Chapter 21

Electric Charge and Electric Field

Goals for Chapter 21

- To study electric charge and charge conservation
- To see how objects become charged
- To calculate the electric force between objects using Coulomb's law
- To learn the distinction between electric force and electric field
- To calculate the electric field due to many charges
- To visualize and interpret electric fields
- To calculate the properties of electric dipoles

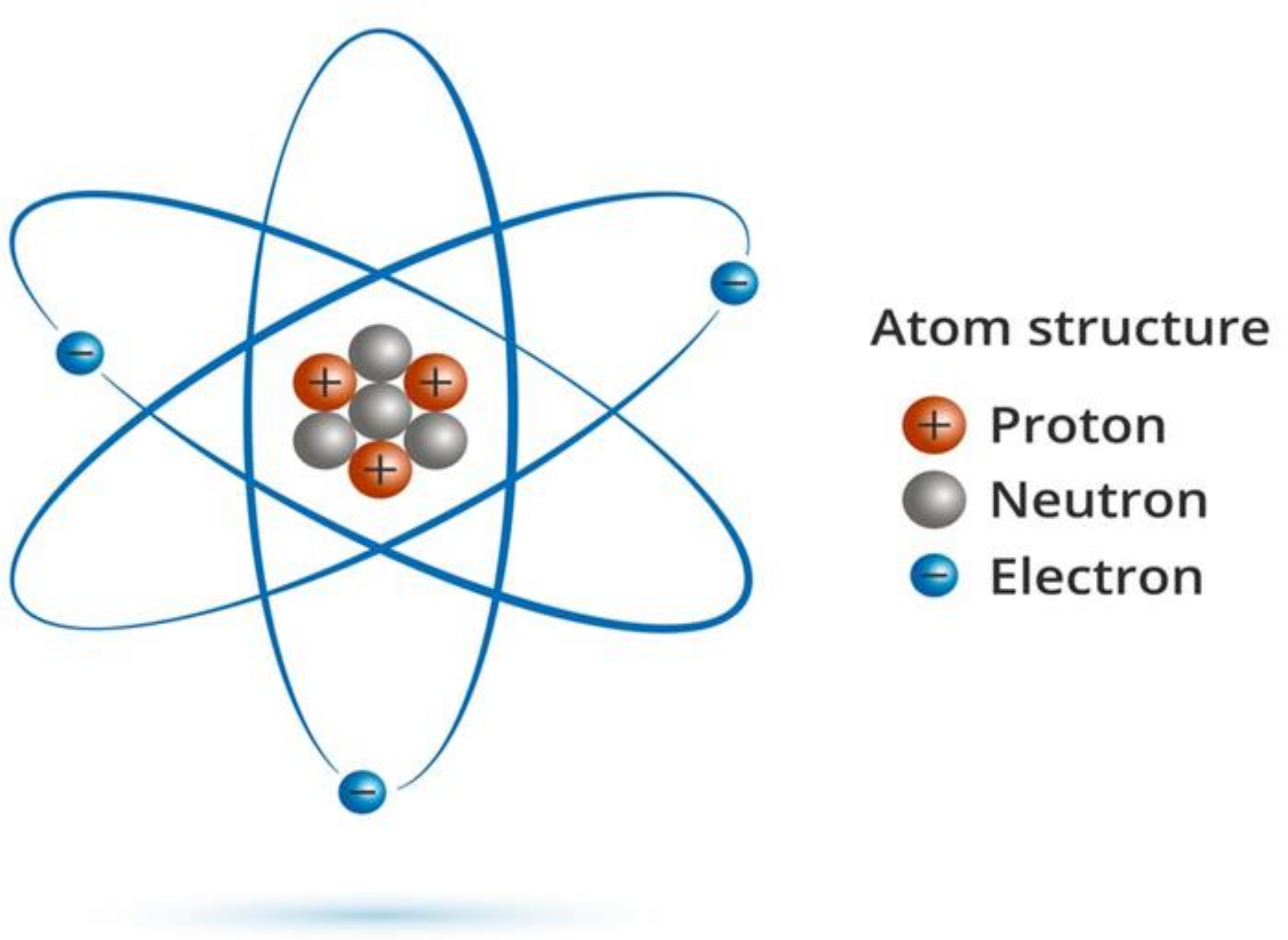
Introduction

- Water makes life possible as a solvent for biological molecules. What electrical properties allow it to do this?

- We now begin our study of *electromagnetism*, one of the four fundamental forces.

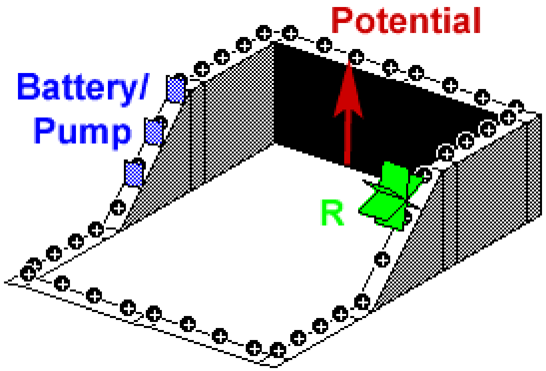
- We start with electric charge and look at electric fields.

