Field strength (N/C)
Inside a current-carrying wire	10^{-3}–10^{-1}
Near the earth's surface	10^{2}–10^{4}
Near objects charged by rubbing	10^{3}–10^{6}
Electric breakdown in air, causing a spark	3×10^{6}
Inside an atom	10^{11}

The Electric Field of Multiple Point Charges

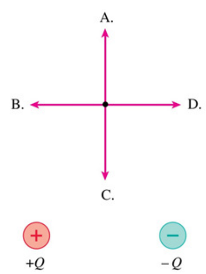
- Suppose the source of an electric field is a group of point charges $q_1, q_2, \ldots$
- The net electric field $\vec{E}_{net}$ is the vector sum of the electric fields due to each charge.
- In other words, electric fields obey the *principle of superposition*.

$$\vec{E}_{net} = \frac{\vec{F}_{on\,q}}{q} = \frac{\vec{F}_{1\,on\,q}}{q} + \frac{\vec{F}_{2\,on\,q}}{q} + \cdots = \vec{E}_1 + \vec{E}_2 + \cdots = \sum_i \vec{E}_i$$

 Slide 23-22

QuickCheck 23.1

What is the direction of the electric field at the dot?

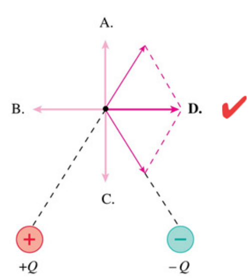


E. None of these.

 Slide 23-23

QuickCheck 23.1

What is the direction of the electric field at the dot?



E. None of these.

 Slide 23-24

Problem-Solving Strategy: The Electric Field of Multiple Point Charges

PROBLEM-SOLVING STRATEGY 23.1

The electric field of multiple point charges

MODEL Model charged objects as point charges.

VISUALIZE For the pictorial representation:

- Establish a coordinate system and show the locations of the charges.
- Identify the point P at which you want to calculate the electric field.
- Draw the electric field of each charge at P.
- Use symmetry to determine if any components of $\vec{E}_{net}$ are zero.

Problem-Solving Strategy: The Electric Field of Multiple Point Charges

PROBLEM-SOLVING STRATEGY 23.1

The electric field of multiple point charges

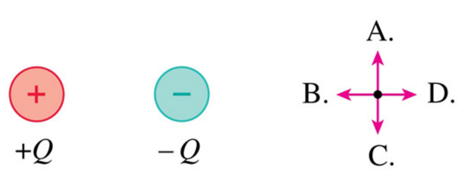
SOLVE The mathematical representation is $\vec{E}_{net} = \sum \vec{E}_i$.

- For each charge, determine its distance from P and the angle of $\vec{E}_i$ from the axes.
- Calculate the field strength of each charge's electric field.
- Write each vector $\vec{E}_i$ in component form.
- Sum the vector components to determine $\vec{E}_{net}$.

ASSESS Check that your result has correct units and significant figures, is reasonable (see TABLE 23.1), and agrees with any known limiting cases.

QuickCheck 23.2

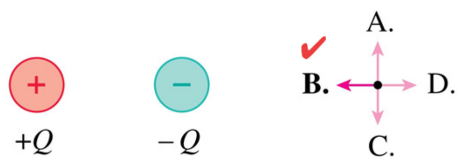
What is the direction of the electric field at the dot?



E. The field is zero.

QuickCheck 23.2

What is the direction of the electric field at the dot?

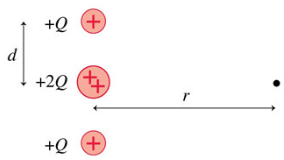


E. The field is zero.

Slide 23-28

QuickCheck 23.3

When $r >> d$, the electric field strength at the dot is



A. $\frac{Q}{4\pi\epsilon_0 r^2}$

B. $\frac{2Q}{4\pi\epsilon_0 r^2}$

C. $\frac{4Q}{4\pi\epsilon_0 r^2}$

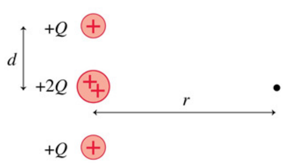
D. $\frac{4Q}{4\pi\epsilon_0 (r^2 + d^2)}$

E. $\frac{4Q}{4\pi\epsilon_0 r}$

Slide 23-29

QuickCheck 23.3

When $r >> d$, the electric field strength at the dot is



A. $\frac{Q}{4\pi\epsilon_0 r^2}$

B. $\frac{2Q}{4\pi\epsilon_0 r^2}$

✔ **C.** $\frac{4Q}{4\pi\epsilon_0 r^2}$ Looks like a point charge $4Q$ at the origin.

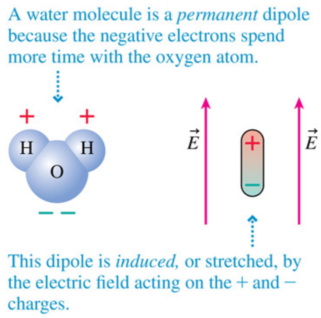
D. $\frac{4Q}{4\pi\epsilon_0 (r^2 + d^2)}$

E. $\frac{4Q}{4\pi\epsilon_0 r}$

Slide 23-30

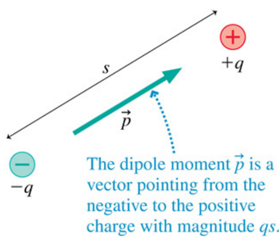
Electric Dipoles

- Two equal but opposite charges separated by a small distance form an *electric dipole*.
- The figure shows two examples.



The Dipole Moment

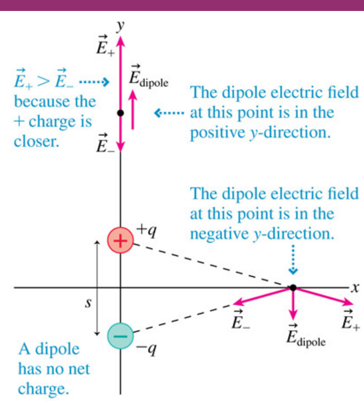
- It is useful to define the dipole moment $\vec{p}$, shown in the figure, as the vector:



$$\vec{p} = (qs, \text{ from the negative to the positive charge})$$

- The SI units of the dipole moment are C m.

