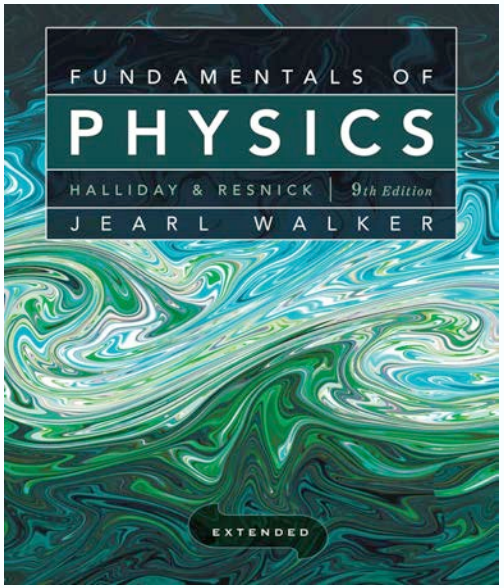
General Physics 2
SCPH 211



Fundamentals of Physics 9th edition

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Marks Distribution

- 20 % midterm
- 15 % 1 Quiz & 2 HWs each 5 Marks
- 25 % lab
- 40 % final exam

Course Curriculum

Chapter 21: Electric Charge

Chapter 22: Electric Field

Chapter 23: Gauss' Law

Chapter 24: Electric Potential

Chapter 25: Capacitance

Chapter 26: Current and Resistance

Chapter 27: Circuits

Chapter 28: Magnetic Fields

Chapter 29: Magnetic Fields due to Currents

Chapter 21
Electric Charge

▲ *Mother and daughter are both enjoying the effects of electrically charging their bodies. Each individual hair on their heads becomes charged and exerts a repulsive force on the other hairs, resulting in the "stand-up" hairdos that you see here. (Courtesy of Resonance Research Corporation)*

Outline

- Electric Charge
- Conductors and Insulators
- Coulomb's Law
- Charge is Quantized
- Charge is Conserved

Electric Charge

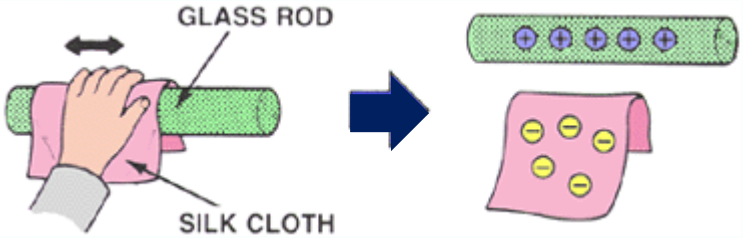
- **Electric charge:** is an intrinsic characteristic of the fundamental particles making up objects (such as electrons & protons)

- Charges in any object is hidden**?**
  Because +ve = -ve charge
  → object is *electrically neutral*;
  → object has ***no*** *net charge*

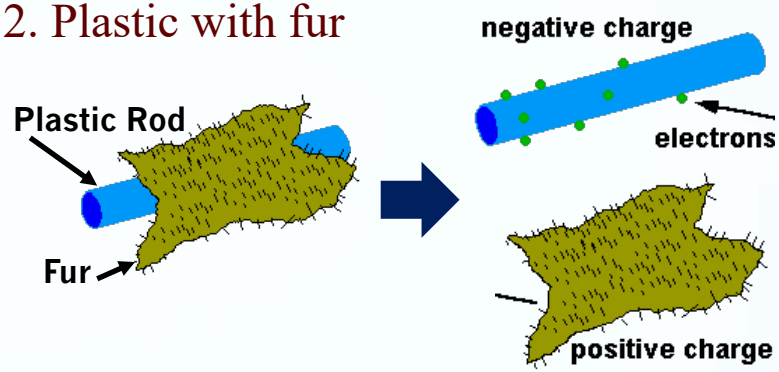
- If +ve ≠ -ve charge
  → object is charged
  → object has a charge imbalance, or has net charge

What happens if you rub:

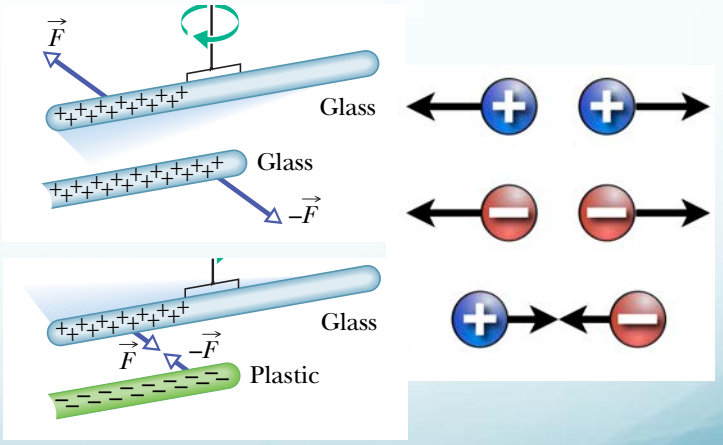
1. Glass with silk



2. Plastic with fur



- Plus signs (+) indicate +ve net charge
  Minus signs (-) indicate a –ve net charge
- Charged objects exert *electrical forces* on each other
- *Similar charges* produce repulsive force,
  → like charges repel
- *Dissimilar charges* produce an *attractive* force,
  → opposite charges attract