Electric charge

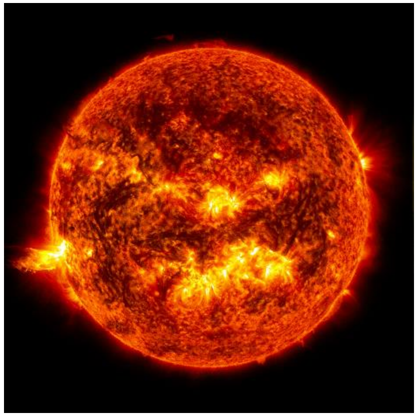


Electric charge : *indirect way*

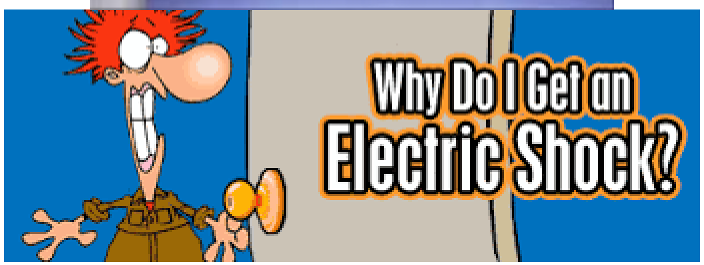
Electric charge : *indirect way*

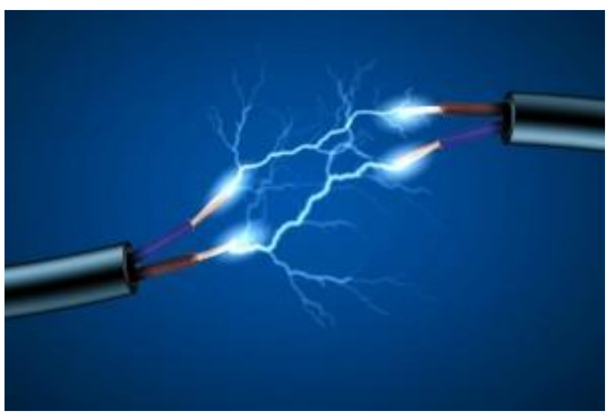


Electric charge : *indirect way*



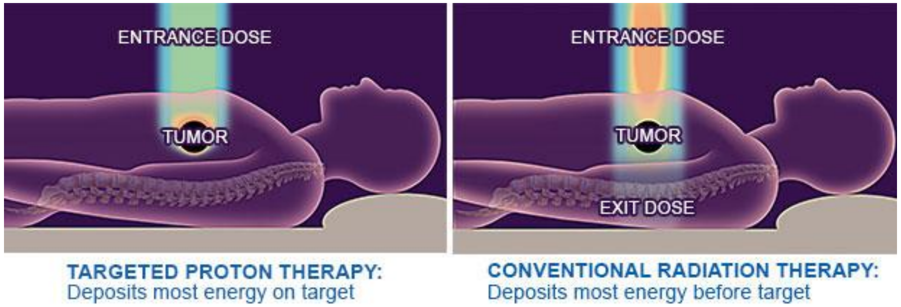
Electric Shock: *direct way*



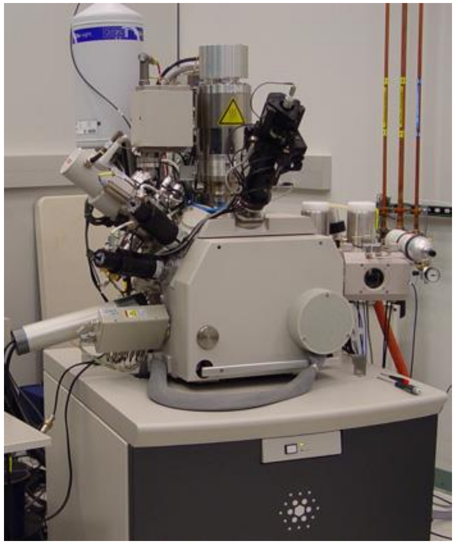


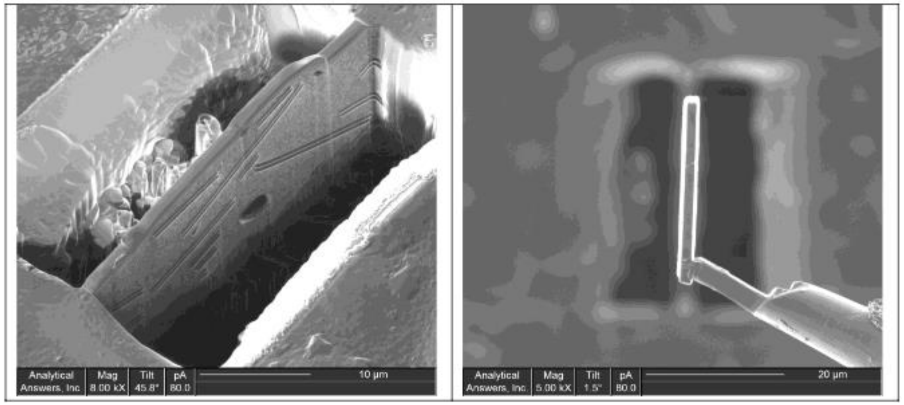
Electrons are matter

Electric charge : manipulation



Proton therapy

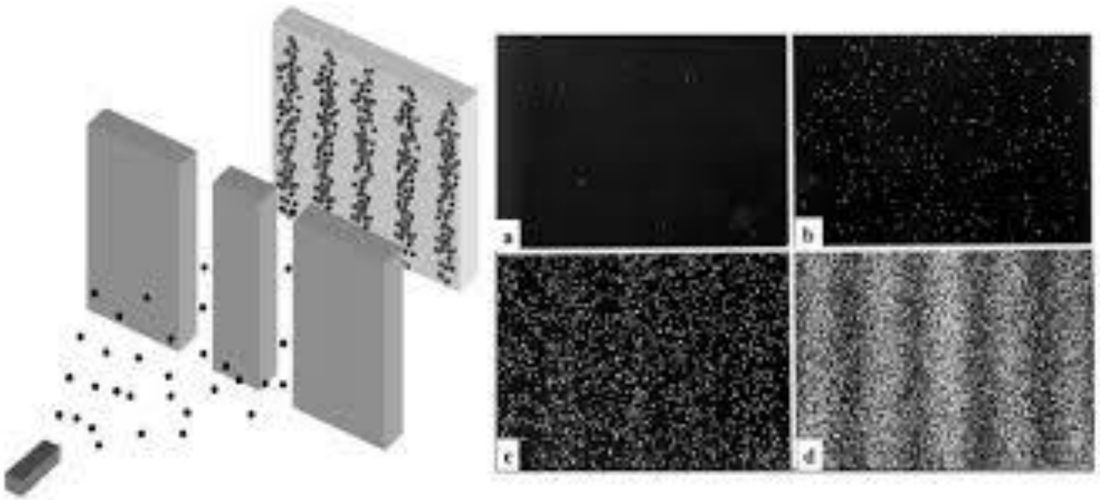




Focused Ion beam

Shanghai Synchrotron Accelerator

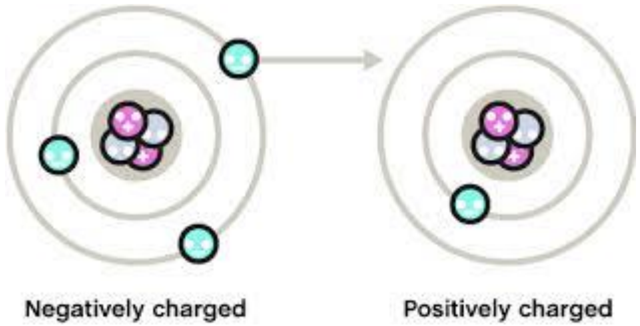
Electric charge: *wave nature*

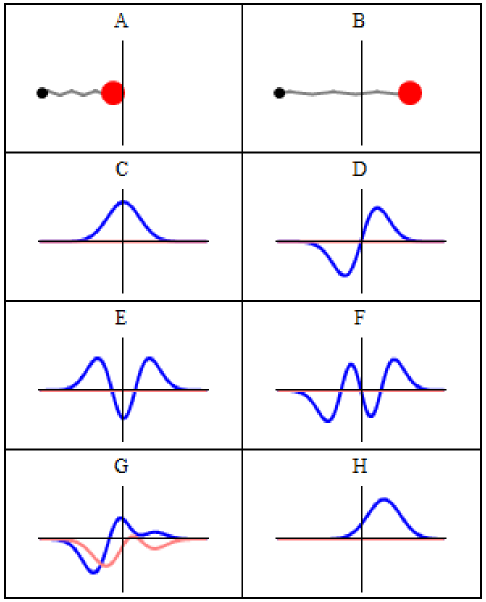


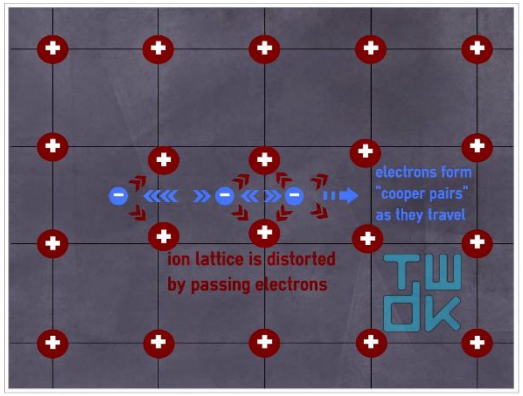
Electron diffraction

Particle or Wave ?

Electric charge: *wave nature*







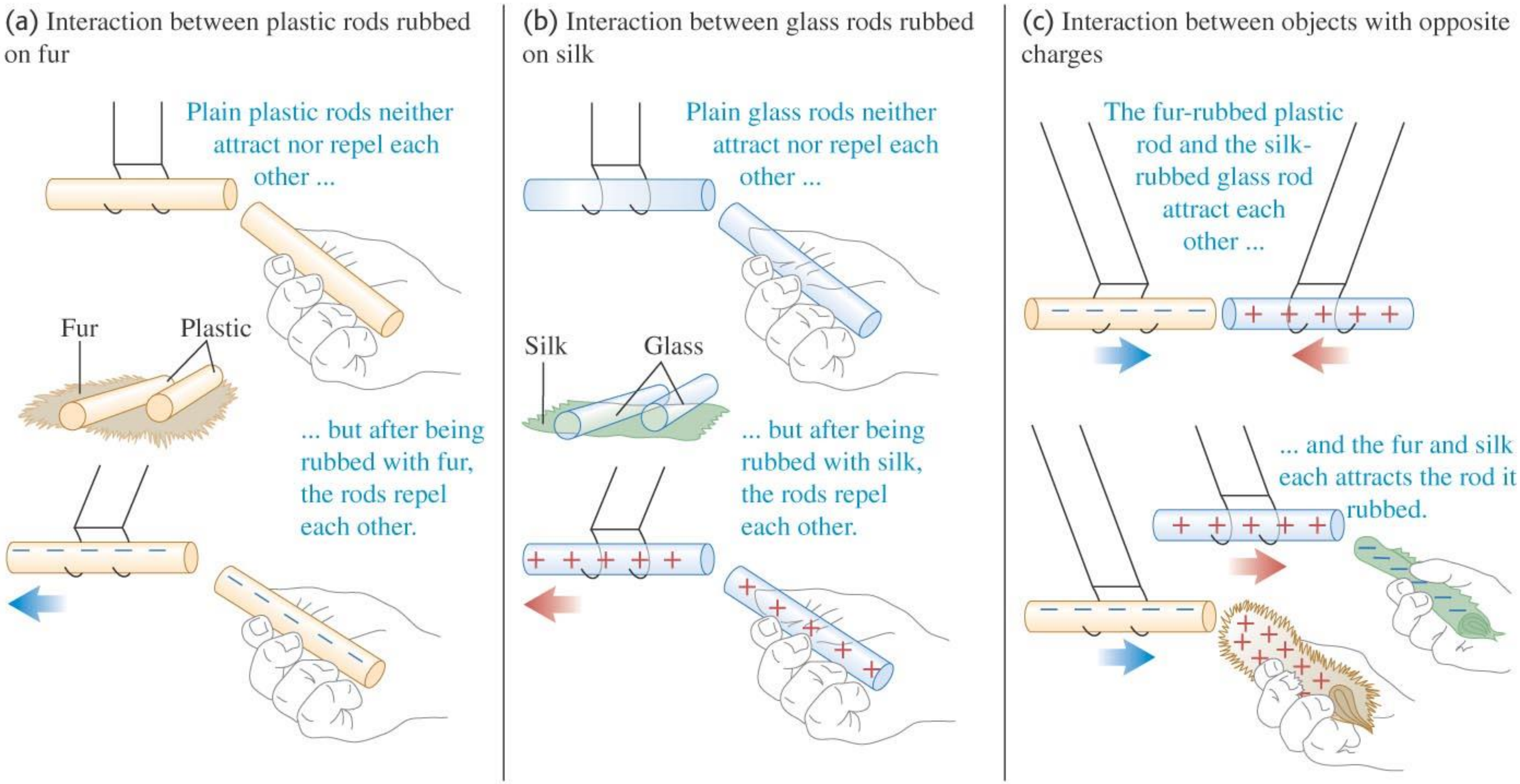
→ Superconductivity

(Cooper pairs: electrons+holes)

Particle or Wave ?