The Dipole Electric Field at Two Points



The Electric Field of a Dipole

- The electric field at a point on the axis of a dipole is

$$\vec{E}_{\text{dipole}} \approx \frac{1}{4\pi\epsilon_0}\frac{2\vec{p}}{r^3} \quad \text{(on the axis of an electric dipole)}$$

where r is the distance measured from the *center* of the dipole.

- The electric field in the plane that bisects and is perpendicular to the dipole is

$$\vec{E}_{\text{dipole}} \approx -\frac{1}{4\pi\epsilon_0}\frac{\vec{p}}{r^3} \quad \text{(bisecting plane)}$$

- This field is opposite to the dipole direction, and it is only half the strength of the on-axis field at the same distance.

Slide 23-34

Example 23.2 The Electric Field of a Water Molecule

EXAMPLE 23.2 | The electric field of a water molecule

The water molecule H_2O has a permanent dipole moment of magnitude 6.2×10^{-30} C m. What is the electric field strength 1.0 nm from a water molecule at a point on the dipole's axis?

MODEL The size of a molecule is ≈ 0.1 nm. Thus $r \gg s$, and we can use Equation 23.10 for the on-axis electric field of the molecule's dipole moment.

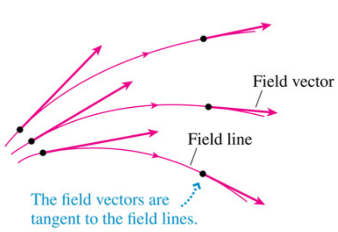
SOLVE The on-axis electric field strength at $r = 1.0$ nm is

$$E \approx \frac{1}{4\pi\epsilon_0}\frac{2p}{r^3} = (9.0 \times 10^9 \text{ N m}^2/\text{C}^2)\frac{2(6.2 \times 10^{-30}\text{ C m})}{(1.0 \times 10^{-9}\text{ m})^3}$$
$$= 1.1 \times 10^8 \text{ N/C}$$

ASSESS By referring to Table 23.1 you can see that the field strength is "strong" compared to our everyday experience with charged objects but "weak" compared to the electric field inside the atoms themselves. This seems reasonable.

Slide 23-35

Electric Field Lines

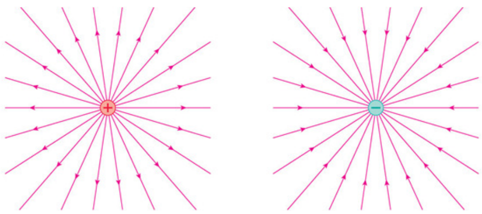


- Electric field lines are *continuous* curves tangent to the electric field vectors.
- Closely spaced field lines indicate a greater field strength.
- Electric field lines start on positive charges and end on negative charges.
- Electric field lines never cross.

Slide 23-36

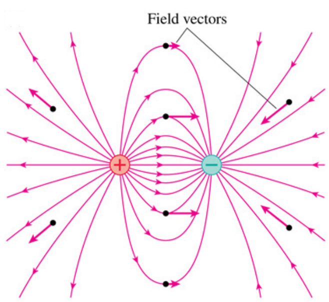
Electric Field Lines of a Point Charge

$$\vec{E} = \frac{1}{4\pi\epsilon_0}\frac{q}{r^2}\hat{r} \quad \text{(electric field of a point charge)}$$



Slide 23-37

The Electric Field of a Dipole



- This figure represents the electric field of a dipole using electric field lines.

Slide 23-38

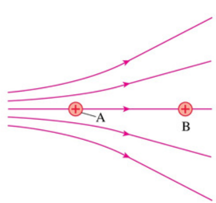
QuickCheck 23.4

Two protons, A and B, are in an electric field. Which proton has the larger acceleration?

A. Proton A

B. Proton B

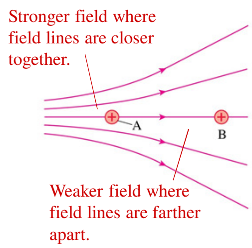
C. Both have the same acceleration.



Slide 23-39

QuickCheck 23.4

Two protons, A and B, are in an electric field. Which proton has the larger acceleration?



✔ **A. Proton A**

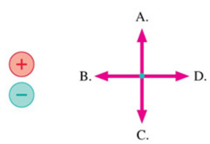
B. Proton B

C. Both have the same acceleration.

Slide 23-40

QuickCheck 23.5

An electron is in the plane that bisects a dipole. What is the direction of the electric force on the electron?

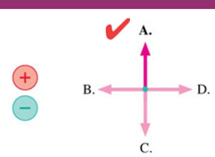


E. The force is zero.

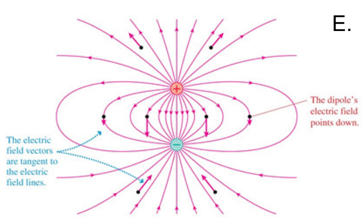
Slide 23-41

QuickCheck 23.5

An electron is in the plane that bisects a dipole. What is the direction of the electric force on the electron?



E. The force is zero.



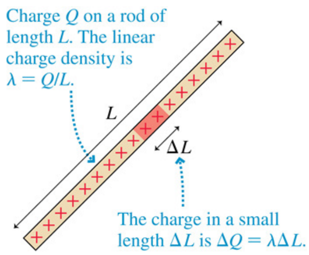
Slide 23-42

Continuous Charge Distributions

- The linear charge density of an object of length L and charge Q is defined as

$$\lambda = \frac{Q}{L}$$

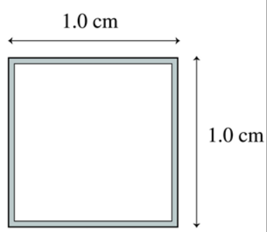
- Linear charge density, which has units of C/m, is the amount of charge *per meter* of length.



