How to save gasoline when you drive a big empty truck?

Electricity and Magnetism

- **Lightning**
- **Vending machine**
- **Electricity generator and motor**
- **Train brake**
- **Wireless battery charger**
- **Airport metal detector**
- **Radio and TV**
- **CD player and tape cassette**

Brief review of classic mechanics

Newton's law: $\sum \vec{F} = d\vec{P}/dt,$ where $\vec{P} = m\vec{\upsilon}$

$\sum \vec{\tau} = d\vec{L}/dt,$ where $\vec{\tau} = \vec{r} \times \vec{F}$ and $\vec{L} = \vec{r} \times \vec{P}$

Momentum conservation: $\vec{P} =$ constant when $\sum \vec{F} = 0.$

Angular momentum conservation: $\vec{L} =$ constant when $\sum \vec{\tau} = 0.$

Energy conservation: $E = T + U,$ where $T = \frac{1}{2} m\upsilon^2.$

Gravitational force: $\vec{F}_g = -G \frac{m_1 m_2}{r^2} \hat{\mathrm{r}}$

Gravitational potential energy: $U_g = -G \frac{m_1 m_2}{r}$

Chapter 23 Electric field

- Properties of electric charges
- Insulators and conductors
- Coulomb's law
- The electric field
- Electric field of a continuous charge distribution
- Electric field line
- Motion of charged particles in a uniform electric field

Properties of electric charges

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Figure 23.1a

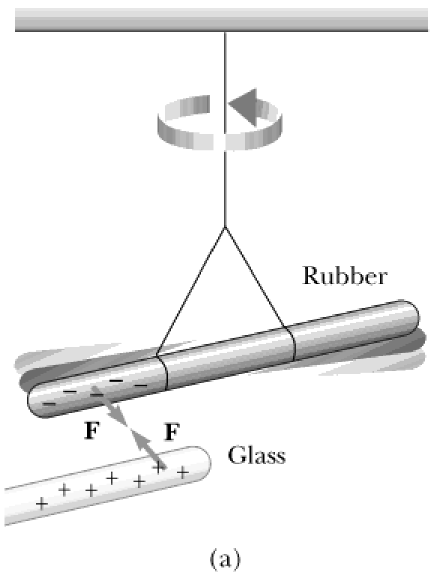

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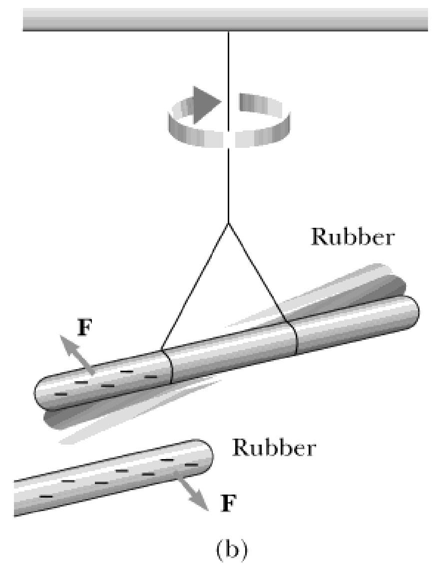
Figure 23.1b



- Two kinds of charges occur in nature; unlike charges attract each other and like charges repel each other.
- Charge is conserved.
- Charge is quantized, i.e., $q = Ne$.

Insulators and conductors

- Electrical conductors are materials in which electric charges move freely whereas electric insulators are materials in which electric charges cannot move freely.
- Conductors: copper, silver, and gold
- Insulators: glass, rubber, and wood
- Semiconductors: silicon and gemanium
- Grounded: When a conductor is connected to the Earth by means of a conducting wire or pipe.