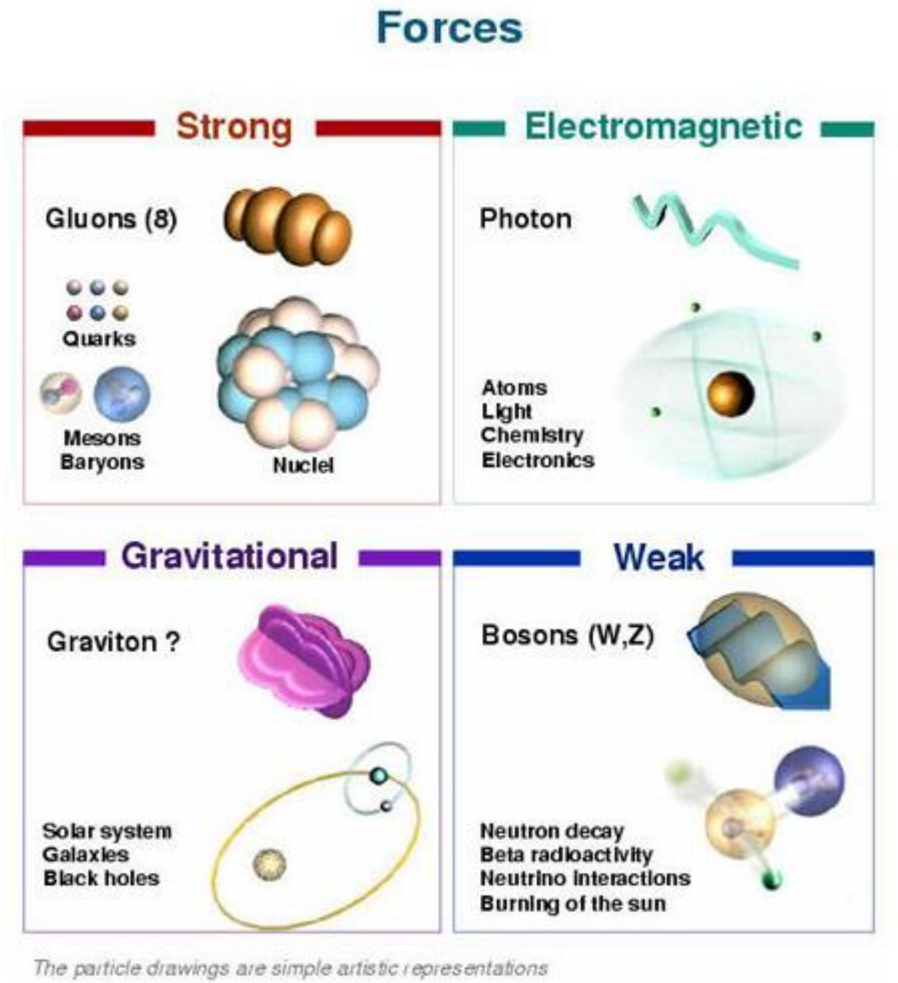
Electric charge

- Two positive or two negative charges repel each other. A positive charge and a negative charge attract each other.
- Figure 21.1 below shows some experiments in *electrostatics*.



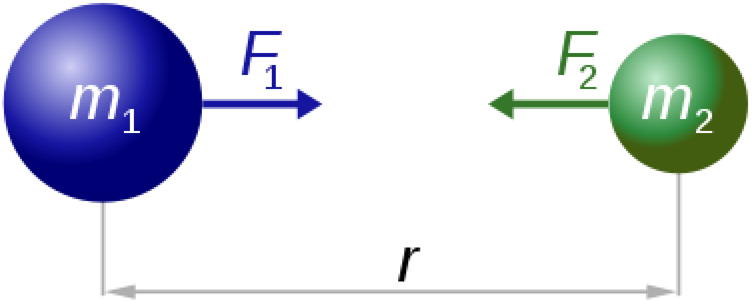
Feel the force

Fundamental interaction



electroscope

Newton's Law Coulomb's law

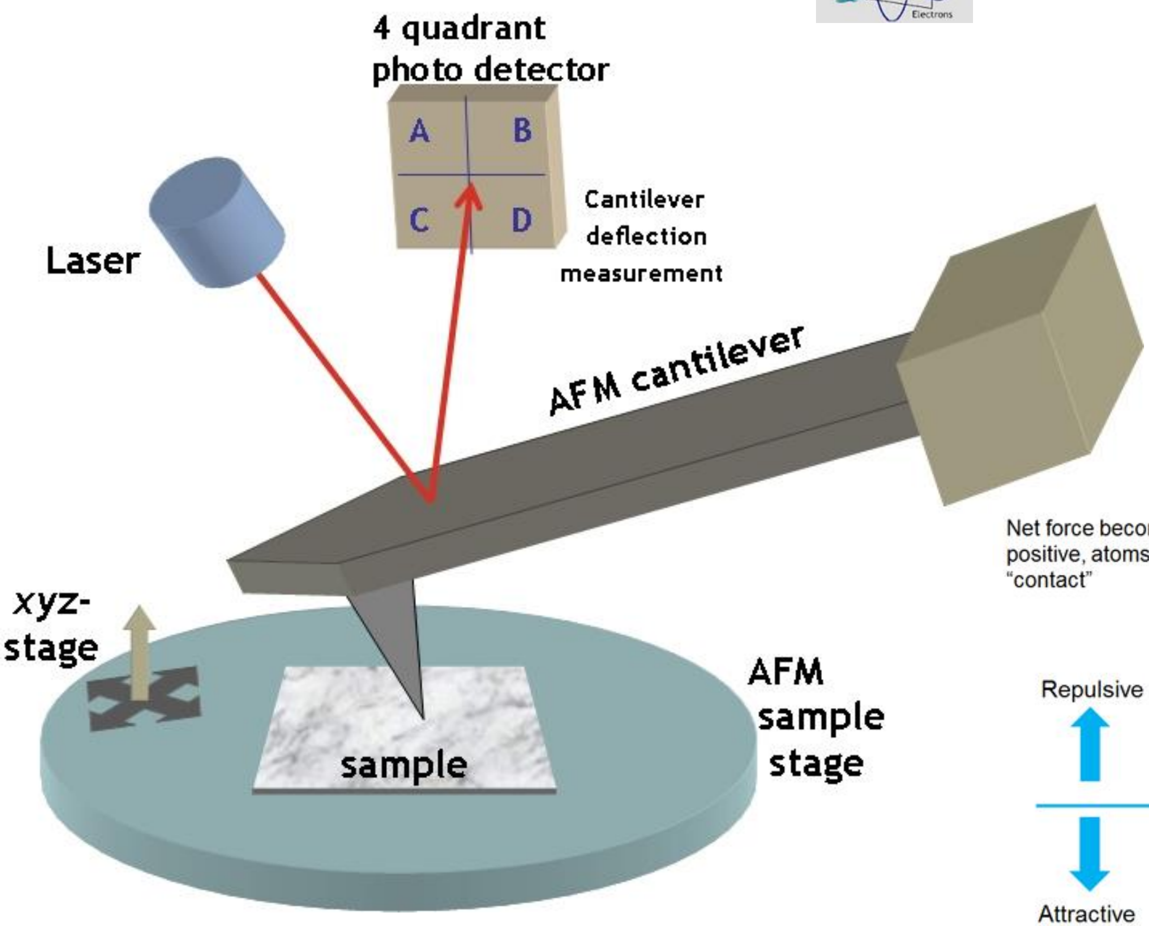


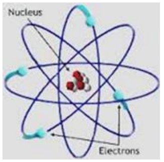
$$F_1 = F_2 = G\frac{m_1 \times m_2}{r^2}$$