Slide 23-43

QuickCheck 23.6

If 8 nC of charge are placed on the square loop of wire, the linear charge density will be

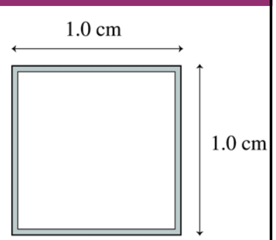


A. 800 nC/m
B. 400 nC/m
C. 200 nC/m
D. 8 nC/m
E. 2 nC/m

Slide 23-44

QuickCheck 23.6

If 8 nC of charge are placed on the square loop of wire, the linear charge density will be



A. 800 nC/m
B. 400 nC/m
✔ **C. 200 nC/m**
D. 8 nC/m
E. 2 nC/m

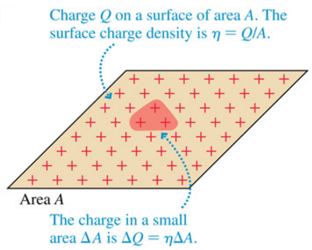
Slide 23-45

Continuous Charge Distributions

- The surface charge density of a two-dimensional distribution of charge across a surface of area is defined as

$$\eta = \frac{Q}{A}$$

- Surface charge density, with units C/m^2, is the amount of charge *per square meter*.

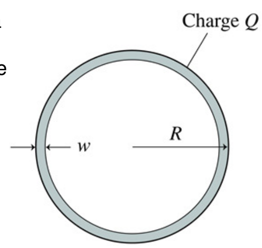


Slide 23-46

QuickCheck 23.7

A flat circular ring is made from a very thin sheet of metal. Charge Q is uniformly distributed over the ring. Assuming $w << R$, the surface charge density η is

A. $Q/2\pi Rw$
B. $Q/4\pi Rw$
C. $Q/\pi R^2$
D. $Q/2\pi R^2$
E. $Q/\pi Rw$



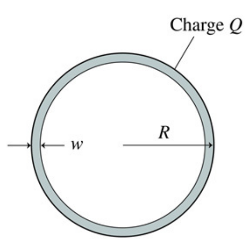
Slide 23-47

QuickCheck 23.7

A flat circular ring is made from a very thin sheet of metal. Charge Q is uniformly distributed over the ring. Assuming $w << R$, the surface charge density η is

A. $Q/2\pi Rw$
✔ **B. $Q/4\pi Rw$**
C. $Q/\pi R^2$
D. $Q/2\pi R^2$
E. $Q/\pi Rw$

The ring has two sides, each of area $2\pi Rw$.



Slide 23-48

Problem-Solving Strategy: The Electric Field of a Continuous Distribution of Charge

PROBLEM-SOLVING STRATEGY 23.2

The electric field of a continuous distribution of charge

MODEL Model the charge distribution as a simple shape.

VISUALIZE For the pictorial representation:

- Draw a picture, establish a coordinate system, and identify the point P at which you want to calculate the electric field.
- Divide the total charge Q into small pieces of charge ΔQ, using shapes for which you *already know* how to determine $\vec{E}$. This is often, but not always, a division into point charges.
- Draw the electric field vector at P for one or two small pieces of charge. This will help you identify distances and angles that need to be calculated.

Problem-Solving Strategy: The Electric Field of a Continuous Distribution of Charge

PROBLEM-SOLVING STRATEGY 23.2

The electric field of a continuous distribution of charge

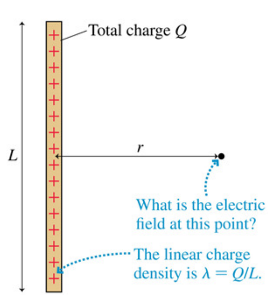
SOLVE The mathematical representation is $\vec{E}_{net} = \sum \vec{E}_i$.

- Write an algebraic expression for *each* of the three components of $\vec{E}$ (unless you are sure one or more is zero) at point P. Let the (x, y, z) coordinates of the point remain variables.
- Replace the small charge ΔQ with an equivalent expression involving a charge density and a coordinate, such as dx. **This is the critical step in making the transition from a sum to an integral** because you need a coordinate to serve as the integration variable.
- Express all angles and distances in terms of the coordinates.
- Let the sum become an integral. The integration limits for this variable must "cover" the entire charged object.

ASSESS Check that your result is consistent with any limits for which you know what the field should be.

Exercise 16

The Electric Field of a Line of Charge

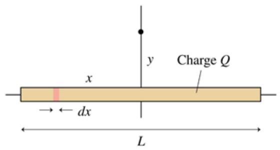


- Example 23.3 in the text uses integration to find the electric field strength at a radial distance r in the plane that bisects a rod of length L with total charge Q:

$$E_{rod} = \frac{1}{4\pi\epsilon_0} \frac{|Q|}{r\sqrt{r^2 + (L/2)^2}}$$

QuickCheck 23.8

At the dot, the y-component of the electric field due to the shaded region of charge is



A. $\dfrac{(Q/L)\,dx}{4\pi\epsilon_0(x^2+y^2)} \times \dfrac{y}{x}$

B. $\dfrac{(Q/L)\,dx}{4\pi\epsilon_0(x^2+y^2)} \times \dfrac{x}{y}$

C. $\dfrac{(Q/L)\,dx}{4\pi\epsilon_0(x^2+y^2)} \times \dfrac{x}{\sqrt{x^2+y^2}}$

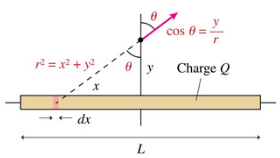
D. $\dfrac{(Q/L)\,dx}{4\pi\epsilon_0(x^2+y^2)} \times \dfrac{y}{\sqrt{x^2+y^2}}$

E. $\dfrac{(Q/L)\,dx}{4\pi\epsilon_0\sqrt{x^2+y^2}} \times \dfrac{y}{\sqrt{x^2+y^2}}$

Slide 23-52

QuickCheck 23.8

At the dot, the y-component of the electric field due to the shaded region of charge is



A. $\dfrac{(Q/L)\,dx}{4\pi\epsilon_0(x^2+y^2)} \times \dfrac{y}{x}$

B. $\dfrac{(Q/L)\,dx}{4\pi\epsilon_0(x^2+y^2)} \times \dfrac{x}{y}$

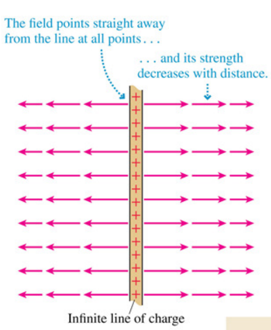
C. $\dfrac{(Q/L)\,dx}{4\pi\epsilon_0(x^2+y^2)} \times \dfrac{x}{\sqrt{x^2+y^2}}$