Induction

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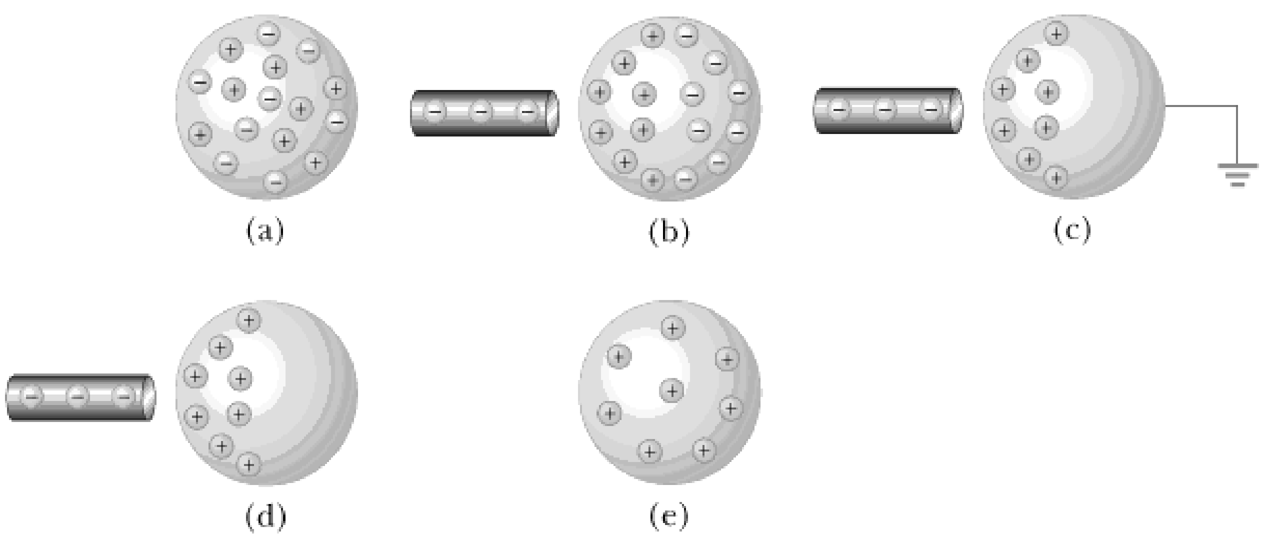
Figure 23.3



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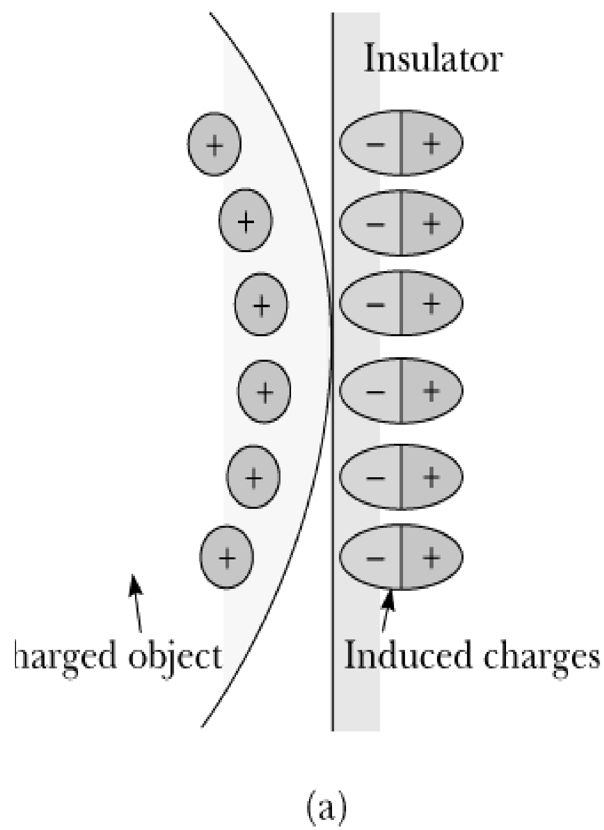

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Coulomb's law

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Electric force

- is inversely proportional to the square of the separation *r* between the particles and direct along the line joining them.
- is proportional to the product of the charges q_1 and q_2 on the two particles.
- is attractive if charges are of opposite sign and repulsive if the charges have the same sign.

