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

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.

LOOKING BACK Section 22.5 The electric field of a point charge
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 \( \Delta Q \).
- 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.

- Point charge
- Line of charge
- Plane of charge
- Sphere of charge

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 Reading Questions

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
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

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

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
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.  [Correct answer]
C. Magnetic resonance imaging.
D. Cosmic rays.
E. Lasers.
The electric field was defined as
\[ E = \frac{F_{\text{elec}}}{q}, \] where \( F_{\text{elec}} \) is the electric force on test charge \( q \).

The SI units of electric field are therefore Newtons per Coulomb (N/C).

### Typical electric field strengths

<table>
<thead>
<tr>
<th>Field location</th>
<th>Field strength (N/C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inside a current-carrying wire</td>
<td>( 10^{-3} - 10^{-1} )</td>
</tr>
<tr>
<td>Near the earth’s surface</td>
<td>( 10^{2} - 10^{4} )</td>
</tr>
<tr>
<td>Near objects charged by rubbing</td>
<td>( 10^{3} - 10^{6} )</td>
</tr>
<tr>
<td>Electric breakdown in air, causing a spark</td>
<td>( 3 \times 10^{6} )</td>
</tr>
<tr>
<td>Inside an atom</td>
<td>10^{11}</td>
</tr>
</tbody>
</table>
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 \( \vec{E}_{\text{net}} \) is the vector sum of the electric fields due to each charge.
- In other words, electric fields obey the principle of superposition.

\[
\vec{E}_{\text{net}} = \frac{\vec{E}_{1}}{q} + \frac{\vec{E}_{2}}{q} + \frac{\vec{E}_{2+}}{q} + \cdots = \vec{E}_1 + \vec{E}_2 + \cdots = \sum \vec{E}_i
\]

QuickCheck 23.1

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

E. None of these.
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 \( \vec{E}_{\text{net}} \) 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 \( \vec{E}_{\text{net}} = \sum \vec{E}_i \).
- 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 \( \vec{E}_{\text{net}} \).

**ASSESS** Check that your result has correct units and significant figures, is reasonable (see Table 23.3), and agrees with any known limiting cases.

---

QuickCheck 23.2

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

\[ +Q \quad -Q \]

A. \( \overrightarrow{A} \)
B. \( \overrightarrow{B} \)
C. \( \overrightarrow{C} \)
D. \( \overrightarrow{D} \)
E. The field is zero.
QuickCheck 23.2
What is the direction of the electric field at the dot?

A. 
B. 
C. 
D. 
E. The field is zero.

QuickCheck 23.3
When \( r \gg d \), the electric field strength at the dot is

A. \( \frac{Q}{4\pi \varepsilon_0 r^2} \)
B. \( \frac{2Q}{4\pi \varepsilon_0 r^2} \)
C. \( \frac{4Q}{4\pi \varepsilon_0 r^2} \)
D. \( \frac{4Q}{4\pi \varepsilon_0 (r^2 + d^2)} \)
E. \( \frac{4Q}{4\pi \varepsilon_0 r'} \)

QuickCheck 23.3
When \( r \gg d \), the electric field strength at the dot is

A. \( \frac{Q}{4\pi \varepsilon_0 r^2} \)
B. \( \frac{2Q}{4\pi \varepsilon_0 r^2} \)
\( \checkmark \) C. \( \frac{4Q}{4\pi \varepsilon_0 r^2} \) Looks like a point charge \( 4Q \) at the origin.
D. \( \frac{4Q}{4\pi \varepsilon_0 (r^2 + d^2)} \)
E. \( \frac{4Q}{4\pi \varepsilon_0 r'} \)
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

- $E_x > E_y \rightarrow \vec{E}_{\text{dipole}}$ because the + charge is closer.

- The dipole electric field at this point is in the positive y-direction.

- The dipole electric field at this point is in the negative y-direction.