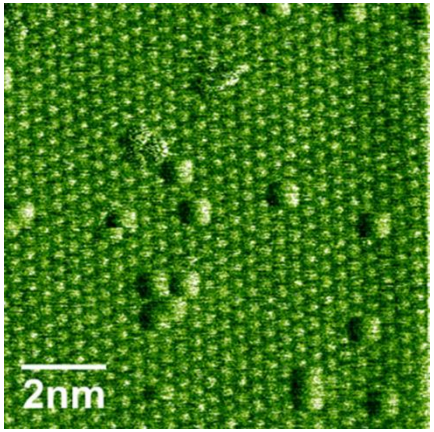
Coulomb's law

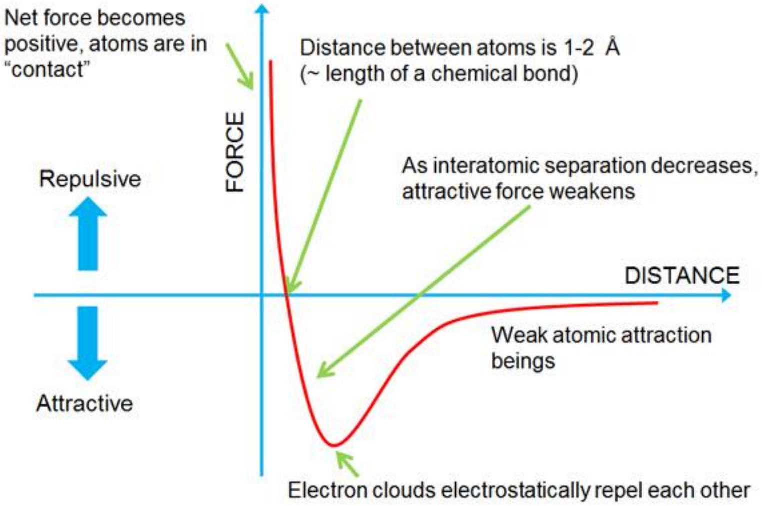
$$F = k|q_1q_2|/r^2$$

Feel the force: atomic force microscope

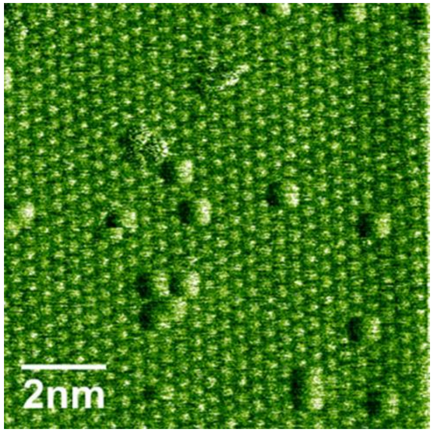


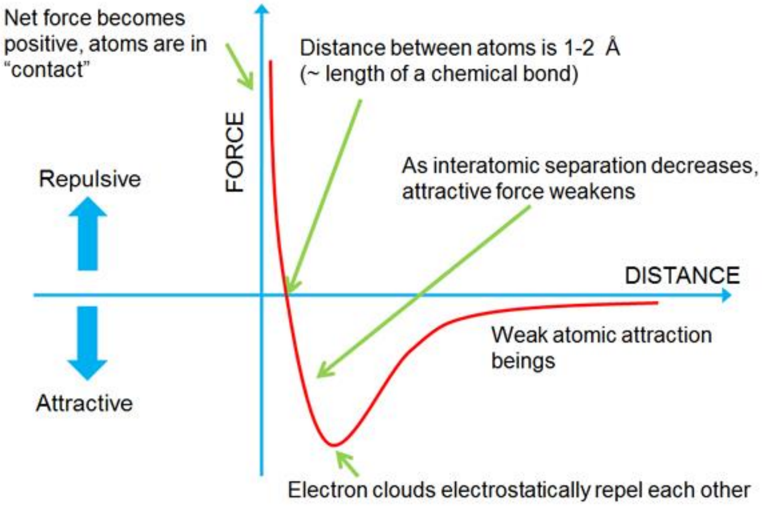






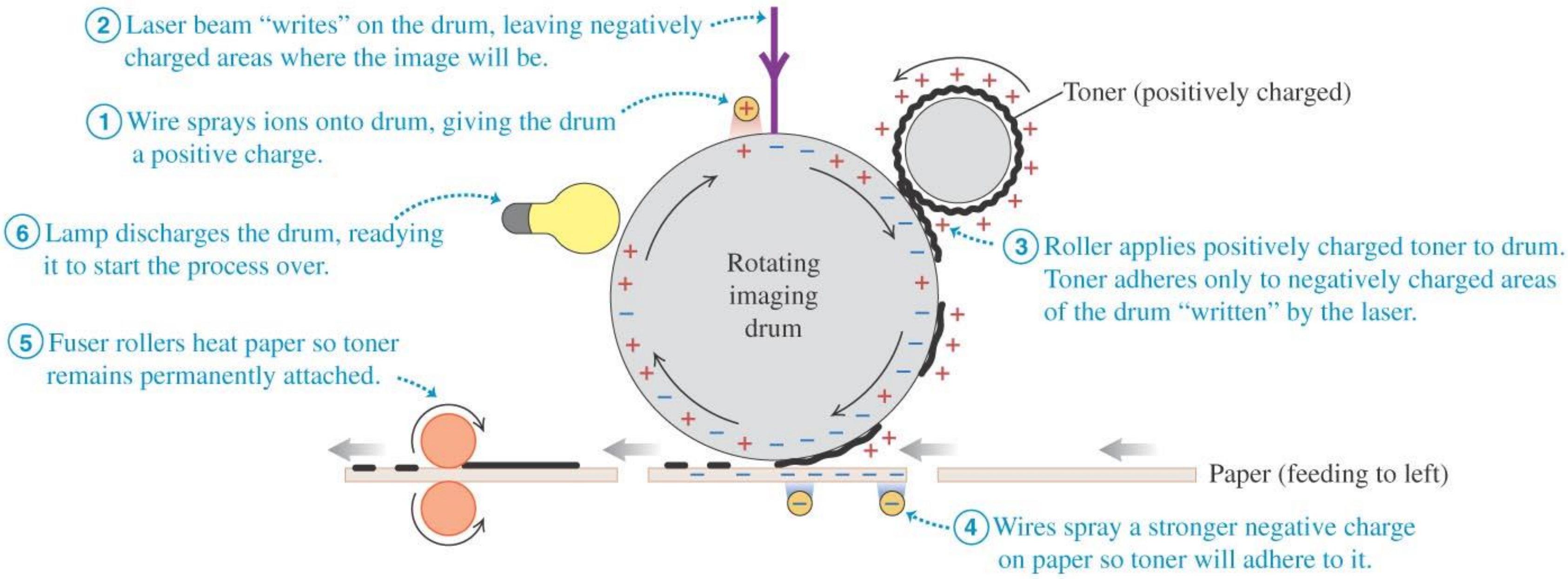
Feel the force: atomic force microscope





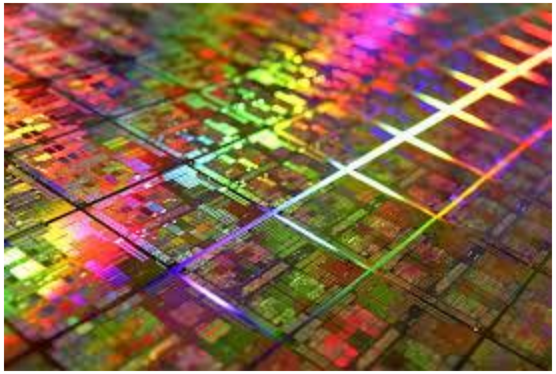
Laser printer

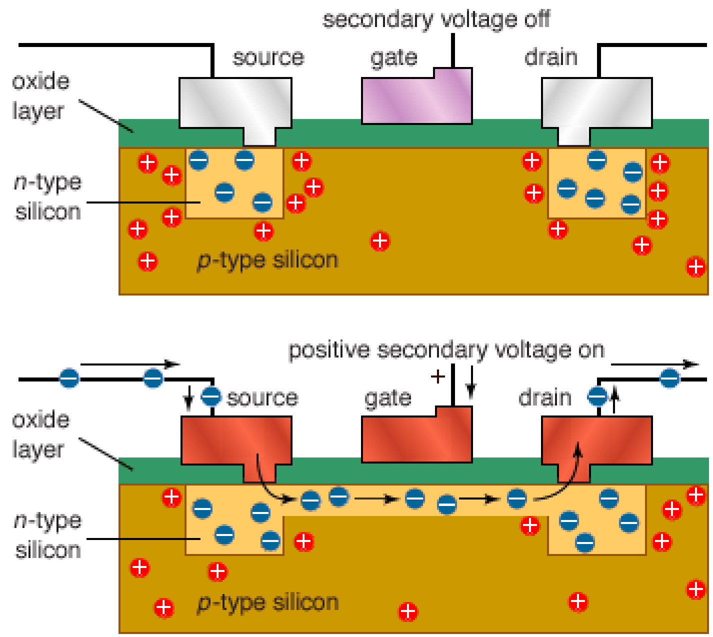
- A laser printer makes use of forces between charged bodies.