✔ **D.** $\dfrac{(Q/L)\,dx}{4\pi\epsilon_0(x^2+y^2)} \times \dfrac{y}{\sqrt{x^2+y^2}}$

E. $\dfrac{(Q/L)\,dx}{4\pi\epsilon_0\sqrt{x^2+y^2}} \times \dfrac{y}{\sqrt{x^2+y^2}}$

Slide 23-53

An Infinite Line of Charge



- The electric field of a thin, uniformly charged rod may be written

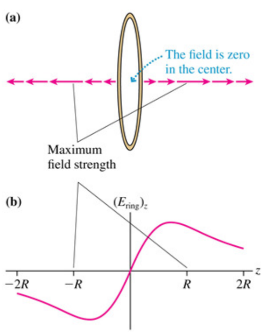
$$E_{\text{rod}} = \frac{1}{4\pi\epsilon_0}\frac{2|\lambda|}{r}\frac{1}{\sqrt{1+4r^2/L^2}}$$

- If we now let $L \to \infty$, the last term becomes simply 1 and we're left with

$$\vec{E}_{\text{line}} = \left(\frac{1}{4\pi\epsilon_0}\frac{2|\lambda|}{r}, \begin{cases}\text{away from line if charge } + \\ \text{toward line if charge } -\end{cases}\right)$$

Slide 23-54

A Ring of Charge

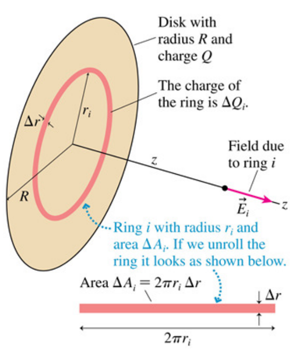


- Consider the on-axis electric field of a positively charged ring of radius R.
- Define the z-axis to be the axis of the ring.
- The electric field on the z-axis points away from the center of the ring, increasing in strength until reaching a maximum when $|z| \approx R$, then decreasing:

$$(E_{\text{ring}})_z = \frac{1}{4\pi\epsilon_0} \frac{zQ}{(z^2 + R^2)^{3/2}}$$

Slide 23-55

A Disk of Charge



- Consider the on-axis electric field of a positively charged disk of radius R.
- Define the z-axis to be the axis of the disk.
- The electric field on the z-axis points away from the center of the disk, with magnitude:

$$(E_{\text{disk}})_z = \frac{\eta}{2\epsilon_0}\left[1 - \frac{z}{\sqrt{z^2 + R^2}}\right]$$

Slide 23-56

Example 23.5 The Electric Field of a Charged Disk

EXAMPLE 23.5 | **The electric field of a charged disk**

A 10-cm-diameter plastic disk is charged uniformly with an extra 10^{11} electrons. What is the electric field 1.0 mm above the surface at a point near the center?

MODEL Model the plastic disk as a uniformly charged disk. We are seeking the on-axis electric field. Because the charge is negative, the field will point *toward* the disk.

Slide 23-57

Example 23.5 The Electric Field of a Charged Disk

EXAMPLE 23.5 The electric field of a charged disk

SOLVE The total charge on the plastic square is $Q = N(-e) = -1.60 \times 10^{-8}$ C. The surface charge density is

$$\eta = \frac{Q}{A} = \frac{Q}{\pi R^2} = \frac{-1.60 \times 10^{-8}\ \text{C}}{\pi(0.050\ \text{m})^2} = -2.04 \times 10^{-6}\ \text{C/m}^2$$

The electric field at $z = 0.0010$ m, given by Equation 23.25, is

$$E_z = \frac{\eta}{2\epsilon_0}\left[1 - \frac{1}{\sqrt{1 + R^2/z^2}}\right] = -1.1 \times 10^5\ \text{N/C}$$

The minus sign indicates that the field points *toward,* rather than away from, the disk. As a vector,

$$\vec{E} = (1.1 \times 10^5\ \text{N/C, toward the disk})$$

ASSESS The total charge, -16 nC, is typical of the amount of charge produced on a small plastic object by rubbing or friction. Thus 10^5 N/C is a typical electric field strength near an object that has been charged by rubbing.

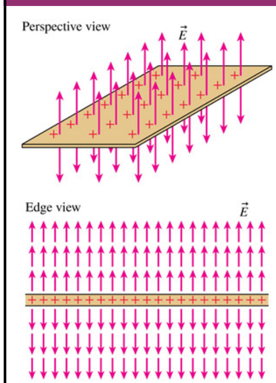
A Plane of Charge

- The electric field of a plane of charge is found from the on-axis field of a charged disk by letting the radius $R \to \infty$.
- The electric field of an infinite plane of charge with surface charge density η is

$$E_{\text{plane}} = \frac{\eta}{2\epsilon_0} = \text{constant}$$

- For a positively charged plane, with $\eta > 0$, the electric field points *away from* the plane on both sides of the plane.
- For a negatively charged plane, with $\eta < 0$, the electric field points *toward* the plane on both sides of the plane.

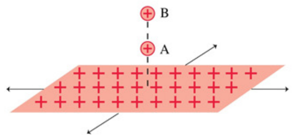
A Plane of Charge



$$\vec{E}_{\text{plane}} = \left(\frac{|\eta|}{2\epsilon_0}, \begin{cases}\text{away from plane if charge } + \\ \text{toward plane if charge } - \end{cases}\right)$$

QuickCheck 23.9

Two protons, A and B, are next to an infinite plane of positive charge. Proton B is twice as far from the plane as proton A. Which proton has the larger acceleration?

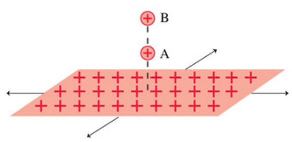


A. Proton A
B. Proton B
C. Both have the same acceleration.

Slide 23-61

QuickCheck 23.9

Two protons, A and B, are next to an infinite plane of positive charge. Proton B is twice as far from the plane as proton A. Which proton has the larger acceleration?