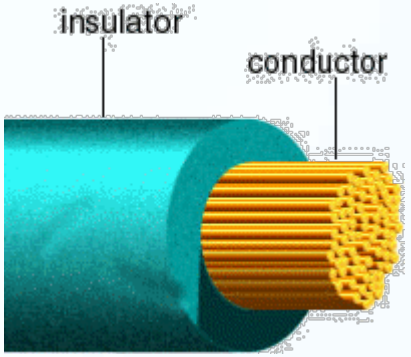


Charges with the same electrical sign repel each other, and charges with opposite electrical signs attract each other.

Conductors and Insulators

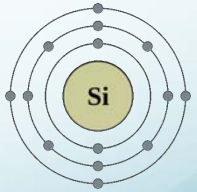
Materials are classified into 4 kinds according to the ability of charge to move through them:

1. **Conductors:** materials that a significant amount of electrons are free to move, e.g., metals (such as copper), human body, and tap water



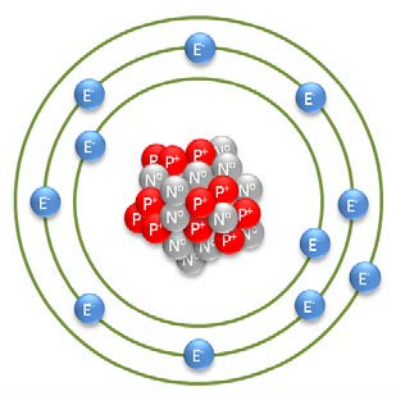
2. **Nonconductor (insulators):** materials that a significant amount of electrons are not free to move; e.g, rubber (such as lamp wire), plastic, glass

3. **Semiconductors:** materials that are intermediate between conductors and insulators, sometimes behave like insulators and sometimes like conductors; e.g., silicon (Si) and germanium (Ge)



4. **Superconductors:** materials that almost all electrons are free to move, they are perfect conductors