Coulomb's law

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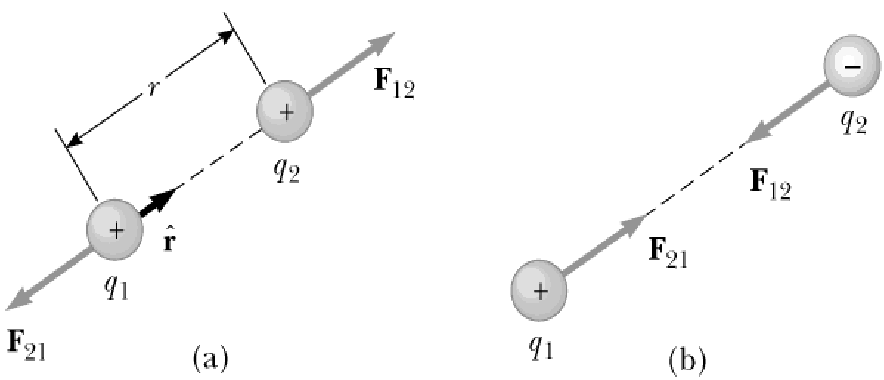
Figure 23.6



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$$F_e = k_e \frac{|q_1||q_2|}{r^2}$$

$$k_e = \frac{1}{4\pi\varepsilon_\circ} = 8.9875 \times 10^9 \mathrm{N} \bullet \mathrm{m}^2/\mathrm{C}^2$$

$$|e| = 1.60219 \times 10^{-19}\mathrm{C}$$

$$\vec{\mathbf{F}}_{12} = k_e \frac{q_1 q_2}{r^2} \hat{\mathbf{r}}$$

$$\vec{\mathbf{F}}_{12} = -\vec{\mathbf{F}}_{21}$$

Example 23.2 Find the resultant force

Consider three point charges located at the corners of a right triangle as shown, where $q_1 = q_3 = 5.0\ \mu C$, $q_2 = -2.0\ \mu C$, and $a = 0.10$ m. Find the resultant force exerted on q_3.

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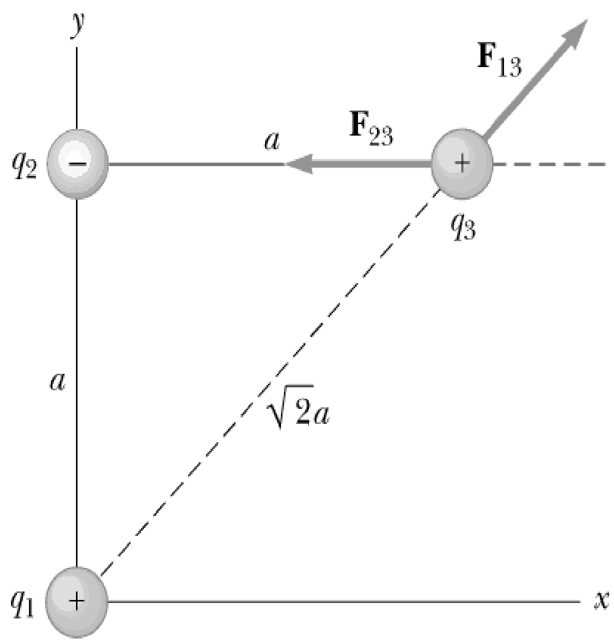
3.7



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$$F_{23} = k_e \frac{|q_2||q_3|}{a^2} = 9.0 \text{ N}$$

$$F_{13} = k_e \frac{|q_1||q_3|}{(\sqrt{2}a)^2} = 11 \text{ N}$$

$$F_{3x} = F_{13}\cos 45^\circ - F_{23} = -1.1 \text{ N}$$

$$F_{3y} = F_{13}\sin 45^\circ = 7.9 \text{ N}$$

$$F_3 = \sqrt{(F_{3x})^2 + (F_{3y})^2} = 8.0 \text{ N}$$

$$\theta = \arctan(F_{3y}/F_{3x}) = 98^\circ$$

Example 23.4 Find the charge on the spheres

Two identical small charged spheres, each having a mass of 3.0×10^{-2} kg, hang in equilibrium as shown. The length of each string is 0.15 m, and the angle θ is 5.0°. Find the charge on each sphere.