A dipole has no net charge.
The Electric Field of a Dipole

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

\[ \vec{E}_{\text{dipole}} \approx \frac{2\mu}{4\pi\varepsilon_0 r^2} \]  

(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

\[ \vec{E}_{\text{dipole}} \approx \frac{1}{4\pi\varepsilon_0 r^2} \]  

(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.

Example 23.2 The Electric Field of a Water Molecule

电场线

- 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.
Electric Field Lines of a Point Charge

\[ \vec{E} = \frac{1}{4\pi\epsilon_0} \frac{q}{r^2} \]  
(electric field of a point charge)

The Electric Field of a Dipole

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

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.
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.

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.
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.

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

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
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 \( \text{C/m}^2 \), is the amount of charge per square meter.

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 \( w \ll R \), the surface charge density \( \eta \) is

A. \( \frac{Q}{2\pi Rw} \)
B. \( \frac{Q}{4\pi Rw} \)
C. \( \frac{Q}{\pi R^2} \)
D. \( \frac{Q}{2\pi R^2} \)
E. \( \frac{Q}{\pi Rw} \)

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 \( w \ll R \), the surface charge density \( \eta \) is

A. \( \frac{Q}{2\pi Rw} \)
B. \( \frac{Q}{4\pi Rw} \)
C. \( \frac{Q}{\pi R^2} \)
D. \( \frac{Q}{2\pi R^2} \)
E. \( \frac{Q}{\pi Rw} \)

The ring has two sides, each of area \( 2\pi Rw \).
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 \( Q \):

\[
E_{\text{rod}} = \frac{1}{4\pi \varepsilon_0} \frac{|Q|}{r \sqrt{r^2 + (L/2)^2}}
\]

What is the electric field at this point?

The linear charge density is \( \lambda = \frac{Q}{L} \).
QuickCheck 23.8

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

A. \[ \frac{(Q/L) \, dx}{4 \pi \varepsilon_0 (x^2 + y^2)} \times \frac{y}{x} \]

B. \[ \frac{(Q/L) \, dx}{4 \pi \varepsilon_0 (x^2 + y^2)} \times \frac{x}{y} \]

C. \[ \frac{(Q/L) \, dx}{4 \pi \varepsilon_0 (x^2 + y^2)} \times \frac{x}{\sqrt{x^2 + y^2}} \]

D. \[ \frac{(Q/L) \, dx}{4 \pi \varepsilon_0 (x^2 + y^2)} \times \frac{y}{\sqrt{x^2 + y^2}} \]

E. \[ \frac{(Q/L) \, dx}{4 \pi \varepsilon_0 (x^2 + y^2)} \times \frac{y}{\sqrt{x^2 + y^2}} \]

An Infinite Line of Charge

- The electric field of a thin, uniformly charged rod may be written as:
  \[ E_{\text{rod}} = \frac{1}{4 \pi \varepsilon_0} \left( \frac{2|\lambda|}{r} \right) \times \frac{1}{\sqrt{1 + 4r^2/L^2}} \]

- If we now let $L \to \infty$, the last term becomes simply 1 and we're left with:
  \[ E_{\text{line}} = \left( \frac{1}{4 \pi \varepsilon_0} \left( \frac{2|\lambda|}{r} \right) \right) \]
**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:

\[
(E_{\text{ring}})_z = \frac{1}{4\pi \varepsilon_0} \frac{zQ}{(z^2 + R^2)^{3/2}}
\]

**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:

\[
(E_{\text{disk}})_z = \frac{\eta}{2\varepsilon_0} \frac{1 - \frac{z}{\sqrt{z^2 + R^2}}}{\sqrt{z^2 + R^2}}
\]

**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 \( 10^7 \) electrons. What is the electric field 1.0 mm above the surface at a point near the center?