Computer


wiseGEEK




secondary voltage off
source
gate
drain
oxide layer
n-type silicon
p-type silicon
positive secondary voltage on
+
source
gate
drain
oxide layer
n-type silicon
p-type silicon
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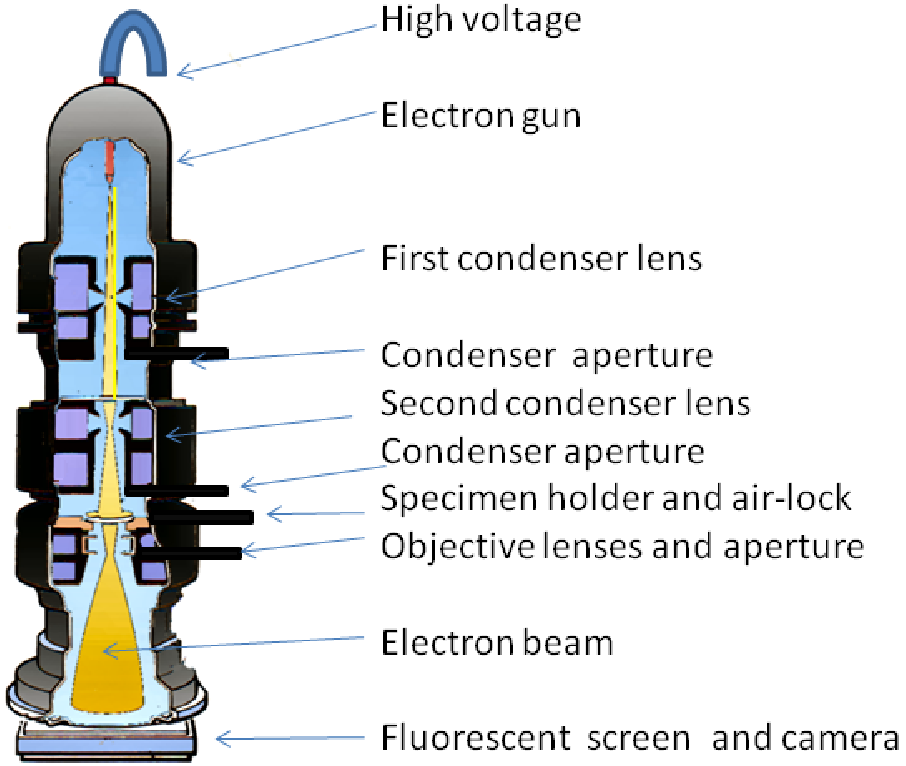
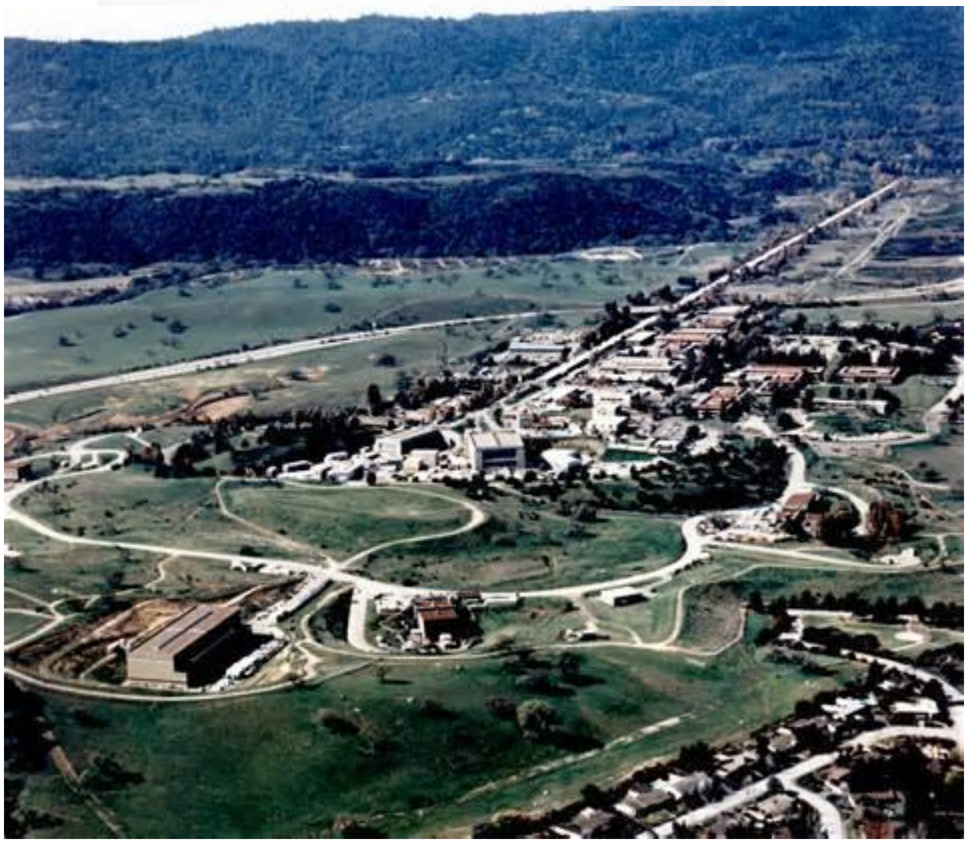
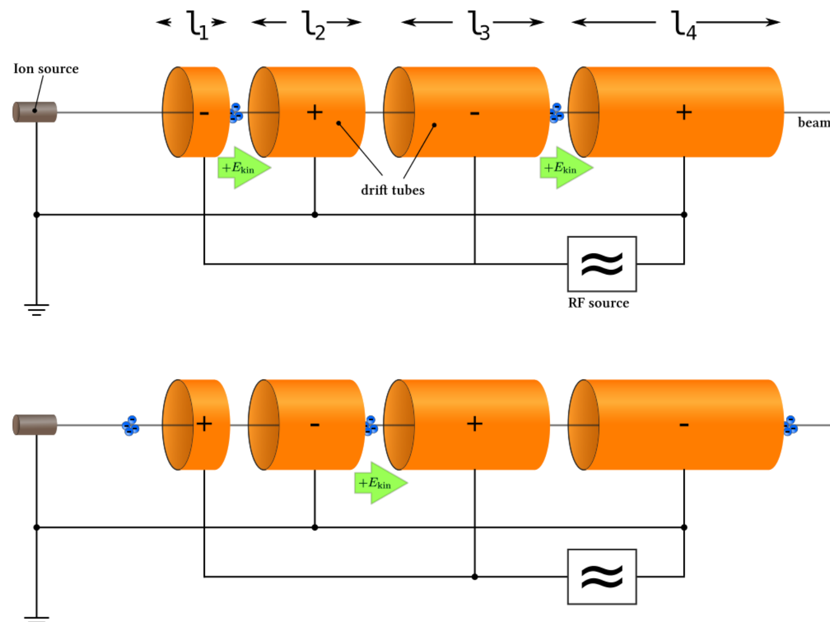
Electron Microscope



Transmission Electron Microscope

SLAC

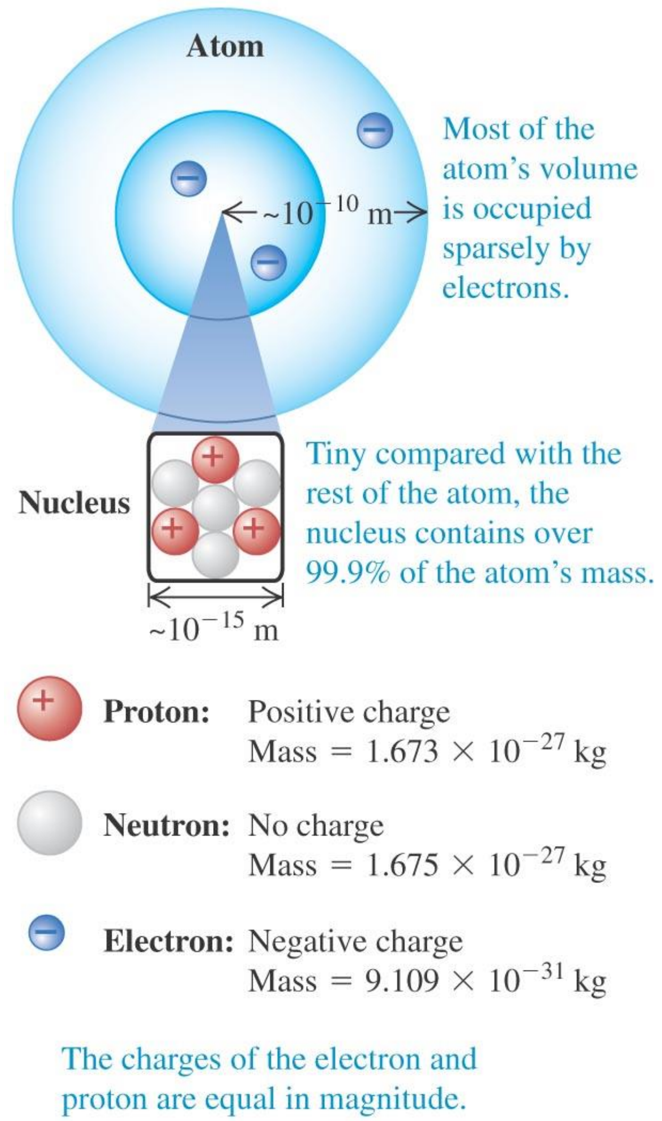




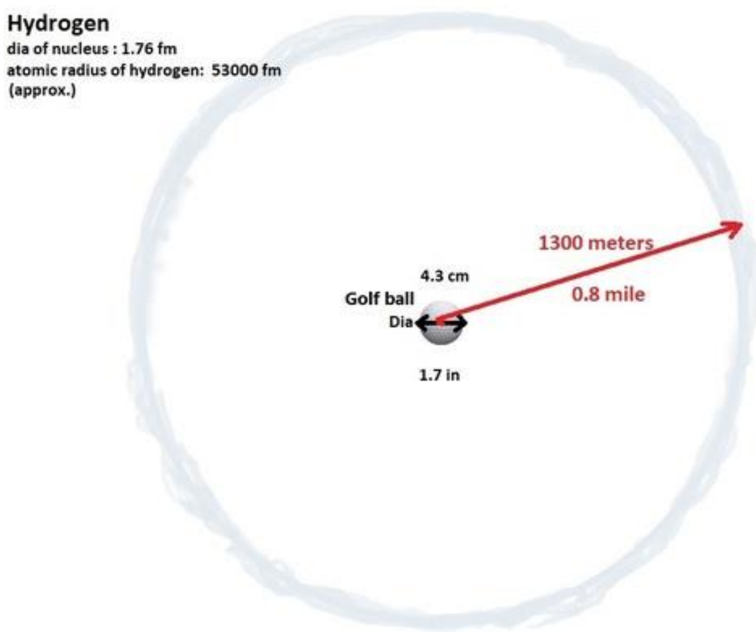
Shanghai Synchrotron Accelerator

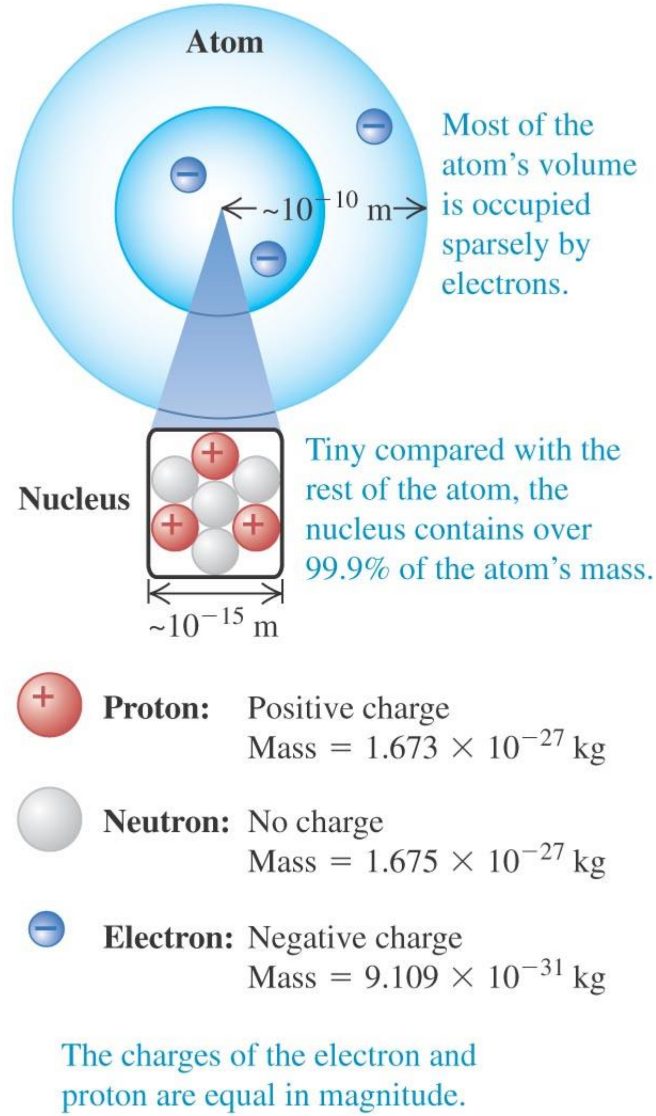
Electric charge and the structure of matter

- The particles of the atom are the negative *electron*, the positive *proton*, and the uncharged *neutron*.
- Protons and neutrons make up the tiny dense nucleus which is surrounded by electrons (see Figure 21.3 at the right).
- The electric attraction between protons and electrons holds the atom together.