A. Proton A
B. Proton B
✔**C. Both have the same acceleration.**

Slide 23-62

A Sphere of Charge

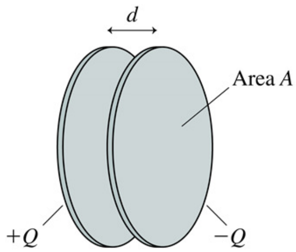
- A sphere of charge Q and radius R, be it a uniformly charged sphere or just a spherical shell, has an electric field *outside* the sphere that is exactly the same as that of a point charge Q located at the center of the sphere:

$$\vec{E}_{\text{sphere}} = \frac{Q}{4\pi\epsilon_0 r^2}\hat{r} \qquad \text{for } r \geq R$$

Slide 23-63

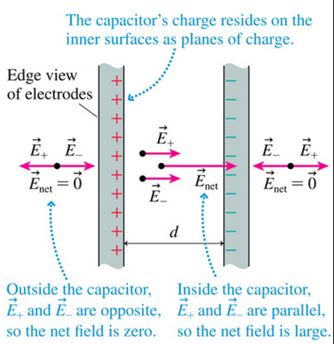
The Parallel-Plate Capacitor

- The figure shows two electrodes, one with charge $+Q$ and the other with $-Q$ placed face-to-face a distance d apart.
- This arrangement of two electrodes, charged equally but oppositely, is called a **parallel-plate capacitor**.
- Capacitors play important roles in many electric circuits.



The Parallel-Plate Capacitor

- The figure shows two capacitor plates, seen from the side.
- Because opposite charges attract, all of the charge is on the *inner* surfaces of the two plates.
- Inside the capacitor, the net field points toward the negative plate.
- Outside the capacitor, the net field is zero.



The Parallel-Plate Capacitor

- The electric field of a capacitor is

$$\vec{E}_{\text{capacitor}} = \begin{cases} \left(\dfrac{Q}{\epsilon_0 A}, \text{ from positive to negative}\right) & \text{inside} \\ \vec{0} & \text{outside} \end{cases}$$

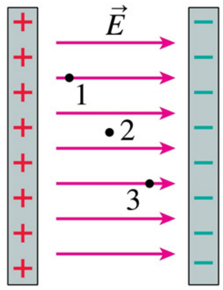
where A is the surface area of each electrode.

- Outside the capacitor plates, where E_+ and E_- have equal magnitudes but *opposite* directions, the electric field is zero.

QuickCheck 23.10

Three points inside a parallel-plate capacitor are marked. Which is true?

A. $E_1 > E_2 > E_3$
B. $E_1 < E_2 < E_3$
C. $E_1 = E_2 = E_3$
D. $E_1 = E_3 > E_2$

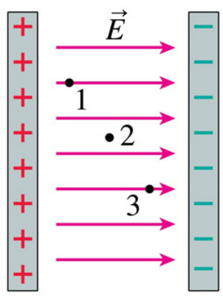


Slide 23-67

QuickCheck 23.10

Three points inside a parallel-plate capacitor are marked. Which is true?

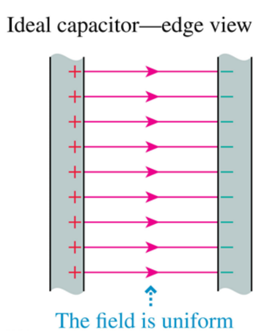
A. $E_1 > E_2 > E_3$
B. $E_1 < E_2 < E_3$
✔**C.** $\mathbf{E_1 = E_2 = E_3}$
D. $E_1 = E_3 > E_2$



Slide 23-68

The Ideal Capacitor

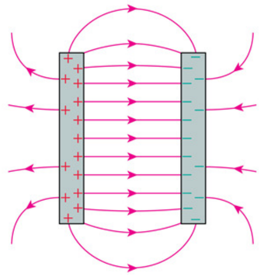
- The figure shows the electric field of an ideal parallel-plate capacitor constructed from two infinite charged planes.
- The ideal capacitor is a good approximation as long as the electrode separation d is much smaller than the electrodes' size.



Slide 23-69

A Real Capacitor

- Outside a real capacitor and near its edges, the electric field is affected by a complicated but weak **fringe field**.
- We will keep things simple by always assuming the plates are very close together and using $E = \eta/\epsilon_0$ for the magnitude of the field inside a parallel-plate capacitor.



Example 23.6 The Electric Field Inside a Capacitor

EXAMPLE 23.6 | **The electric field inside a capacitor**

Two 1.0 cm × 2.0 cm rectangular electrodes are 1.0 mm apart. What charge must be placed on each electrode to create a uniform electric field of strength 2.0×10^6 N/C? How many electrons must be moved from one electrode to the other to accomplish this?

MODEL The electrodes can be modeled as an ideal parallel-plate capacitor because the spacing between them is much smaller than their lateral dimensions.

Example 23.6 The Electric Field Inside a Capacitor

EXAMPLE 23.6 | **The electric field inside a capacitor**

SOLVE The electric field strength inside the capacitor is $E = Q/\epsilon_0 A$. Thus the charge to produce a field of strength E is

$$Q = (8.85 \times 10^{-12}\ \mathrm{C^2/N\,m^2})(2.0 \times 10^{-4}\ \mathrm{m^2})(2.0 \times 10^6\ \mathrm{N/C})$$
$$= 3.5 \times 10^{-9}\ \mathrm{C} = 3.5\ \mathrm{nC}$$

The positive plate must be charged to +3.5 nC and the negative plate to −3.5 nC. In practice, the plates are charged by using a *battery* to move electrons from one plate to the other. The number of electrons in 3.5 nC is

$$N = \frac{Q}{e} = \frac{3.5 \times 10^{-9}\ \mathrm{C}}{1.60 \times 10^{-19}\ \mathrm{C/electron}} = 2.2 \times 10^{10}\ \text{electrons}$$

Thus 2.2×10^{10} electrons are moved from one electrode to the other. Note that the capacitor *as a whole* has no net charge.

