Ley de Coulomb
Campo eléctrico
\[ F_e = k_e \frac{q_1 q_2}{r^2} \]

\[ k_e = 8.9875 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2 \]

\[ k_e = \frac{1}{4\pi\varepsilon_0} \]

**Figure 23.6** Coulomb’s torsion balance, used to establish the inverse-square law for the electric force between two charges.

### Charge and Mass of the Electron, Proton, and Neutron

<table>
<thead>
<tr>
<th>Particle</th>
<th>Charge (C)</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron ((e))</td>
<td>(-1.6021917 \times 10^{-19})</td>
<td>(9.1095 \times 10^{-31})</td>
</tr>
<tr>
<td>Proton ((p))</td>
<td>(+1.6021917 \times 10^{-19})</td>
<td>(1.67261 \times 10^{-27})</td>
</tr>
<tr>
<td>Neutron ((n))</td>
<td>0</td>
<td>(1.67492 \times 10^{-27})</td>
</tr>
</tbody>
</table>
the electric field vector $\mathbf{E}$ at a point in space is defined as the electric force $\mathbf{F}_e$ acting on a positive test charge $q_0$ placed at that point divided by the test charge:

$$\mathbf{E} = \frac{\mathbf{F}_e}{q_0}$$  \hspace{1cm} (23.7)

### Typical Electric Field Values

<table>
<thead>
<tr>
<th>Source</th>
<th>$E$ (N/C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluorescent lighting tube</td>
<td>10</td>
</tr>
<tr>
<td>Atmosphere (fair weather)</td>
<td>100</td>
</tr>
<tr>
<td>Balloon rubbed on hair</td>
<td>1000</td>
</tr>
<tr>
<td>Atmosphere (under thundercloud)</td>
<td>10000</td>
</tr>
<tr>
<td>Photocopier</td>
<td>100000</td>
</tr>
<tr>
<td>Spark in air</td>
<td>$&gt;3,000,000$</td>
</tr>
<tr>
<td>Near electron in hydrogen atom</td>
<td>$5 \times 10^{11}$</td>
</tr>
</tbody>
</table>
Example 23.5  Electric Field Due to Two Charges

A charge \( q_1 = 7.0 \, \mu \text{C} \) is located at the origin, and a second charge \( q_2 = -5.0 \, \mu \text{C} \) is located on the \( x \) axis, 0.30 m from the origin (Fig. 23.14). Find the electric field at the point \( P \), which has coordinates \((0, 0.40)\) m.

**Solution** First, let us find the magnitude of the electric field at \( P \) due to each charge. The fields \( \mathbf{E}_1 \) due to the 7.0-\( \mu \text{C} \) charge and \( \mathbf{E}_2 \) due to the \(-5.0-\mu \text{C} \) charge are shown in Figure 23.14. Their magnitudes are

\[
\mathbf{E}_1 = k_e \frac{|q_1|}{r_1^2} = (8.99 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2) \frac{(7.0 \times 10^{-6} \text{ C})}{(0.40 \text{ m})^2} = 3.9 \times 10^5 \text{ N/C}
\]

\[
\mathbf{E}_2 = k_e \frac{|q_2|}{r_2^2} = (8.99 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2) \frac{(5.0 \times 10^{-6} \text{ C})}{(0.50 \text{ m})^2} = 1.8 \times 10^5 \text{ N/C}
\]

The vector \( \mathbf{E}_1 \) has only a \( y \) component. The vector \( \mathbf{E}_2 \) has an \( x \) component given by \( E_2 \cos \theta = \frac{2}{5} E_2 \) and a negative \( y \) component given by \(-E_2 \sin \theta = -\frac{4}{5} E_2\). Hence, we can express the vectors as

\[
\mathbf{E}_1 = 3.9 \times 10^5 \hat{j} \text{ N/C}
\]

\[
\mathbf{E}_2 = (1.1 \times 10^5 \hat{i} - 1.4 \times 10^5 \hat{j}) \text{ N/C}
\]

The resultant field \( \mathbf{E} \) at \( P \) is the superposition of \( \mathbf{E}_1 \) and \( \mathbf{E}_2 \):

\[
\mathbf{E} = \mathbf{E}_1 + \mathbf{E}_2 = (1.1 \times 10^5 \hat{i} + 2.5 \times 10^5 \hat{j}) \text{ N/C}
\]

From this result, we find that \( \mathbf{E} \) makes an angle \( \phi \) of 66° with the positive \( x \) axis and has a magnitude of \( 2.7 \times 10^5 \text{ N/C} \).
LI NEAS DE FUERZA

Figure 23.21 The electric field lines for a point charge. (a) For a positive point charge, the lines are directed radially outward. (b) For a negative point charge, the lines are directed radially inward. Note that the figures show only those field lines that lie in the plane of the page. (c) The dark areas are small pieces of thread suspended in oil, which align with the electric field produced by a small charged conductor at the center.
Example 23.10  An Accelerating Positive Charge

A positive point charge \( q \) of mass \( m \) is released from rest in a uniform electric field \( E \) directed along the \( x \) axis, as shown in Figure 23.25. Describe its motion.