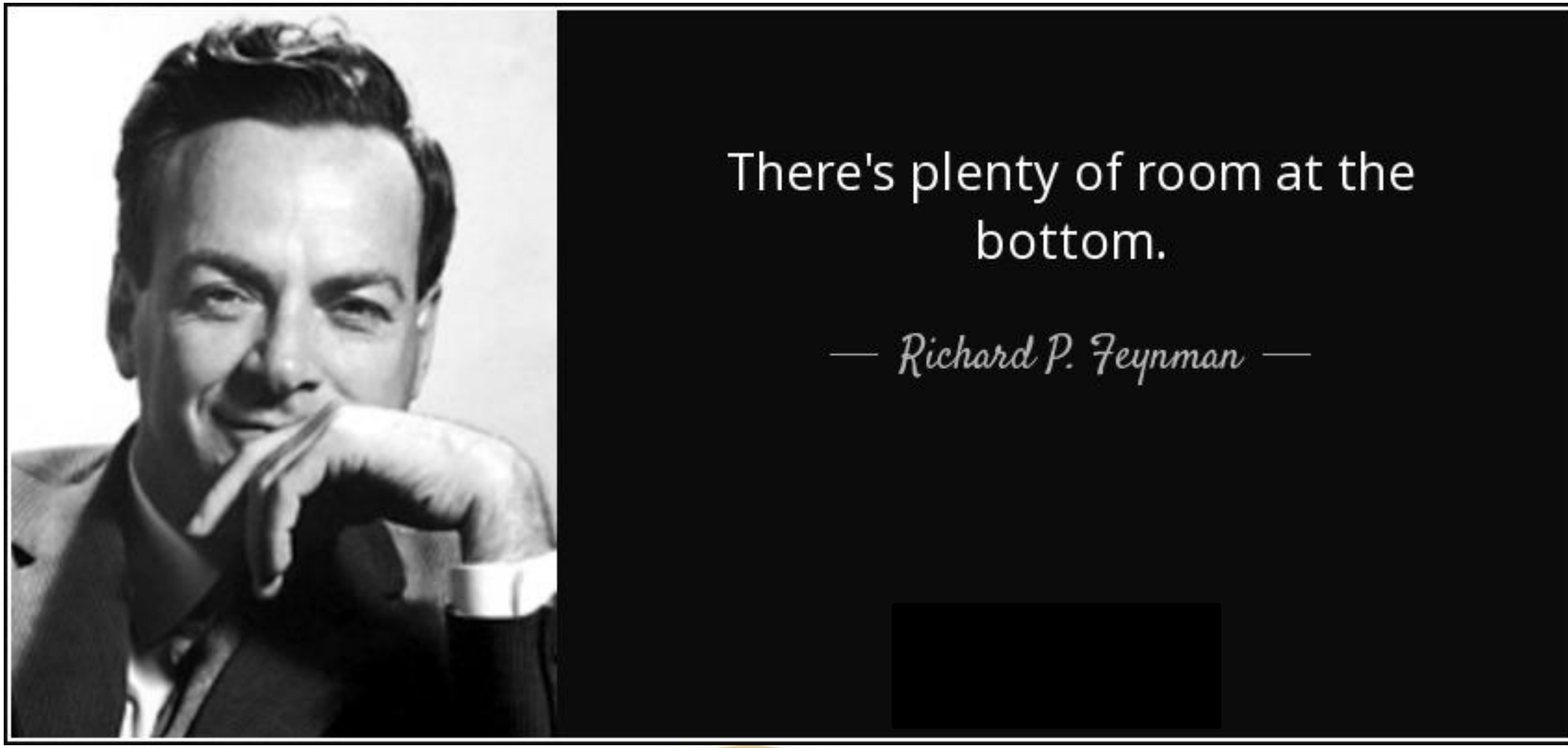


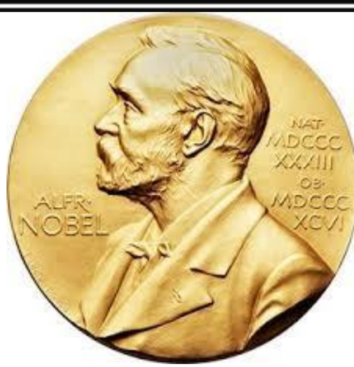
Electric charge and the structure of matter



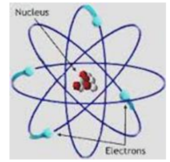


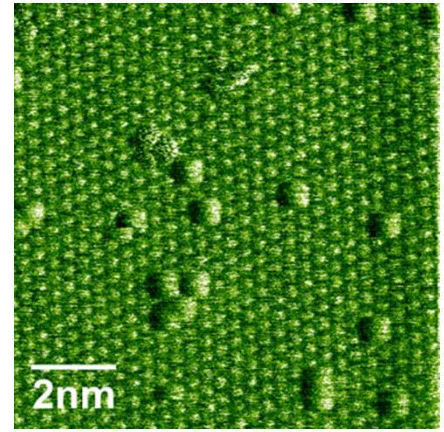
Electric charge and the structure of matter