Neutral and Charged Atoms

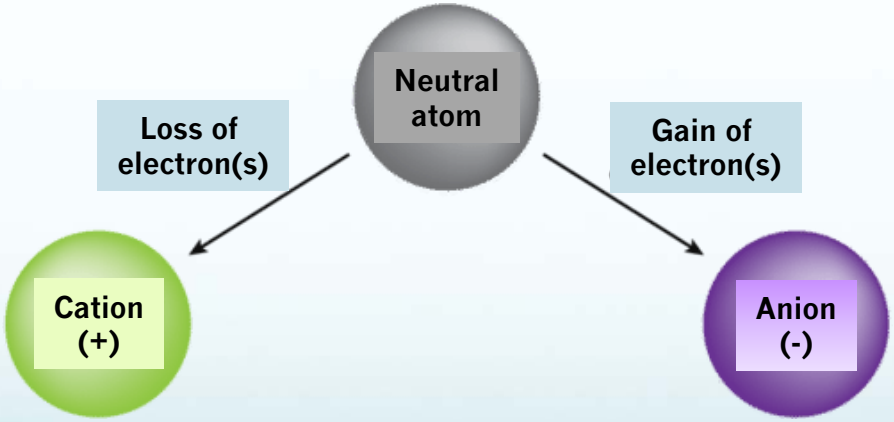


Neutral Atom
Number of protons = Numbers of electrons

Table 21-1

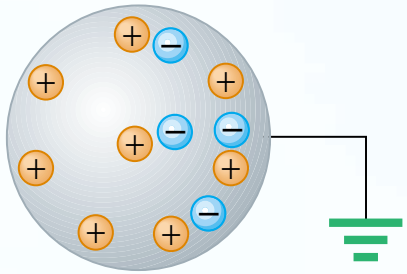
The Charges of Three Particles

Particle	Symbol	Charge
Electron	e or e^-	$-e$
Proton	p	$+e$
Neutron	n	0

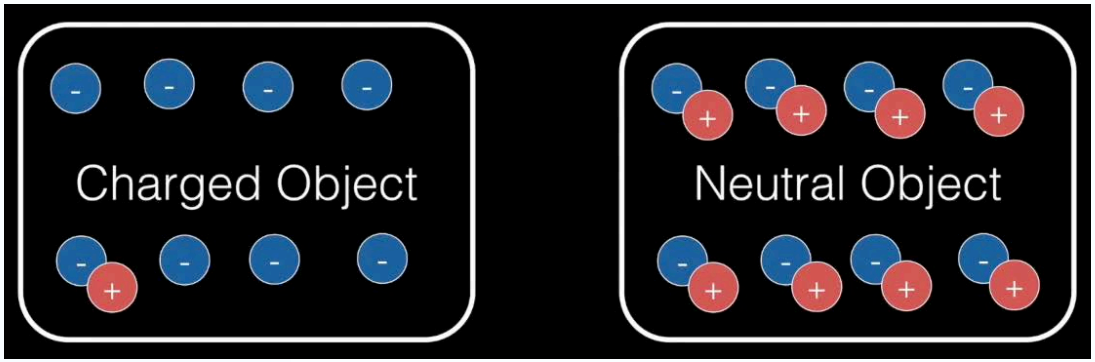


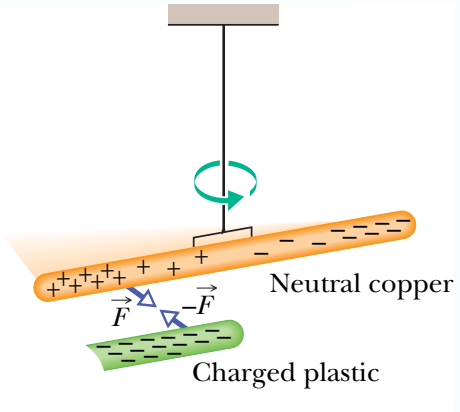
- The mobile electrons are called **conduction electrons**
- Only conduction electrons can move; +ve ions are fixed

Grounding or neutralizing an object: means to set up a pathway of conductors between an object and Earth's surface to discharge the object
(eliminate an unbalanced +ve or –ve charge)



To demonstrate the mobility of charge in a conductor:

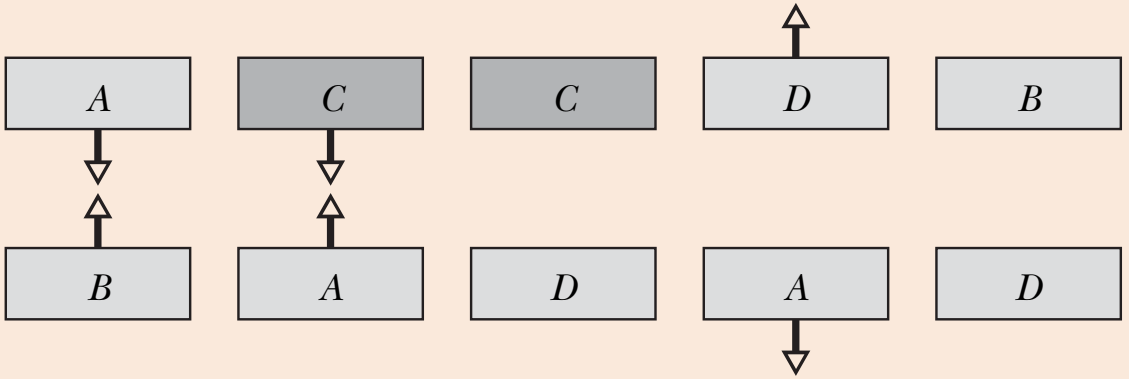




- Conduction electrons in copper rod repelled by the –ve charge on plastic rod
- Some conduction electrons in copper rod move to the far end of the copper rod,
  → the near end will have +ve charge
  → the +ve charge in copper rod attract the –ve charge in plastic rod
- Although the copper rod is still neutral, it has an ***induced charge***, which means that some of its +ve and –ve charges have been separated due to the presence of a nearby charge

CHECKPOINT 1

The figure shows five pairs of plates: A, B, and D are charged plastic plates and C is an electrically neutral copper plate. The electrostatic forces between the pairs of plates are shown for three of the pairs. For the remaining two pairs, do the plates repel or attract each other?



A & B have opposite charge, say A is +ve & B is –ve
A & C have opposite charge, say A is +ve & C is –ve
A & D have similar charge, say A & D are +ve
→ C & D have opposite charge→ the plastic plates will attract each other
→ B & D have opposite charge→ the plastic plates will attract each other