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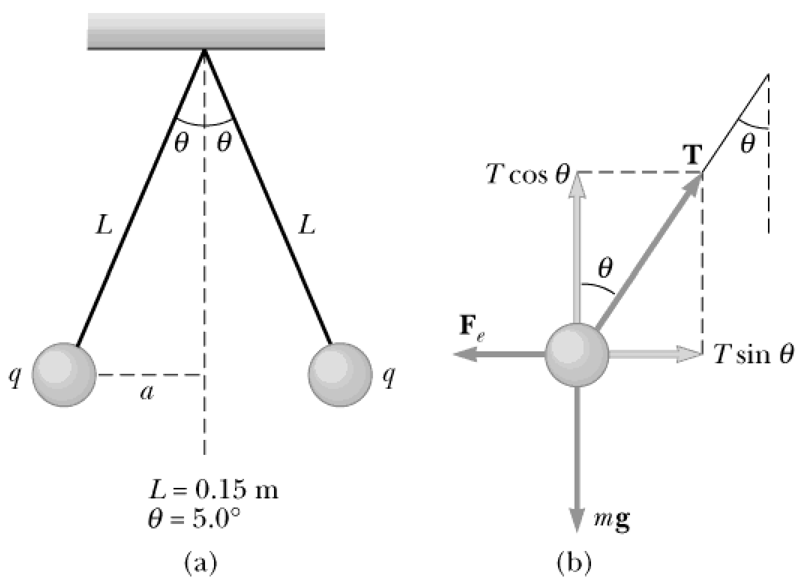
Figure 23.9



$$\sum F_x = T\sin\theta - F_e = 0$$

$$\sum F_y = T\cos\theta - mg = 0$$

$$F_e = mg\tan\theta = k_e \frac{q^2}{(2a)^2}$$

$$q = \sqrt{\frac{(2a)^2 mg\tan\theta}{k_e}}$$

$$= 4.4\times10^{-8}\ \text{C}$$

The electric field

The gravitational field: $\vec{g}$ (produced by massive objects)

The gravitational force for a particle with mass *m*: $\vec{F}_g = m\vec{g}$

The electric field: $\vec{E}$ (produced by charged objects)

The electric field is the electric force acting on a unit positive charge

The electric force acting on a charge *q*: $\vec{F}_e = q\vec{E}$

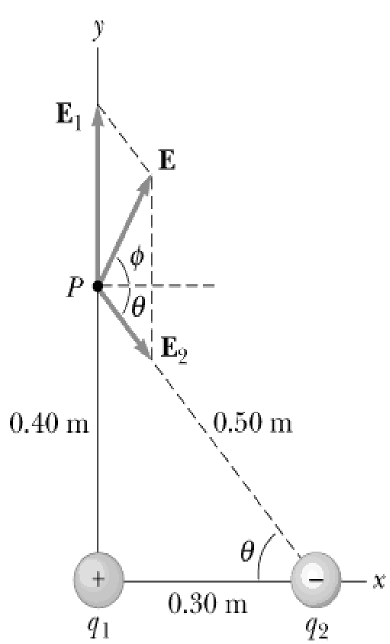
The electric field of a point charge *q*: $\vec{E} = k_e \frac{q}{r^2}\hat{r}$

The electric field of a group of charges: $\vec{E} = k_e \sum \frac{q_i}{r_i^2}\hat{r}_i$

The electric field of a continuous charge distribution: $\vec{E} = k_e \int \frac{dq}{r^2}\hat{r}$

Example 23.5 Electric field due to two charges

A charge q_1 = 7.0 μC is located at the origin, and a second charge q_2 = 5.0 μC is located on the x axis, 3.0 m from the origin. Find the electric field at P, which has coordinates (0, 0.40) m.