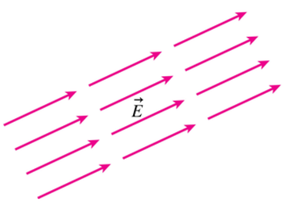
Example 23.6 The Electric Field Inside a Capacitor

EXAMPLE 23.6 The electric field inside a capacitor

ASSESS The plate spacing does not enter the result. As long as the spacing is much smaller than the plate dimensions, as is true in this example, the field is independent of the spacing.

 Slide 23-73

Uniform Electric Fields

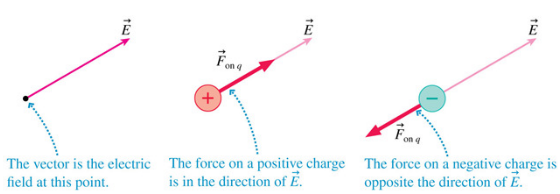


- The figure shows an electric field that is the *same*—in strength and direction—at every point in a region of space.
- This is called a **uniform electric field**.
- The easiest way to produce a uniform electric field is with a parallel-plate capacitor.

 Slide 23-74

Motion of a Charged Particle in an Electric Field

- Consider a particle of charge q and mass m at a point where an electric field $\vec{E}$ has been produced by *other* charges, the source charges.
- The electric field exerts a force $\vec{F}_{\text{on } q} = q\vec{E}$.



 Slide 23-75

Motion of a Charged Particle in an Electric Field

- The electric field exerts a force $\vec{F}_{\text{on } q} = q\vec{E}$ on a charged particle.
- If this is the only force acting on q, it causes the charged particle to accelerate with

$$\vec{a} = \frac{\vec{F}_{\text{on } q}}{m} = \frac{q}{m}\vec{E}$$

- In a uniform field, the acceleration is constant:

$$a = \frac{qE}{m} = \text{constant}$$

Slide 23-76

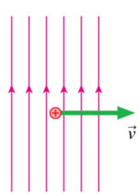
Motion of a Charged Particle in an Electric Field

- “DNA fingerprints” are measured with the technique of *gel electrophoresis*.
- A solution of negatively charged DNA fragments migrate through the gel when placed in a uniform electric field.
- Because the gel exerts a drag force, the fragments move at a terminal speed inversely proportional to their size.

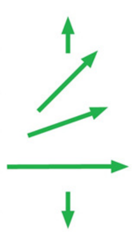
Slide 23-77

QuickCheck 23.11

A proton is moving to the right in a vertical electric field. A very short time later, the proton’s velocity is



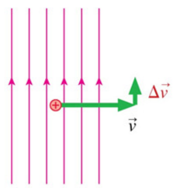
A.
B.
C.
D.
E.



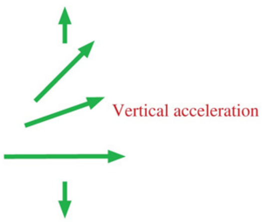
Slide 23-78

QuickCheck 23.11

A proton is moving to the right in a vertical electric field. A very short time later, the proton's velocity is

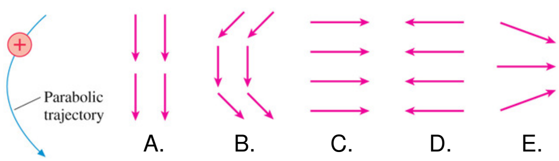


A.
B.
✔ **C.**
D.
E.



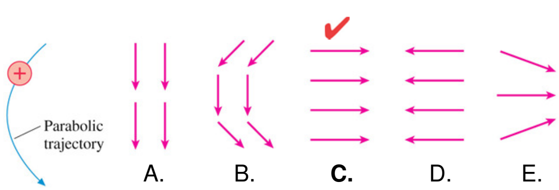
QuickCheck 23.12

Which electric field is responsible for the proton's trajectory?



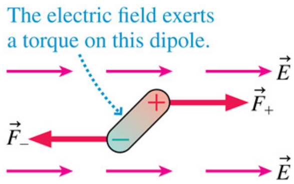
QuickCheck 23.12

Which electric field is responsible for the proton's trajectory?



Dipoles in a Uniform Electric Field

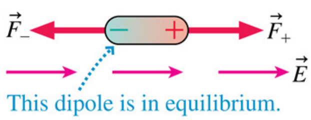
- The figure shows an electric dipole placed in a *uniform* external electric field.
- The net force on the dipole is zero.
- The electric field exerts a *torque* on the dipole that causes it to *rotate*.



Slide 23-82

Dipoles in a Uniform Electric Field

- The figure shows an electric dipole placed in a *uniform* external electric field.
- The torque causes the dipole to rotate until it is aligned with the electric field, as shown.
- Notice that the positive end of the dipole is in the direction in which $\vec{E}$ points.

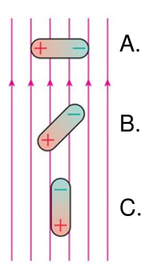


Slide 23-83

QuickCheck 23.13

Which dipole experiences no net force in the electric field?

A. Dipole A
B. Dipole B
C. Dipole C
D. Both dipoles A and C
E. All three dipoles

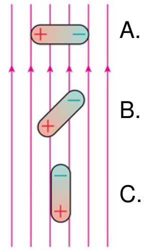


Slide 23-84

QuickCheck 23.13

Which dipole experiences no net force in the electric field?

A. Dipole A
B. Dipole B
C. Dipole C
D. Both dipoles A and C
✔**E. All three dipoles**

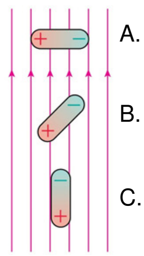


Slide 23-85

QuickCheck 23.14

Which dipole experiences no net torque in the electric field?

A. Dipole A
B. Dipole B
C. Dipole C
D. Both dipoles A and C
E. All three dipoles

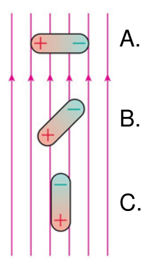


Slide 23-86

QuickCheck 23.14

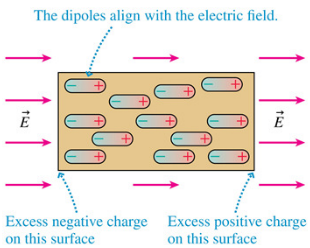
Which dipole experiences no net torque in the electric field?