Coulomb's Law

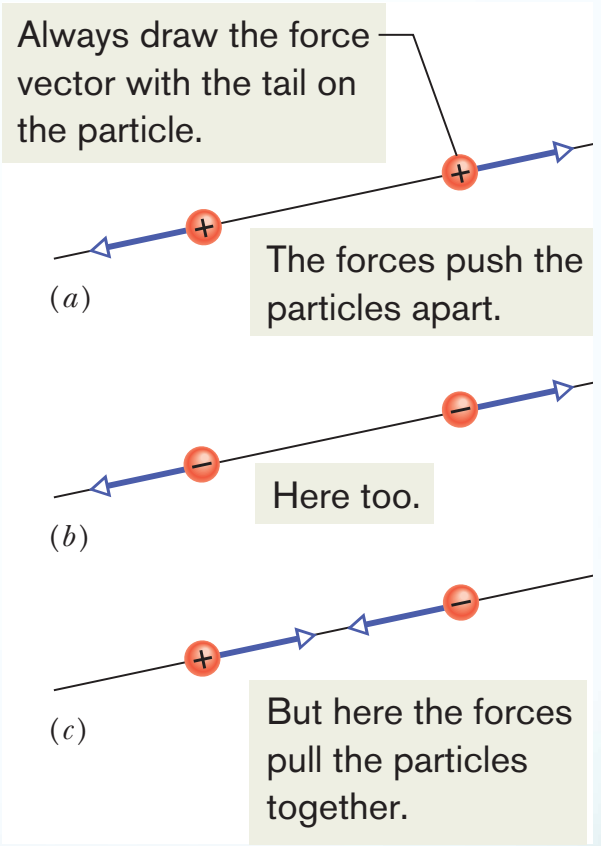
- **Electrostatic force:** the force of repulsion or attraction due to the charge properties of objects
  - If particle 1 has charge q_1 and particle 2 has charge q_2, the force on particle 1 is

$$\vec{F} = k\frac{q_1 q_2}{r^2}\hat{\mathrm{r}} \qquad \text{(Coulomb's law)}$$

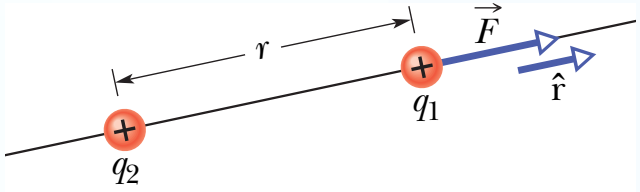
$\hat{\mathrm{r}}$ is a unit vector along an axis extending through the two particles

r is the distance between them,

k is the *electrostatic constant* = $1/4\pi\varepsilon_0$



$$\vec{F} = k\frac{q_1 q_2}{r^2}\hat{\mathrm{r}} \qquad \text{(Coulomb's law)}$$



- If q_1 & q_2 have same signs
  → F on particle 1 is in the direction of $\hat{\mathrm{r}}$
- If q_1 & q_2 have opposite signs
  → F on particle 1 is in opposite direction of $\hat{\mathrm{r}}$
- Coulomb's law describes inverse square laws that involve a property of the interacting particles
- Comparisons between two forces:

$$\vec{F} = k\frac{q_1 q_2}{r^2}\hat{\mathrm{r}}$$

Coulomb's law

k: electrostatic constant
r: distance between charges
F: electric force between two charges q_1 & q_2
F: +ve or –ve

$$\vec{F} = G\frac{m_1 m_2}{r^2}\hat{\mathrm{r}}$$

Newton's law

G: gravitational constant
r: distance between masses
F: gravitational force between two masses m_1 & m_2
F: always +ve

- The SI unit of charge is the coulomb (C)

$$i = \frac{dq}{dt} \qquad \text{(electric current)}$$

i is the current (in amperes) and *dq* (in coulombs) is the amount of charge moving through a region in time *dt* (in seconds)

$$1\ \text{C} = (1\ \text{A})(1\ \text{s})$$

- The magnitude of the force in Coulomb's law is:

$$F = \frac{1}{4\pi\varepsilon_0}\frac{|q_1||q_2|}{r^2} \qquad \text{(Coulomb's law)}$$

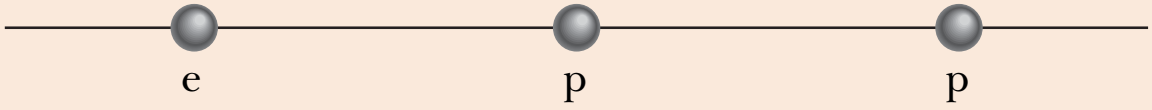
Where: electrostatic constant $k = \dfrac{1}{4\pi\varepsilon_0} = 8.99 \times 10^9\ \text{N}\cdot\text{m}^2/\text{C}^2$.

The the permittivity constant $\varepsilon_0 = 8.85 \times 10^{-12}\ \text{C}^2/\text{N}\cdot\text{m}^2$

- **Superposition principle:** If we have *n* charged particles, they interact independently in pairs, and the force on any one of them, let us say particle 1, is given by the vector sum

$$\vec{F}_{1,\text{net}} = \vec{F}_{12} + \vec{F}_{13} + \vec{F}_{14} + \vec{F}_{15} + \cdots + \vec{F}_{1n}$$

CHECKPOINT 2



The figure shows two protons (symbol p) and one electron (symbol e) on an axis. What is the direction of (a) the electrostatic force on the central proton due to the electron, (b) the electrostatic force on the central proton due to the other proton, and (c) the net electrostatic force on the central proton?

- (a) leftward;
- (b) leftward;
- (c) leftward

Problems

Two charges 4 μC and - 3 μC are separated by 2 cm. Calculate the force between them?