$$E_x = E_{2x} = E_2 \cos\theta$$

$$= k_e \frac{|q_2|}{r_2^2} \cos\theta = 1.1\times 10^5 \,\mathrm{N/C}$$

$$E_y = E_{1y} + E_{2y} = E_1 - E_2 \sin\theta$$

$$= k_e \frac{|q_1|}{r_1^2} - k_e \frac{|q_2|}{r_2^2} \sin\theta = 2.5\times 10^5 \,\mathrm{N/C}$$

$$\phi = \tan^{-1}(E_y / E_x) = 66^\circ$$

Example 23.7 The electric field due to a charge rod

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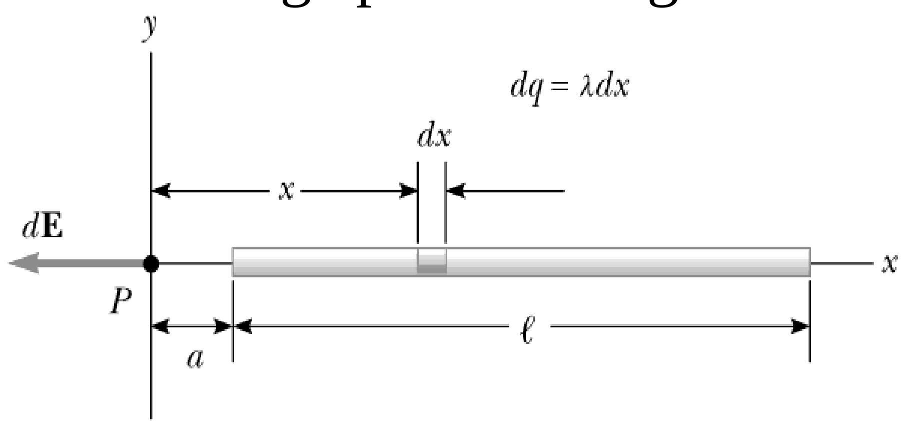
Figure 23.16

Total charge: Q

Charge per unit length: λ



$$dE_x = -k_e \frac{dq}{x^2}$$

$$dq = \lambda dx$$

$$dE_x = -k_e \lambda \frac{dx}{x^2}$$

$$E_x = -k_e \lambda \int_a^{l+a} \frac{dx}{x^2} = -k_e \lambda \left[-\frac{1}{x} \right]_a^{l+a}$$

$$= -k_e \lambda \left(\frac{1}{a} - \frac{1}{l+a}\right) = -\frac{k_e \lambda l}{a(l+a)}$$

$$= -\frac{k_e Q}{a(l+a)}$$

Example 23.8 The electric field of a uniform ring of charge

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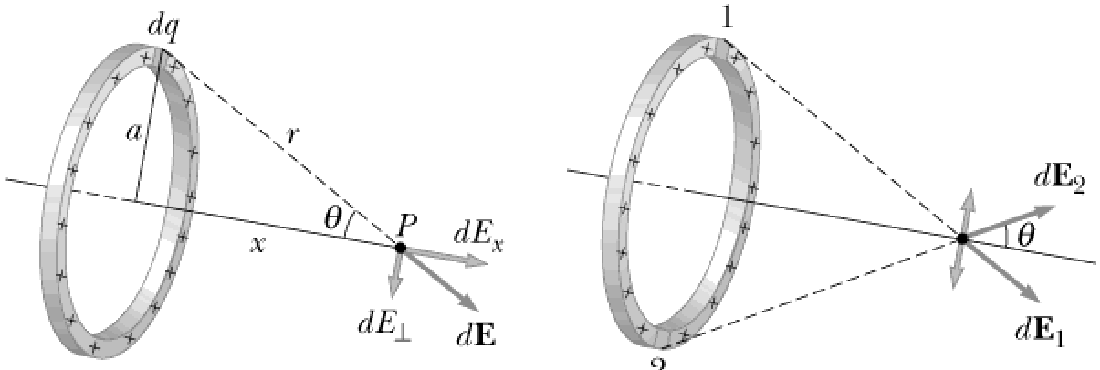
Figure 23.17

Total charge: Q



(a) (b)