A. Dipole A
B. Dipole B
✔**C. Dipole C**
D. Both dipoles A and C
E. All three dipoles



Slide 23-87

Dipoles in a Uniform Electric Field

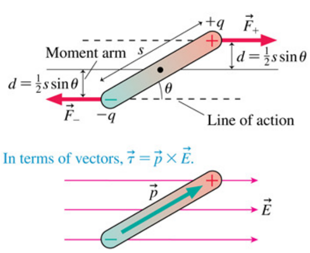


- The figure shows a sample of permanent dipoles, such as water molecules, in an external electric field.
- All the dipoles rotate until they are aligned with the electric field.
- This is the mechanism by which the sample becomes *polarized*.

The Torque on a Dipole

- The torque on a dipole placed in a uniform external electric field is

$$\tau = 2 \times dF_+ = 2(\tfrac{1}{2}s\sin\theta)(qE) = pE\sin\theta$$



Example 23.9 The Angular Acceleration of a Dipole Dumbbell

EXAMPLE 23.9 **The angular acceleration of a dipole dumbbell**

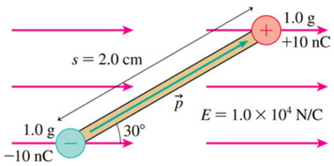
Two 1.0 g balls are connected by a 2.0-cm-long insulating rod of negligible mass. One ball has a charge of +10 nC, the other a charge of −10 nC. The rod is held in a 1.0×10^4 N/C uniform electric field at an angle of 30° with respect to the field, then released. What is its initial angular acceleration?

MODEL The two oppositely charged balls form an electric dipole. The electric field exerts a torque on the dipole, causing an angular acceleration.

Example 23.9 The Angular Acceleration of a Dipole Dumbbell

EXAMPLE 23.9 | **The angular acceleration of a dipole dumbbell**

VISUALIZE FIGURE 23.29 shows the dipole in the electric field.



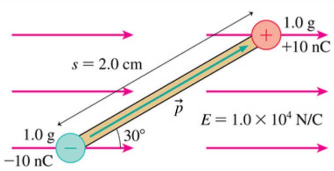
Example 23.9 The Angular Acceleration of a Dipole Dumbbell

EXAMPLE 23.9 | **The angular acceleration of a dipole dumbbell**

SOLVE The dipole moment is $p = qs = (1.0 \times 10^{-8}\ \text{C}) \times (0.020\ \text{m}) = 2.0 \times 10^{-10}\ \text{C m}$. The torque exerted on the dipole moment by the electric field is

$$\tau = pE\sin\theta = (2.0 \times 10^{-10}\ \text{C m})(1.0 \times 10^{4}\ \text{N/C})\sin 30^\circ$$
$$= 1.0 \times 10^{-6}\ \text{N m}$$

You learned in Chapter 12 that a torque causes an angular acceleration $\alpha = \tau/I$, where I is the moment of inertia.



Example 23.9 The Angular Acceleration of a Dipole Dumbbell

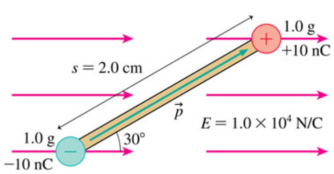
EXAMPLE 23.9 | **The angular acceleration of a dipole dumbbell**

SOLVE The dipole rotates about its center of mass, which is at the center of the rod, so the moment of inertia is

$$I = m_1 r_1^2 + m_2 r_2^2 = 2m(\tfrac{1}{2}s)^2 = \tfrac{1}{2}ms^2 = 2.0 \times 10^{-7}\ \text{kg m}^2$$

Thus the rod's angular acceleration is

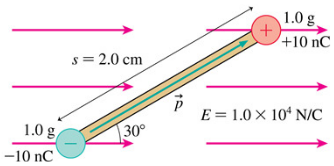
$$\alpha = \frac{\tau}{I} = \frac{1.0 \times 10^{-6}\ \text{N m}}{2.0 \times 10^{-7}\ \text{kg m}^2} = 5.0\ \text{rad/s}^2$$



Example 23.9 The Angular Acceleration of a Dipole Dumbbell

EXAMPLE 23.9 The angular acceleration of a dipole dumbbell

ASSESS This value of α is the initial angular acceleration, when the rod is first released. The torque and the angular acceleration will decrease as the rod rotates toward alignment with $\vec{E}$.



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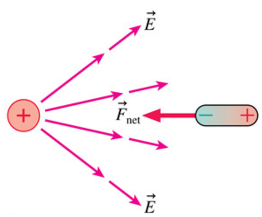
Dipoles in a Nonuniform Electric Field

- Suppose that a dipole is placed in a nonuniform electric field, such as the field of a positive point charge.
- The first response of the dipole is to rotate until it is aligned with the field.



- Once the dipole is aligned, the leftward attractive force on its negative end is slightly stronger than the rightward repulsive force on its positive end.
- This causes a net force to the *left*, toward the point charge.

Slide 23-95

Dipoles in a Nonuniform Electric Field

- A dipole near a negative point charge is also attracted toward the point charge.
- The net force on a dipole is toward the direction of the strongest field.
- Because field strength increases as you get closer to any finite-sized charged object, we can conclude that a **dipole will experience a net force toward any charged object**.

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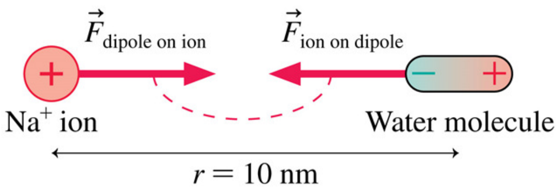
Example 23.10 The Force on a Water Molecule

EXAMPLE 23.10 | **The force on a water molecule**

The water molecule H_2O has a permanent dipole moment of magnitude 6.2×10^{-30} C m. A water molecule is located 10 nm from a Na^+ ion in a saltwater solution. What force does the ion exert on the water molecule?

VISUALIZE FIGURE 23.31 shows the ion and the dipole. The forces are an action/reaction pair.