Solution

Since the signs of the charges are different, they produce an attractive force. The magnitude of this force is

$$F = \frac{k|q_1||q_2|}{r^2}$$

$$F = \frac{9 \times 10^9 \times 4 \times 10^{-6} \times 3 \times 10^{-6}}{0.02^2} = 270 \text{ N}$$

Calculate the distance between two point charges 2.4 μC and – 1.8 μC for the electrostatic force to be of magnitude 10.8 N?

Solution

The magnitude of the electrostatic force is given by

$$F = \frac{k|\,q_1||\,q_2|}{r^2} \qquad \rightarrow \qquad r = \sqrt{\frac{k|\,q_1||\,q_2|}{F}}$$

$$r = \sqrt{\frac{k|\,q_1||\,q_2|}{F}} = \sqrt{\frac{9 \times 10^9 \times 2.4 \times 10^{-6} \times 1.8 \times 10^{-6}}{10.8}} = 0.06\,m = 6\,cm$$

A point charge 2.0 μC is placed at a distance 4 cm from another point charge q. If the attractive force between them is 56.25 N, find q.

Solution

The magnitude of the electrostatic force is given by

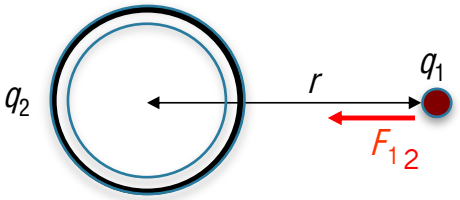
$$F = \frac{k|q_1||q_2|}{r^2} \qquad \rightarrow \qquad q_2 = \frac{F\,r^2}{k\,q_1}$$

$$q_2 = \frac{56.25 \times 0.04^2}{9\times10^9\times2.0\times10^{-6}} = 5.0 \times 10^{-6}\text{C} = 5\mu C$$

Since the force is ATTRACTIVE, the signs of the charges are DIFFERENT. Therefore the unknown charge is negative -5.0 μC .

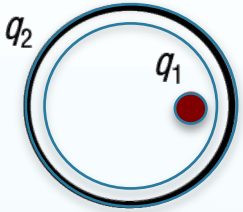
The shell theorem

A shell of uniform charge attracts or repels a charged particle that is outside the shell as if all the shell's charge were concentrated at its center.



$$F_{12} = \frac{1}{4\pi\varepsilon_0}\frac{|q_1||q_2|}{r^2}$$

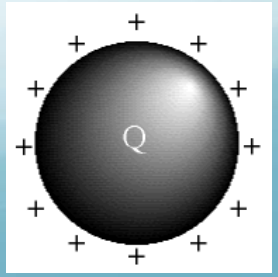
If a charged particle is located inside a shell of uniform charge, there is no net electrostatic force on the particle from the shell.



$$F_{12} = 0$$

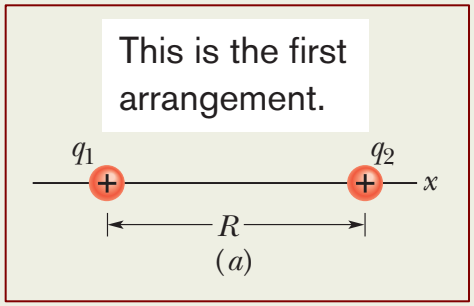
Spherical Conductor

If excess charge is placed on a spherical shell that is made of conducting material, the excess charge spreads uniformly over the (outer) surface



Sample Problem

(a) Figure 21-8*a* shows two positively charged particles fixed in place on an *x* axis. The charges are $q_1 = 1.60 \times 10^{-19}$ C and $q_2 = 3.20 \times 10^{-19}$ C, and the particle separation is $R = 0.0200$ m. What are the magnitude and direction of the electrostatic force $\vec{F}_{12}$ on particle 1 from particle 2?



$$F_{12} = \frac{1}{4\pi\varepsilon_0}\frac{|q_1||q_2|}{R^2}$$

$$= (8.99 \times 10^9\ \text{N}\cdot\text{m}^2/\text{C}^2) \times \frac{(1.60 \times 10^{-19}\ \text{C})(3.20 \times 10^{-19}\ \text{C})}{(0.0200\ \text{m})^2}$$

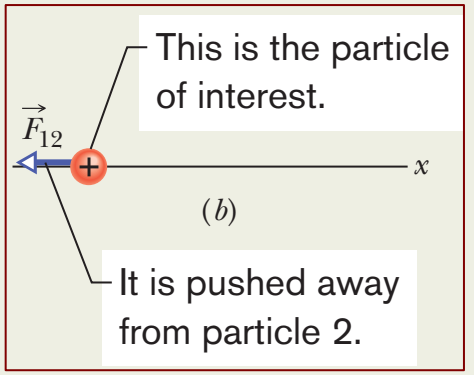
$$= 1.15 \times 10^{-24}\ \text{N}.$$

Thus, force $\vec{F}_{12}$ has the following magnitude and direction (relative to the positive direction of the *x* axis):

$$1.15 \times 10^{-24}\ \text{N} \quad \text{and} \quad 180°. \qquad \text{(Answer)}$$