**Solution:** 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.
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 plane is \( Q = N \varepsilon_0 = -1.00 \times 10^{-9} \) C. The surface charge density is:

\[
\eta = \frac{Q}{A} = \frac{-1.00 \times 10^{-9} \text{ C}}{\pi R^2} = -2.04 \times 10^{-9} \text{ C/m}^2
\]

The electric field at \( z = 0.030 \) m, given by Equation 23.25, is

\[
E_z = \frac{\eta}{2 \varepsilon_0} \left( \frac{1}{\sqrt{1 + \frac{z^2}{R^2}}} \right) = -1.1 \times 10^5 \text{ N/C}
\]

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

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

**ASSESS** The total charge, \(-1.00 \times 10^{-9} \text{ C}\), is typical of the amount of charge produced on a small plastic object by rubbing or friction. Then \(10^5 \text{ N/C}\) 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 \( \eta \) is

\[E_{\text{plane}} = \frac{\eta}{2 \varepsilon_0} = \text{constant}\]

* 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

**Perspective view**

**Edge view**

**Formula:**

\[E_{\text{plane}} = \left( \frac{\eta}{2 \varepsilon_0} \right) \begin{cases} \text{away from plane if charge} & + \\ \text{toward plane if charge} & - \end{cases}\]
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.

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:

$$E_{\text{sphere}} = \frac{Q}{4\pi\varepsilon_0 r^2} \text{ for } r > R$$
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.

![Diagram of parallel-plate capacitor with charges +Q and -Q and distance d between them.]

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.

![Diagram of capacitor plates showing electric field inside and outside.]

The Parallel-Plate Capacitor

- The electric field of a capacitor is

\[
\overrightarrow{E}_{\text{Cap}} = \begin{cases} \frac{Q}{\varepsilon_0 A} & \text{from positive to negative} \\ 0 & \text{outside} \end{cases}
\]

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. $E_1 = E_3 > E_2$

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.
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 $E = \frac{\eta}{\varepsilon_0}$ 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 10 cm x 20 cm rectangular electrodes are 1.0 cm apart. What change must be placed on each electrode to create a uniform electric field of strength $2.3 \times 10^5$ 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

**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.

---

**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.

---

**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 $E$ has been produced by other charges, the source charges.
- The electric field exerts a force $F_{\text{exq}} = qE$. 

---
Motion of a Charged Particle in an Electric Field

- The electric field exerts a force \( \vec{F}_{\text{ex}} = q\vec{E} \) on a charged particle.
- If this is the only force acting on \( q \), it causes the charged particle to accelerate with
  \[
  \vec{a} = \frac{\vec{F}_{\text{ex}}}{m} = \frac{q\vec{E}}{m}
  \]
- In a uniform field, the acceleration is constant:
  \[
  a = \frac{qE}{m} = \text{constant}
  \]

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.

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. 

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

**QuickCheck 23.11**

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

- A. 
- B. 
- C. 
- D. 
- E. 

**QuickCheck 23.12**

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

- A. 
- B. 
- C. 
- D. 
- E.
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.

The electric field exerts a torque on this dipole.

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 $E$ points.

This dipole is in equilibrium.

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
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

Correct Answer: E. All three dipoles

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

Correct Answer: C. Dipole C
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

\[ \tau = 2 \times \mu \times E = 2qE \sin \theta \]

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 rod ending in negligible force. One ball has a charge of \( +10 \mu C \), the other a charge of \(-10 \mu C \). The rod holds a 3.0 \( \times \) 10\(^{-6} \) N\( \cdot \)C uniform electric field at an angle of 30° with respect to the axis, 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

The angular acceleration of a dipole dumbbell

\[ \tau = \mu \times B = (1.0 \times 10^{-9} \text{ C}) \times (10 \text{ T} \cdot \text{m}) = 1.0 \times 10^{-8} \text{ N}\cdot\text{m} \]

The torque caused by the electric field is

\[ \tau = (\mu_0 E \sin \theta) \cdot (10 \text{ N/C}) \times 10^9 \text{m} = 1.0 \times 10^{-5} \text{ N}\cdot\text{m} \]

The torque is given by

\[ \tau = I \alpha \]

where \( I \) is the moment of inertia.
Example 23.9 The Angular Acceleration of a Dipole Dumbbell

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.