**Solution** The acceleration is constant and is given by \( qE/m \). The motion is simple linear motion along the \( x \) axis. Therefore, we can apply the equations of kinematics in one dimension (see Chapter 2):

\[
x_f = x_i + v_i t + \frac{1}{2} a t^2
\]

\[
v_f = v_i + at
\]

\[
v_f^2 = v_i^2 + 2a(x_f - x_i)
\]

Choosing the initial position of the charge as \( x_i = 0 \) and assigning \( v_i = 0 \) because the particle starts from rest, the position of the particle as a function of time is

\[
x_f = \frac{1}{2} at^2 = \frac{qE}{2m} t^2
\]

The speed of the particle is given by

\[
v_f = at = \frac{qE}{m} t
\]

The third kinematic equation gives us

\[
v_f^2 = 2ax_f = \left( \frac{2qE}{m} \right) x_f
\]

from which we can find the kinetic energy of the charge after it has moved a distance \( \Delta x = x_f - x_i \):

\[
K = \frac{1}{2} mv_f^2 = \frac{1}{2} m \left( \frac{2qE}{m} \right) \Delta x = qE \Delta x
\]

We can also obtain this result from the work–kinetic energy theorem because the work done by the electric force is \( F_e \Delta x = qE \Delta x \) and \( W = \Delta K \).

![Figure 23.25](image)

(Example 23.10) A positive point charge \( q \) in a uniform electric field \( E \) undergoes constant acceleration in the direction of the field.
**Active Figure 23.26** An electron is projected horizontally into a uniform electric field produced by two charged plates. The electron undergoes a downward acceleration (opposite \( \mathbf{E} \)), and its motion is parabolic while it is between the plates.

\[
v_x = v_i = \text{constant}
\]

\[
v_y = a_y t = -\frac{eE}{m_e} t
\]

\[
x_f = v_i t
\]

\[
y_f = \frac{1}{2} a_y t^2 = -\frac{1}{2} \frac{eE}{m_e} t^2
\]
Example 23.11  An Accelerated Electron

An electron enters the region of a uniform electric field as shown in Figure 23.26, with \( v_i = 3.00 \times 10^6 \) m/s and \( E = 200 \) N/C. The horizontal length of the plates is \( \ell = 0.100 \) m.

(A) Find the acceleration of the electron while it is in the electric field.

Solution  The charge on the electron has an absolute value of \( 1.60 \times 10^{-19} \) C, and \( m_e = 9.11 \times 10^{-31} \) kg. Therefore, Equation 23.13 gives

\[
\mathbf{a} = -\frac{eE}{m_e} \mathbf{j} = -\frac{(1.60 \times 10^{-19} \text{ C})(200 \text{ N/C})}{9.11 \times 10^{-31} \text{ kg}} \mathbf{j}
\]

\[
= -3.51 \times 10^{13} \mathbf{j} \text{ m/s}^2
\]

(B) If the electron enters the field at time \( t = 0 \), find the time at which it leaves the field.

Solution  The horizontal distance across the field is \( \ell = 0.100 \) m. Using Equation 23.16 with \( x_f = \ell \), we find that the time at which the electron exits the electric field is

\[
t = \frac{\ell}{v_i} = \frac{0.100 \text{ m}}{3.00 \times 10^6 \text{ m/s}} = 3.33 \times 10^{-8} \text{ s}
\]

(C) If the vertical position of the electron as it enters the field is \( y_i = 0 \), what is its vertical position when it leaves the field?

Solution  Using Equation 23.17 and the results from parts (A) and (B), we find that

\[
y_f = \frac{1}{2} a_f t^2 = \frac{1}{2} (3.51 \times 10^{13} \text{ m/s}^2) (3.33 \times 10^{-8} \text{ s})^2
\]

\[
= -0.0195 \text{ m} = -1.95 \text{ cm}
\]

If the electron enters just below the negative plate in Figure 29.26 and the separation between the plates is less than the value we have just calculated, the electron will strike the positive plate.
Figure 23.27 Schematic diagram of a cathode ray tube. Electrons leaving the cathode C are accelerated to the anode A. In addition to accelerating electrons, the electron gun is also used to focus the beam of electrons, and the plates deflect the beam.
49. Protons are projected with an initial speed $v_i = 9.55 \times 10^3$ m/s into a region where a uniform electric field $\mathbf{E} = -720 \hat{j}$ N/C is present, as shown in Figure P23.49. The protons are to hit a target that lies at a horizontal distance of 1.27 mm from the point where the protons cross the plane and enter the electric field in Figure P23.49. Find (a) the two projection angles $\theta$ that will result in a hit and (b) the total time of flight (the time interval during which the proton is above the plane in Figure P23.49) for each trajectory.
69. Eight point charges, each of magnitude $q$, are located on the corners of a cube of edge $s$, as shown in Figure P23.69. (a) Determine the $x$, $y$, and $z$ components of the resultant force exerted by the other charges on the charge located at point $A$. (b) What are the magnitude and direction of this resultant force? 

**Figure P23.69** Problems 69 and 70.