We can also write $\vec{F}_{12}$ in unit-vector notation as

$$\vec{F}_{12} = -(1.15 \times 10^{-24}\ \text{N})\hat{\text{i}}. \qquad \text{(Answer)}$$



(b) Figure 21-8*c* is identical to Fig. 21-8*a* except that particle 3 now lies on the x axis between particles 1 and 2. Particle 3 has charge $q_3 = -3.20 \times 10^{-19}$ C and is at a distance $\frac{3}{4}R$ from particle 1. What is the net electrostatic force $\vec{F}_{1,\text{net}}$ on particle 1 due to particles 2 and 3?

$$F_{13} = \frac{1}{4\pi\varepsilon_0}\frac{|q_1||q_3|}{(\frac{3}{4}R)^2}$$

$$= (8.99 \times 10^9\ \text{N}\cdot\text{m}^2/\text{C}^2) \times \frac{(1.60 \times 10^{-19}\ \text{C})(3.20 \times 10^{-19}\ \text{C})}{(\frac{3}{4})^2(0.0200\ \text{m})^2}$$

$$= 2.05 \times 10^{-24}\ \text{N}.$$

We can also write $\vec{F}_{13}$ in unit-vector notation:

$$\vec{F}_{13} = (2.05 \times 10^{-24}\ \text{N})\hat{\text{i}}.$$

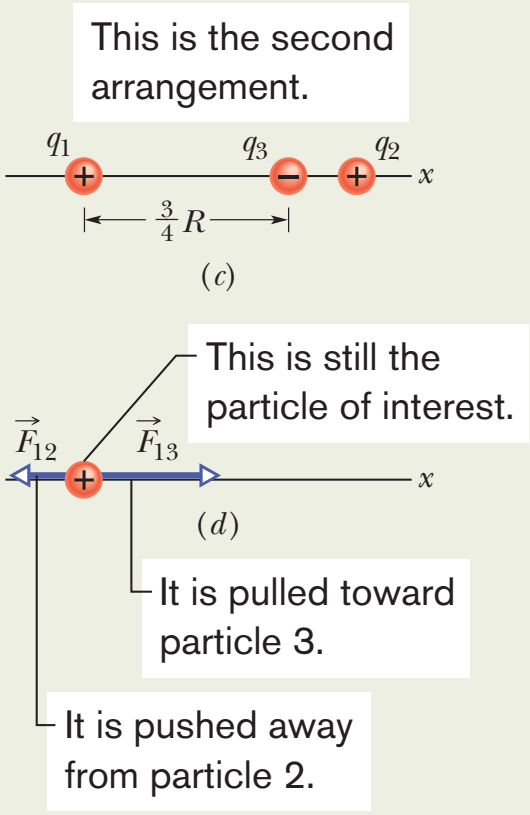
$$\vec{F}_{1,\text{net}} = \vec{F}_{12} + \vec{F}_{13}$$

$$= -(1.15 \times 10^{-24}\ \text{N})\hat{\text{i}} + (2.05 \times 10^{-24}\ \text{N})\hat{\text{i}}$$

$$= (9.00 \times 10^{-25}\ \text{N})\hat{\text{i}}. \qquad \text{(Answer)}$$

Thus, $\vec{F}_{1,\text{net}}$ has the following magnitude and direction (relative to the positive direction of the x axis):

$$9.00 \times 10^{-25}\ \text{N} \quad \text{and} \quad 0°. \qquad \text{(Answer)}$$



(c) Figure 21-8*e* is identical to Fig. 21-8*a* except that particle 4 is now included. It has charge $q_4 = -3.20 \times 10^{-19}$ C, is at a distance $\frac{3}{4}R$ from particle 1, and lies on a line that makes an angle $\theta = 60°$ with the x axis. What is the net electrostatic force $\vec{F}_{1,\text{net}}$ on particle 1 due to particles 2 and 4?

$$\begin{aligned} F_{1,\text{net},x} &= F_{12,x} + F_{14,x} = F_{12} + F_{14}\cos 60° \\ &= -1.15 \times 10^{-24}\ \text{N} + (2.05 \times 10^{-24}\ \text{N})(\cos 60°) \\ &= -1.25 \times 10^{-25}\ \text{N}. \end{aligned}$$

The sum of the y components gives us

$$\begin{aligned} F_{1,\text{net},y} &= F_{12,y} + F_{14,y} = 0 + F_{14}\sin 60° \\ &= (2.05 \times 10^{-24}\ \text{N})(\sin 60°) \\ &= 1.78 \times 10^{-24}\ \text{N}. \end{aligned}$$