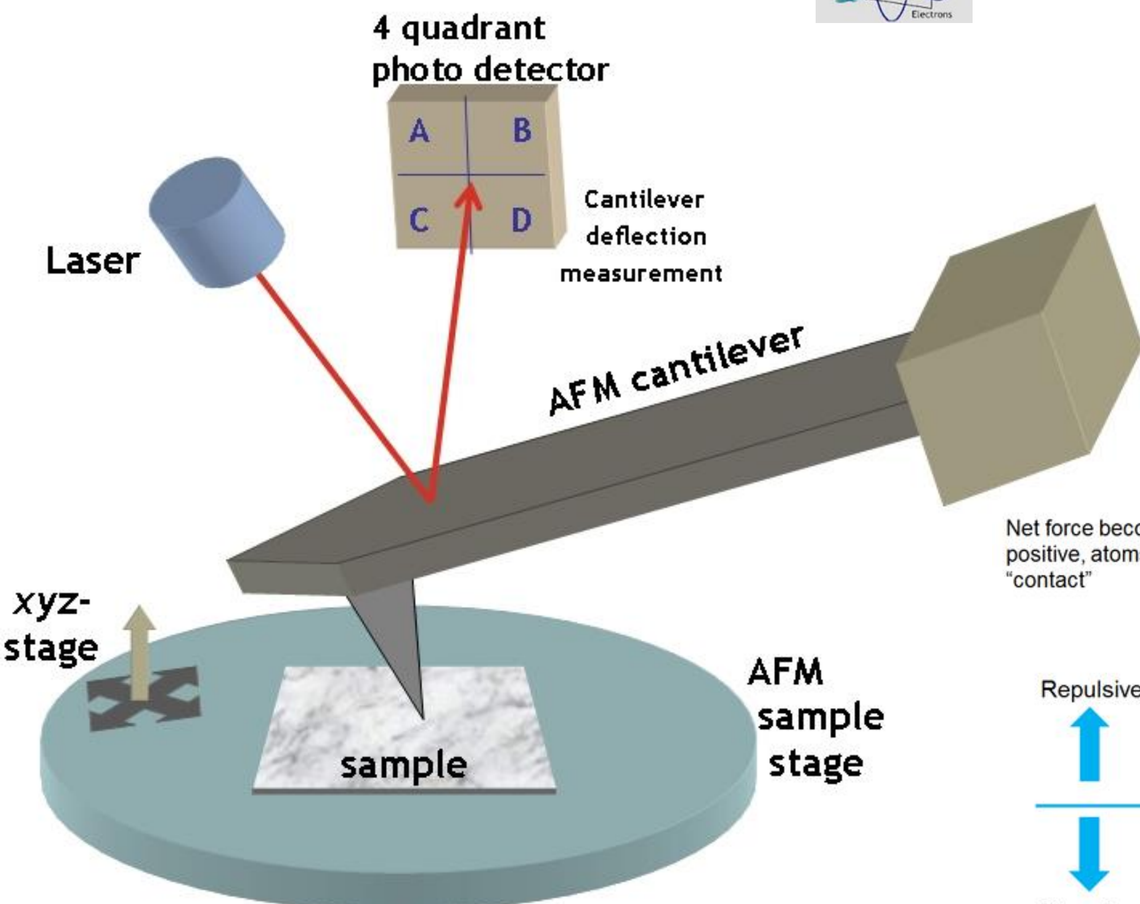


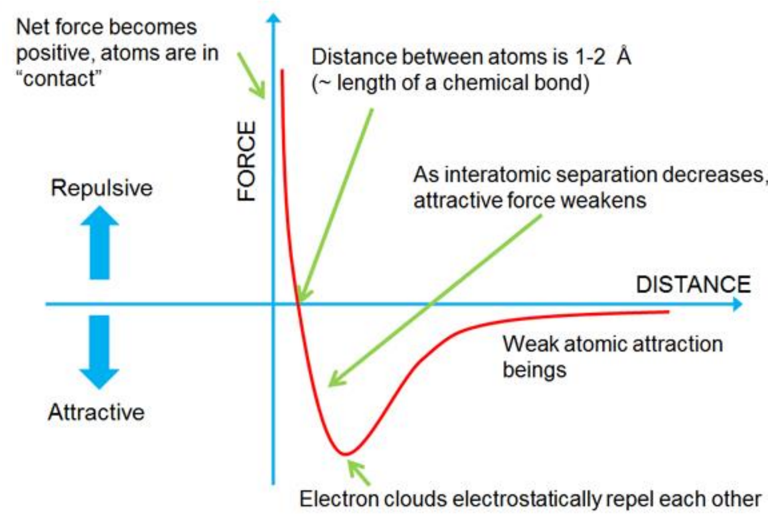


Feel the force: atomic force microscope





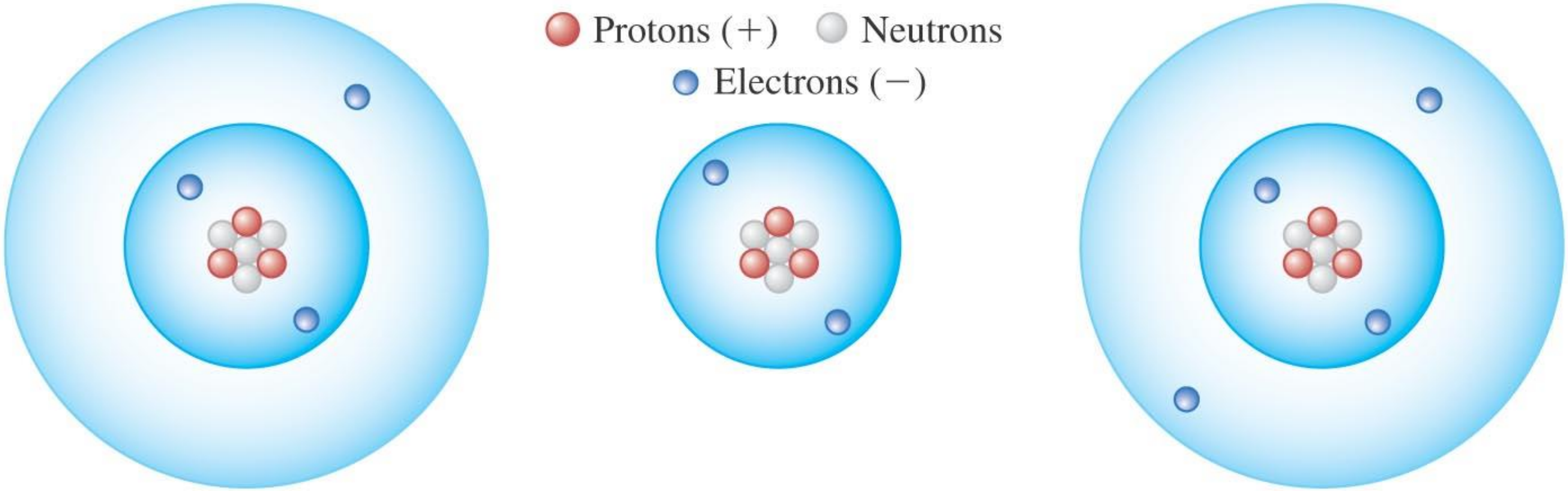




Atoms and ions

Atoms and ions

- A neutral atom has the same number of protons as electrons.
- A *positive ion* is an atom with one or more electrons removed. A *negative ion* has gained one or more electrons.



(a) Neutral lithium atom (Li):
3 protons (3+)
4 neutrons
3 electrons (3−)
Electrons equal protons:
Zero net charge

(b) Positive lithium ion (Li^+):
3 protons (3+)
4 neutrons
2 electrons (2−)
Fewer electrons than protons:
Positive net charge

(c) Negative lithium ion (Li^-):
3 protons (3+)
4 neutrons
4 electrons (4−)
More electrons than protons:
Negative net charge

Atoms and ions

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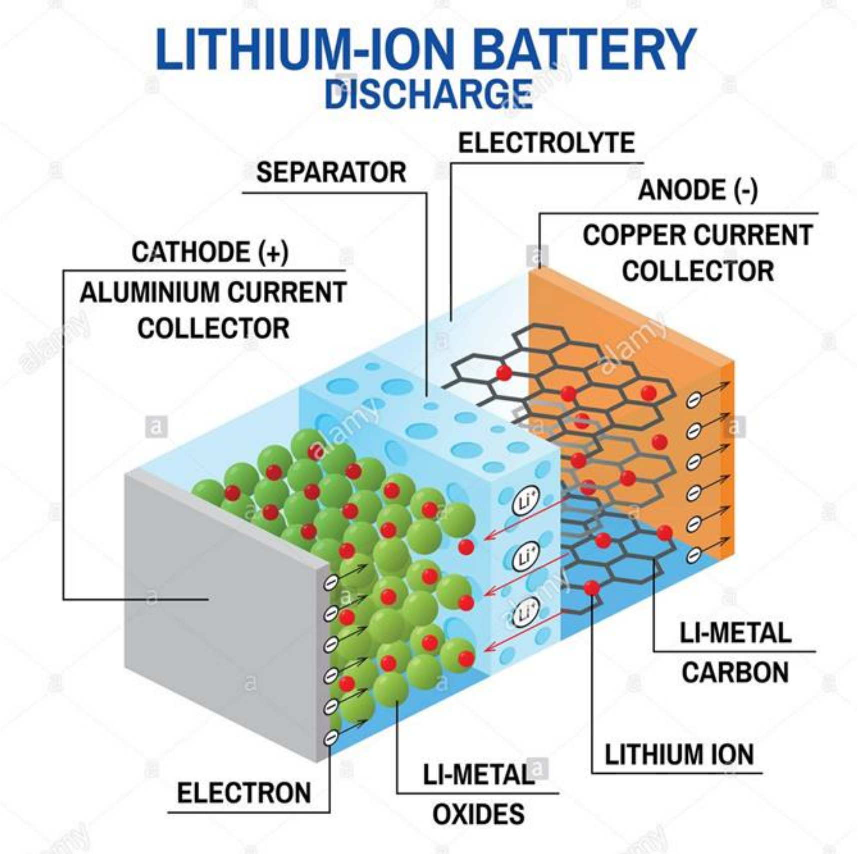
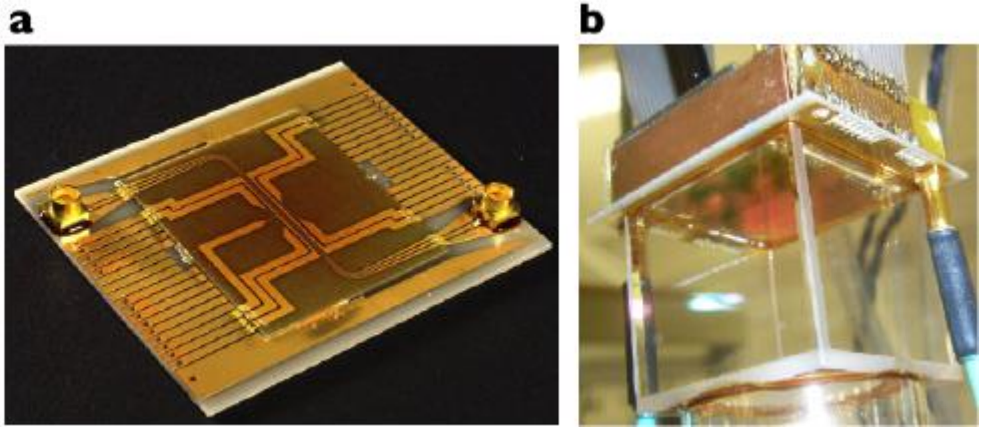
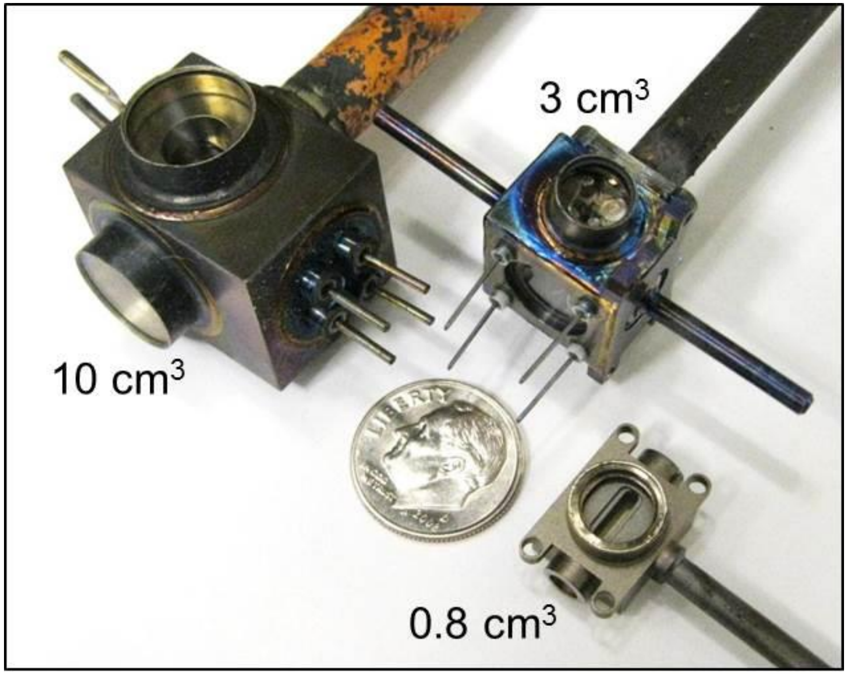
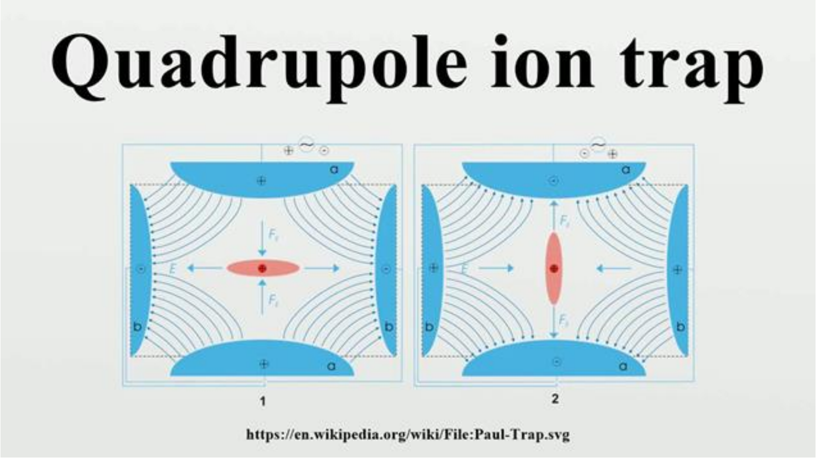