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$$dE_x = dE\cos\theta$$

$$= k_e \frac{\mathrm{d}q}{r^2}\frac{x}{r} = \frac{k_e x\,\mathrm{d}q}{(x^2+a^2)^{3/2}}$$

$$E_x = \int \frac{k_e x\,\mathrm{d}q}{(x^2+a^2)^{3/2}}$$

$$= \frac{k_e x}{(x^2+a^2)^{3/2}}\int \mathrm{d}q$$

$$= \frac{k_e x}{(x^2+a^2)^{3/2}} Q$$

Electric field lines

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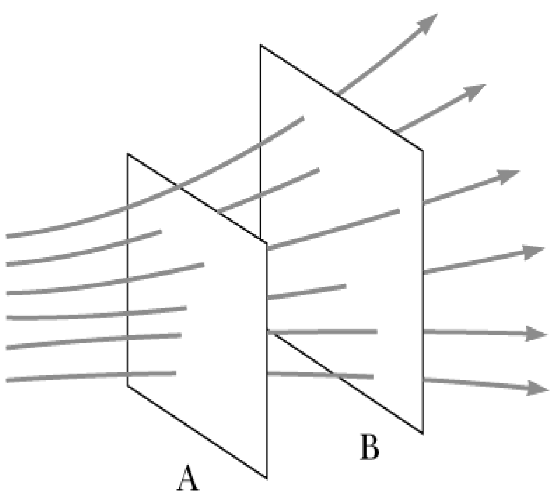
Figure 23.19



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Electric field lines are related to the electric field in any region of space as:

- The electric field vector is tangent to the electric field line at each point.
- The number of lines per unit cross-sectional area is proportional to the magnitude of the electric field in that region.

Electric field lines for a point charge

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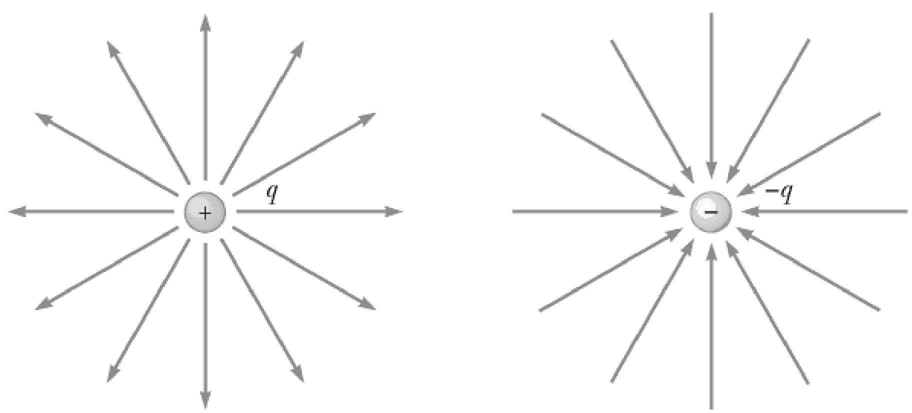
Figure 23.20



(a) (b)

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The rules for drawing electric field lines:

- The lines must begin on a positive charge and terminate on a negative charge.
- The number of lines leaving a positive charge or approaching a negative charge is proportional to the magnitude of the charge.
- No two field lines can cross.