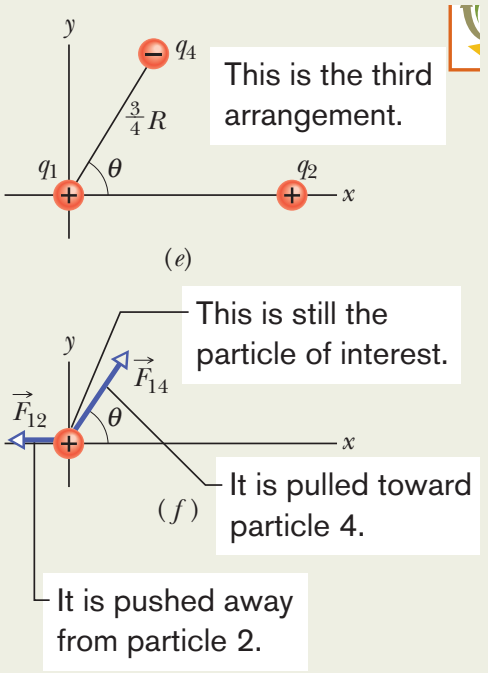
The net force $\vec{F}_{1,\text{net}}$ has the magnitude

$$F_{1,\text{net}} = \sqrt{F_{1,\text{net},x}^2 + F_{1,\text{net},y}^2} = 1.78 \times 10^{-24}\ \text{N}. \quad \text{(Answer)}$$

To find the direction of $\vec{F}_{1,\text{net}}$, we take

$$\theta = \tan^{-1}\frac{F_{1,\text{net},y}}{F_{1,\text{net},x}} = -86.0°.$$

$$-86.0° + 180° = 94.0°.$$



Sample Problem

The nucleus in an iron atom has a radius of about 4.0×10^{-15} m and contains 26 protons.

(a) What is the magnitude of the repulsive electrostatic force between two of the protons that are separated by 4.0×10^{-15} m?

$$F = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r^2}$$

$$= \frac{(8.99 \times 10^9\ \mathrm{N \cdot m^2/C^2})(1.602 \times 10^{-19}\ \mathrm{C})^2}{(4.0 \times 10^{-15}\ \mathrm{m})^2}$$

$$= 14\ \mathrm{N}. \qquad \text{(Answer)}$$

Charge is Quantized
Charge is Conserved

Table 21-1

The Charges of Three Particles

Particle	Symbol	Charge
Electron	e or e^-	$-e$
Proton	p	$+e$
Neutron	n	0

- **Electric charge is quantized:**
  Quantized quantity: a physical quantity, such as charge, that have only discrete values rather than any value
  - Any +ve or –ve charge q that can be detected can be written as
    $$q = ne, \qquad n = \pm 1, \pm 2, \pm 3, \ldots, \qquad e = 1.602 \times 10^{-19}\ \text{C}.$$
    in which e, the elementary charge, has the value
  - It is possible to find a particle that has no charge at all or a charge of -10e or +6e, but not a particle with a charge of 3.57e

- **Electric charge is conserved:** the net charge of any isolated system cannot change

CHECKPOINT 4

Initially, sphere A has a charge of $-50e$ and sphere B has a charge of $+20e$. The spheres are made of conducting material and are identical in size. If the spheres then touch, what is the resulting charge on sphere A?

-15e (net charge of -30e is equally shared)

Problems

5×10^{20} electrons pass between two points in 4sec, Calculate the current.

$$i = dq / dt$$

$$q = ne$$

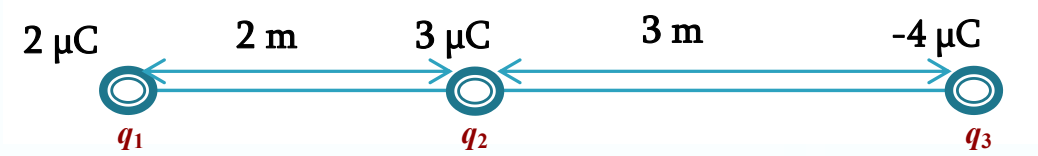
$$i = \frac{ne}{t} = \frac{5 \times 10^{20} \times 1.6 \times 10^{-19}}{4} = 20A$$

How many electrons would be removed from a metal to have a charge of 4.8μC?

$$q = ne$$

$$n = q / e = 4.8 \times 10^{-6} / 1.6 \times 10^{-19} = 3 \times 10^{13} electron$$

Three point charges 2.0, 3.0, and -4.0 μC are located as shown in the figure. Find the magnitude of the force acting on the 2 μC charge due to the others.