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.
Example 23.10 The Force on a Water Molecule

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

The water molecules $H_2O$ has a permanent dipole moment of magnitude $4.2 \times 10^{-34}$ 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?

**VISUAL:** Figure 23.19 shows the ion and the dipole. The forces are in action-reaction pairs.

$$F_{dipole \text{ on ion}} \quad F_{ion \text{ on dipole}}$$

$Na^+$ ion $\quad$ Water molecule

$r = 10$ nm

---

---

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---

---
Example 23.10 The Force on a Water Molecule

**Example 23.10** The force on a water molecule

**Assess:** While $1.5 \times 10^{-19}$ N may seem like a very small force, it is much larger than the van der Waals' gravitational force on these atomic particles. Forces such as these cause water molecules to cluster around any ion that are to solutions. This clustering plays an important role in the microscopic physics of solutions studied in chemistry and biochemistry.

\[ \vec{F}_{\text{dipole on ion}} \quad \vec{F}_{\text{ion on dipole}} \]

Na$^+$ ion \quad \text{Water molecule}

\[ r = 10 \text{ nm} \]

---

**Chapter 23 Summary Slides**

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**General Principles**

**Sources of $\vec{E}$**
- Electric fields are caused by charges.
- Multiple point charges
- Model: Model objects as point charges.

**Visualize:** Establish a coordinate system and draw field vectors.

**Solve:** Use superposition. $\vec{E} = \vec{E}_1 + \vec{E}_2 + \cdots$

**Continuous distribution of charge**
- Model: Model objects as simple shapes.
- Visualize:
  - Establish a coordinate system.
  - Divide the charge into small segments $dQ$.
  - Show a total vector for one or two pieces of charge.

**Solve:**
- Find the field of each $dQ$.
- Write $\vec{E}$ as the sum of the fields of all $dQ$. Don’t forget that it’s a vector sum, not components.
- Use the charge density $\rho (x, y, z)$ to replace $dQ$ with an integration constant, then integrate.
General Principles

Consequences of \( \mathbf{E} \)
- The electric field exerts a force on a charged particle: \( \mathbf{F} = q\mathbf{E} \)
- Force causes acceleration: \( \mathbf{a} = \frac{q\mathbf{E}}{m} \)
- Trajectories of charged particles are calculated with kinematics.

The electric field exerts a torque on a dipole:
- \( \mathbf{\tau} = \mathbf{p} \times \mathbf{E} \)
- 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.

Applications

Four Key Electric Field Models
- Point charge with charge \( q \)
  - \( \mathbf{E} = \frac{1}{4\pi\varepsilon_0} \frac{q}{r^2} \) (infinite plane of charge with surface charge density \( \sigma \))
- Infinite line of charge with linear charge density \( \lambda \)
  - \( \mathbf{E} = \frac{1}{4\pi\varepsilon_0} \frac{\lambda}{2\pi r} \) (infinite line of charge with linear charge density \( \lambda \))
- Sphere of charge with total charge \( Q \)
  - \( \mathbf{E} = \frac{1}{4\pi\varepsilon_0} \frac{Q}{r^2} \) (same as a point charge \( Q \) for \( r > R \))

Applications

Electric dipole
- The electric dipole moment is \( \mathbf{p} = (\alpha, \text{from negative to positive}) \)
- Field on axis: \( \mathbf{E} = \frac{1}{4\pi\varepsilon_0} \frac{p}{r^3} \)
- Field in bisecting plane: \( \mathbf{E} = \frac{1}{4\pi\varepsilon_0} \frac{p}{r^3} \)

Parallel plate capacitor
- The electric field inside an ideal capacitor is a uniform electric field: \( \mathbf{E} = \frac{V}{d} \) (from positive to negative)