The electric field lines for an electric dipole

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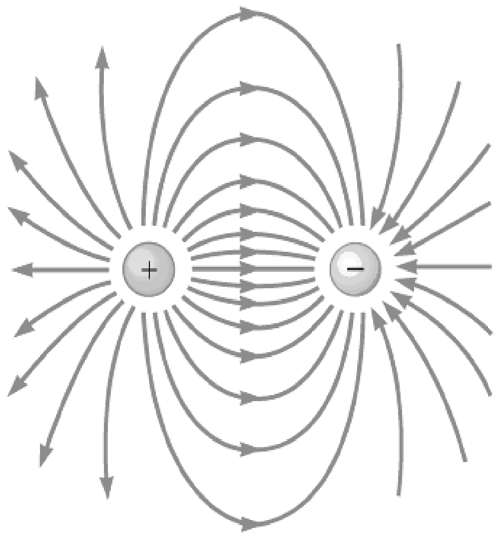
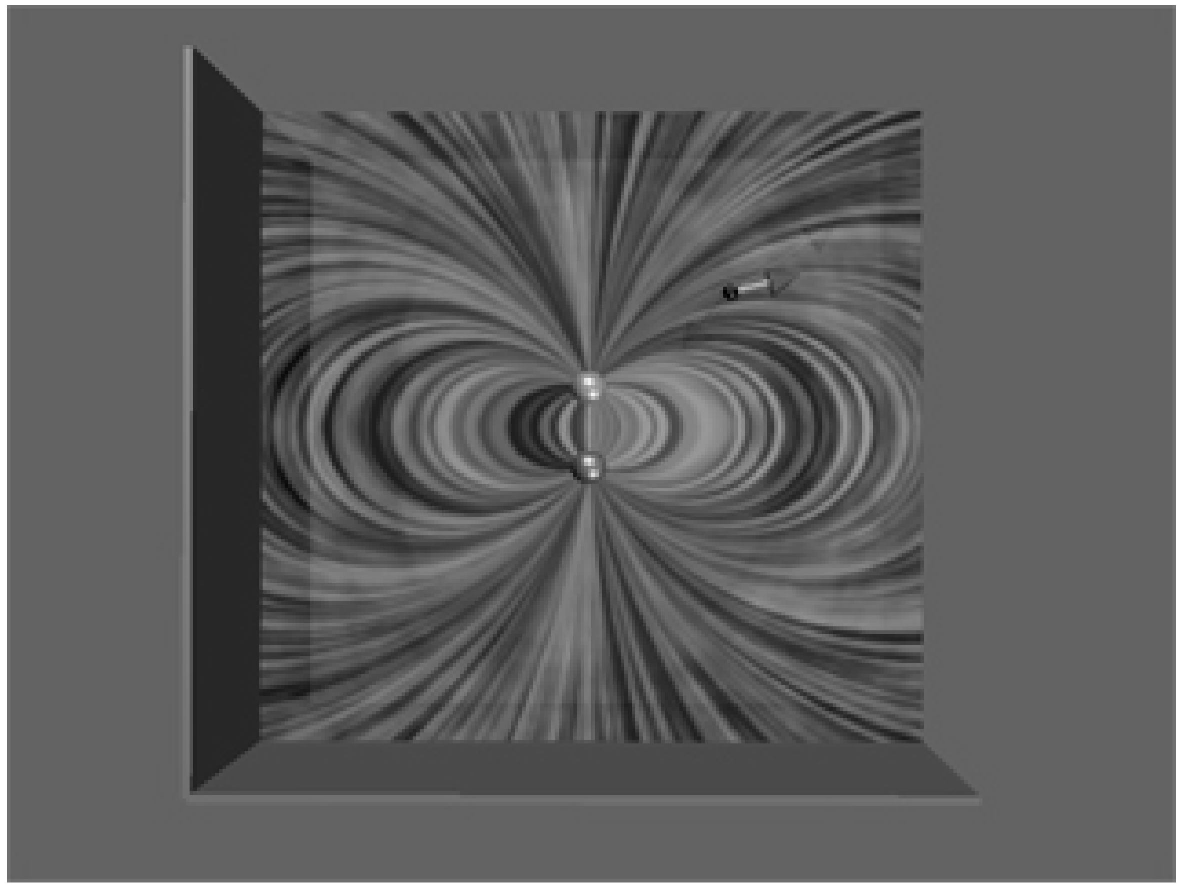
3.21a



(a)



The electric field lines for two point charges

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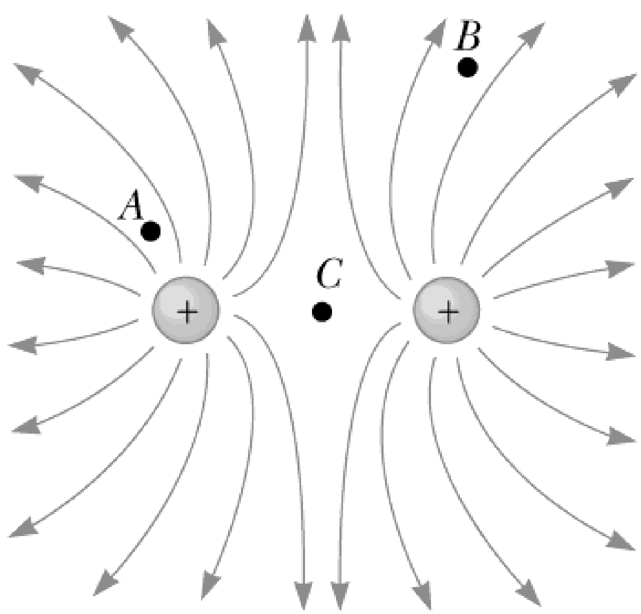
.22a