Solution

Since the signs of charges (2 μC and 3 μC) are similar, the force is repulsive. That means the force will be to left and its magnitude is

$$F_{12} = \frac{9 \times 10^9 \times 2 \times 10^{-6} \times 3 \times 10^{-6}}{2^2} = 0.0135 \text{ N}$$

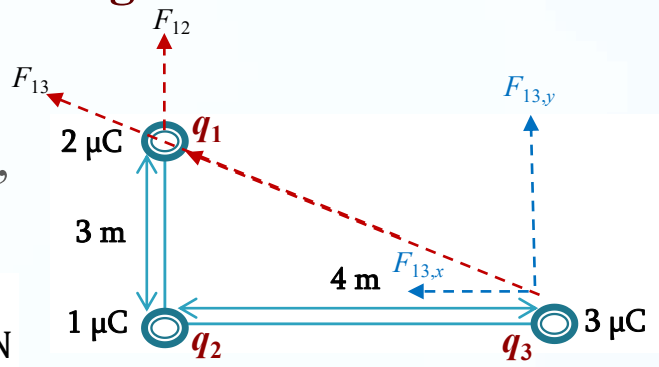
Since the signs of charges (2 μC and -4 μC) are dissimilar, the force is attractive. That means the force will be to right and its magnitude is

$$F_{13} = \frac{9 \times 10^9 \times 2 \times 10^{-6} \times 4 \times 10^{-6}}{5^2} = 0.00288 \text{ N}$$

Therefore the magnitude of the force on the 2 μC particle due to the other charged particles is

$$F = |F_{12} - F_{13}| = |0.0135 - 0.00288| = 0.01062 \text{ N}$$

Three point charges 1.0, 2.0, and 3.0 μC are arranged as shown in the figure. Find the magnitude of the force acting on the 2 μC charge due to the others.



Solution

Since the signs of charges (1 μC and 2 μC) are similar, the force will be up along the +y direction with magnitude of

$$F_{12} = \frac{9 \times 10^9 \times 1 \times 10^{-6} \times 2 \times 10^{-6}}{3^2} = 0.002 \text{ N}$$

Since the signs of charges (2 μC and 3 μC) are also similar, the force will have two components (one along -x and other along +y axes)

$$F_{13x} = \frac{9 \times 10^9 \times 2 \times 10^{-6} \times 3 \times 10^{-6}}{5^2} \cdot \frac{4}{5} = 0.00173 \text{ N}$$

$$F_{13y} = \frac{9 \times 10^9 \times 2 \times 10^{-6} \times 3 \times 10^{-6}}{5^2} \cdot \frac{3}{5} = 0.0013 \text{ N}$$

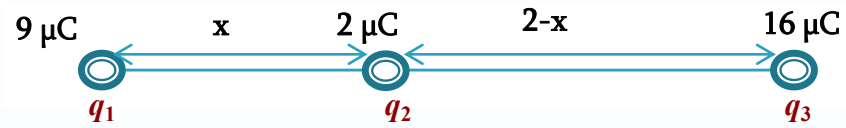
Therefore the magnitude of the force on the 2 μC particle due to the other charged particles is

$$F_x = 0.00173\ N$$

$$F_y = 0.002 + 0.0013 = 0.0033\ N$$

$$F = \sqrt{F_x^2 + F_y^2} = 0.00372\ N$$

Two charges 9.0 and 16.0 μC are separated by a distance of 2 m. Where should a third charge 2 μC be placed between them for a zero net force on it?



Solution

As the charges are of same sign, the third charge must be placed between them and close to the smaller charge in order to have a zero net force.

$$F_{21} = F_{23}$$

$$\frac{9 \times 10^9 \times 2 \times 10^{-6} \times 9 \times 10^{-6}}{x^2} = \frac{9 \times 10^9 \times 2 \times 10^{-6} \times 16 \times 10^{-6}}{(2-x)^2}$$

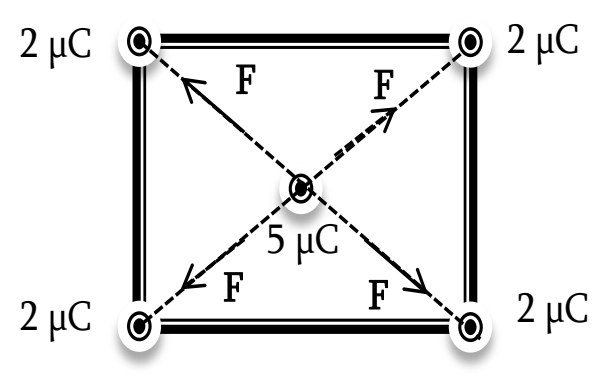
$$\frac{9}{x^2} = \frac{16}{(2-x)^2}$$

$$\frac{3}{x} = \frac{4}{2-x}$$

$$x = \frac{6}{7} = 0.86\ m$$

Four identical charges (2 μC) are located at the vertices of a square of side 5 cm. Calculate the magnitude of the electric force on a 5 μC located at the center of the square.

Solution



The electric forces on the 5 μC due to the other charges have the same magnitude. Each charge along the diagonal will experience equal and opposite force on the 5 μC charge, therefore, the resultant force is zero.