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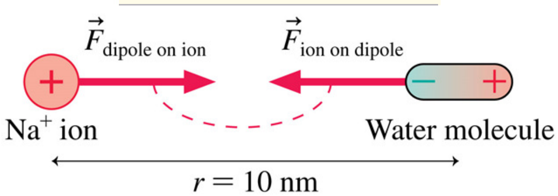
Example 23.10 The Force on a Water Molecule

EXAMPLE 23.10 | **The force on a water molecule**

SOLVE A Na^+ ion has charge $q = +e$. The electric field of the ion aligns the water's dipole moment and exerts a net force on it. We could calculate the net force on the dipole as the small difference between the attractive force on its negative end and the repulsive force on its positive end. Alternatively, we know from Newton's third law that the force $\vec{F}_{\text{dipole on ion}}$ has the same magnitude as the force $\vec{F}_{\text{ion on dipole}}$ that we are seeking. We calculated the on-axis field of a dipole in Section 23.2. An ion of charge $q = e$ will experience a force of magnitude $F = qE_{\text{dipole}} = eE_{\text{dipole}}$ when placed in that field.



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Example 23.10 The Force on a Water Molecule

EXAMPLE 23.10 | **The force on a water molecule**

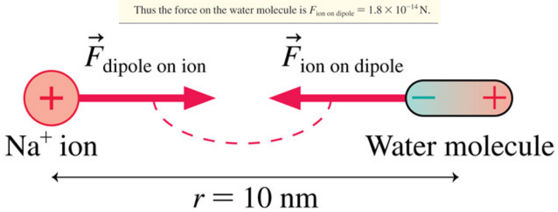
SOLVE The dipole's electric field, which we found in Equation 23.10, is

$$E_{\text{dipole}} = \frac{1}{4\pi\epsilon_0}\frac{2p}{r^3}$$

The force on the ion at distance $r = 1.0 \times 10^{-8}$ m is

$$F_{\text{dipole on ion}} = eE_{\text{dipole}} = \frac{1}{4\pi\epsilon_0}\frac{2ep}{r^3} = 1.8 \times 10^{-14}\text{ N}$$

Thus the force on the water molecule is $F_{\text{ion on dipole}} = 1.8 \times 10^{-14}$ N.



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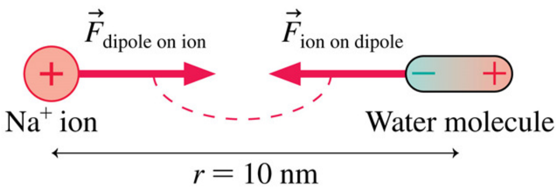
Example 23.10 The Force on a Water Molecule

EXAMPLE 23.10 The force on a water molecule

ASSESS While 1.8×10^{-14} N may seem like a very small force, it is $\approx 10^{11}$ times larger than the size of the earth's gravitational force on these atomic particles. Forces such as these cause water molecules to cluster around any ions that are in solution. This clustering plays an important role in the microscopic physics of solutions studied in chemistry and biochemistry.



Slide 23-100

Chapter 23 Summary Slides

Slide 23-101

General Principles

Sources of $\vec{E}$

Electric fields are created by charges.

Multiple point charges

MODEL Model objects as point charges.

VISUALIZE Establish a coordinate system and draw field vectors.

SOLVE Use superposition: $\vec{E} = \vec{E}_1 + \vec{E}_2 + \vec{E}_3 + \cdots$

Continuous distribution of charge

MODEL Model objects as simple shapes.

VISUALIZE

- Establish a coordinate system.
- Divide the charge into small segments ΔQ.
- Draw a field vector for one or two pieces of charge.

SOLVE

- Find the field of each ΔQ.
- Write $\vec{E}$ as the sum of the fields of all ΔQ. Don't forget that it's a *vector* sum; use components.
- Use the charge density (λ or η) to replace ΔQ with an integration coordinate, then integrate.

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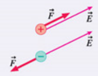
General Principles

Consequences of $\vec{E}$

The electric field exerts a force on a charged particle:

$$\vec{F} = q\vec{E}$$



The force causes acceleration:

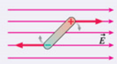
$$\vec{a} = (q/m)\vec{E}$$

Trajectories of charged particles are calculated with kinematics.

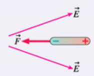
The electric field exerts a torque on a dipole:

$$\tau = pE\sin\theta$$

The torque tends to align the dipoles with the field.



In a nonuniform electric field, a dipole has a net force in the direction of increasing field strength.



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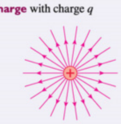
Applications

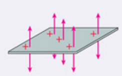
Four Key Electric Field Models

Point charge with charge q



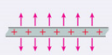
$$\vec{E} = \frac{1}{4\pi\epsilon_0}\frac{q}{r^2}\hat{r}$$

Infinite plane of charge with surface charge density η



$$\vec{E}_{\text{plane}} = \left(\frac{|\eta|}{2\epsilon_0}, \begin{cases}\text{away if } + \\ \text{toward if } -\end{cases}\right)$$

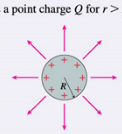
Infinite line of charge with linear charge density λ



$$\vec{E}_{\text{line}} = \left(\frac{1}{4\pi\epsilon_0}\frac{2|\lambda|}{r}, \begin{cases}\text{away if } + \\ \text{toward if } -\end{cases}\right)$$

Sphere of charge with total charge Q

Same as a point charge Q for $r > R$



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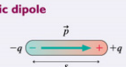
Applications

Electric dipole



The electric dipole moment is

$$\vec{p} = (qs, \text{from negative to positive})$$

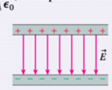
Field on axis: $\vec{E} = \frac{1}{4\pi\epsilon_0}\frac{2\vec{p}}{r^3}$

Field in bisecting plane: $\vec{E} = -\frac{1}{4\pi\epsilon_0}\frac{\vec{p}}{r^3}$

Parallel-plate capacitor

The electric field inside an ideal capacitor is a **uniform electric field:**

$$\vec{E} = \left(\frac{\eta}{\epsilon_0}, \text{from positive to negative}\right)$$



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