(a)

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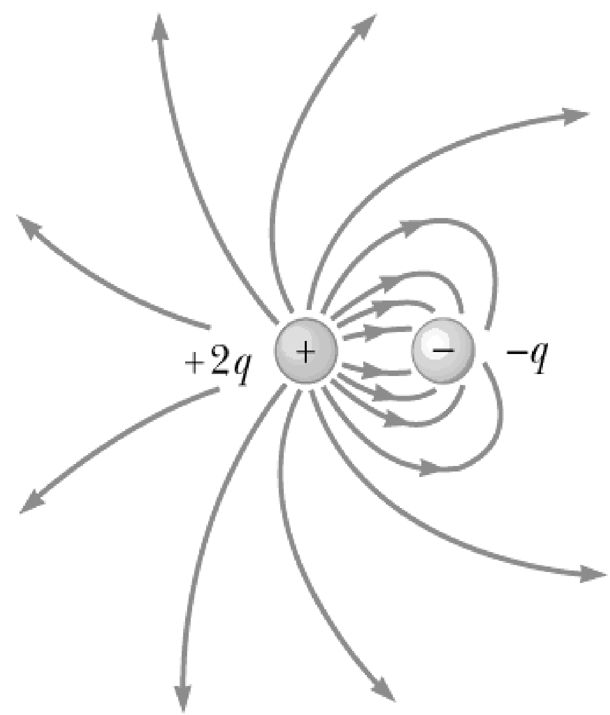
Figure 23.23



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Motion of charged particle in a uniform electric field

$$\vec{F}_e = q\vec{E} = m\vec{a}$$

$$\vec{a} = \frac{q\vec{E}}{m}$$

If $\vec{E}$ is uniform over space, $\vec{a}$ is constant, then the motion of a charged particle will be similar to the motion of a neutral particle in gravitational field.

Motion of charged particle in a uniform electric field

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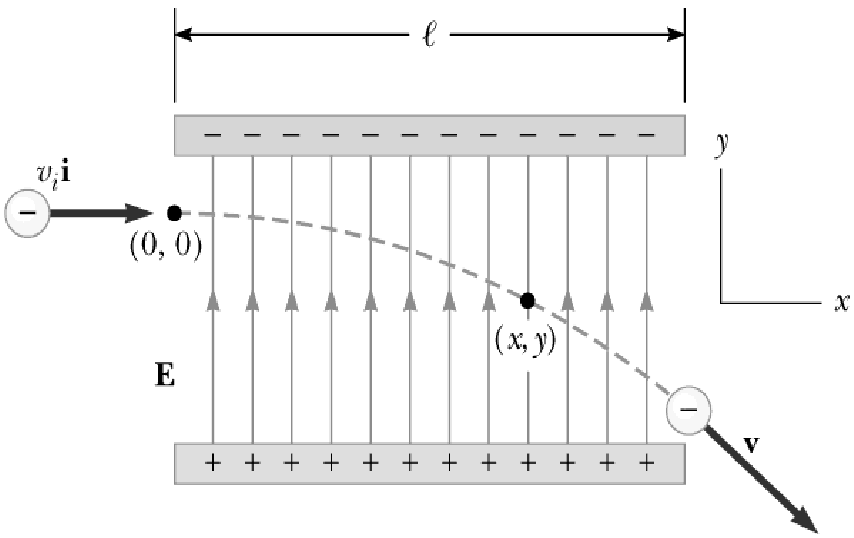
Figure 23.25



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When the initial velocity is perpendicular to the electric field, we have $\upsilon_{xi} = \upsilon_i$ and $\upsilon_{yi} = 0$.

Motion along the *x* direction:

$\upsilon_x = \upsilon_i$ (no force and acceleration)

$x = \upsilon_i t$

Motion along the *y* direction:

$$\upsilon_y = a_y t = \frac{qE}{m} t$$

$$y = \frac{1}{2} a_y t^2 = \frac{1}{2} \frac{qE}{m} t^2$$