Atoms and ions





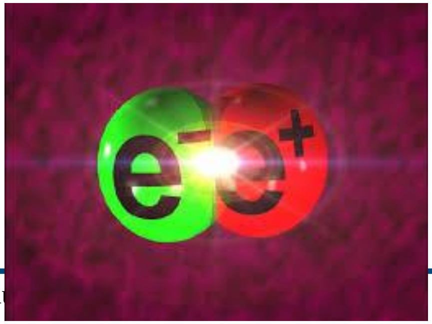


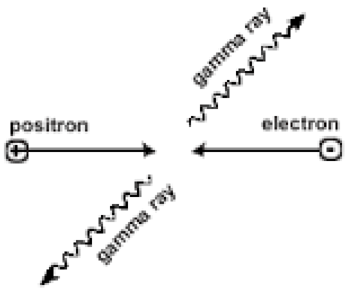
Conservation of charge

Conservation of charge

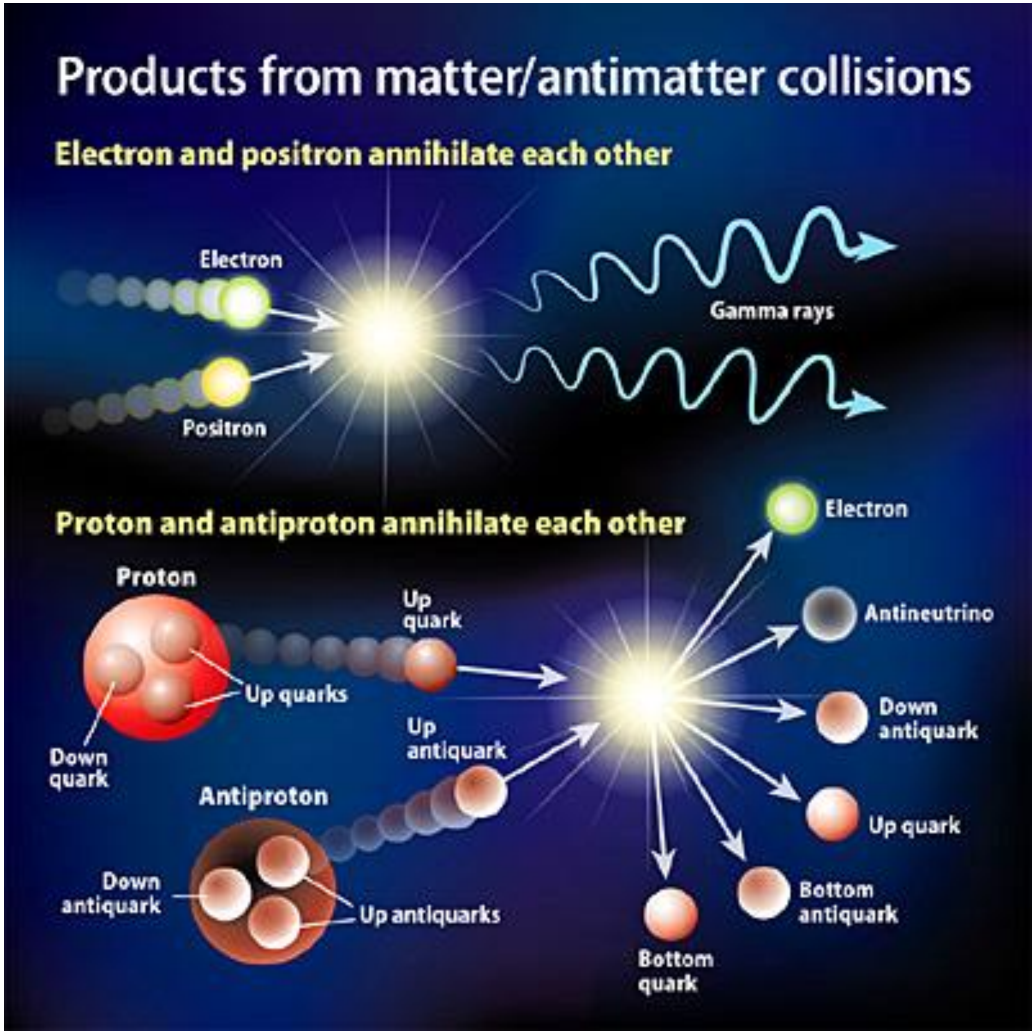
- The proton and electron have the same magnitude charge.
- The magnitude of charge of the electron or proton is a natural unit of charge. All observable charge is *quantized* in this unit.
- The universal *principle of charge conservation* states that the algebraic sum of all the electric charges in any closed system is constant.

Can't create / eliminate a electron !

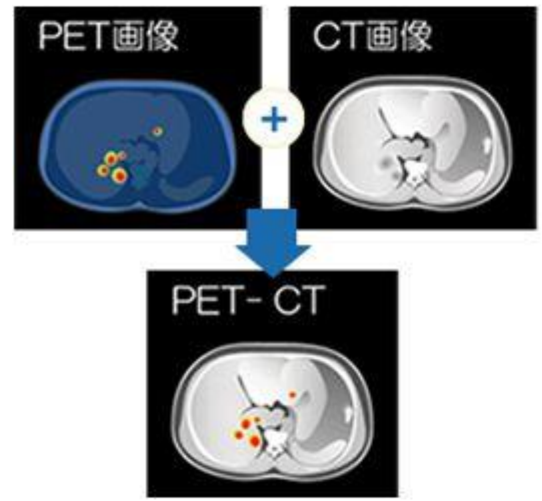




Conservation of charge: matter and anti-matter



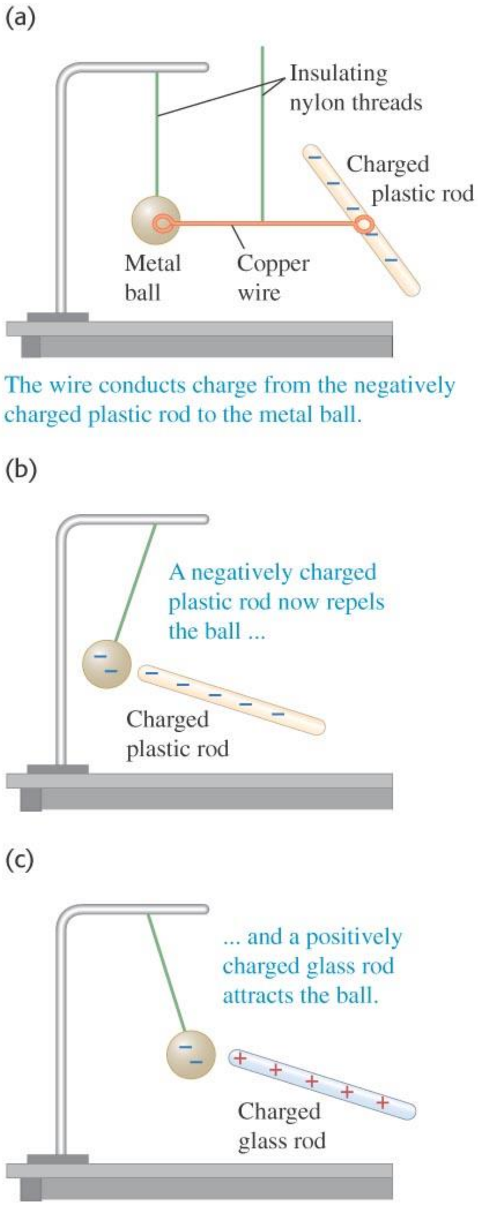
Conservation of charge: matter and anti-matter



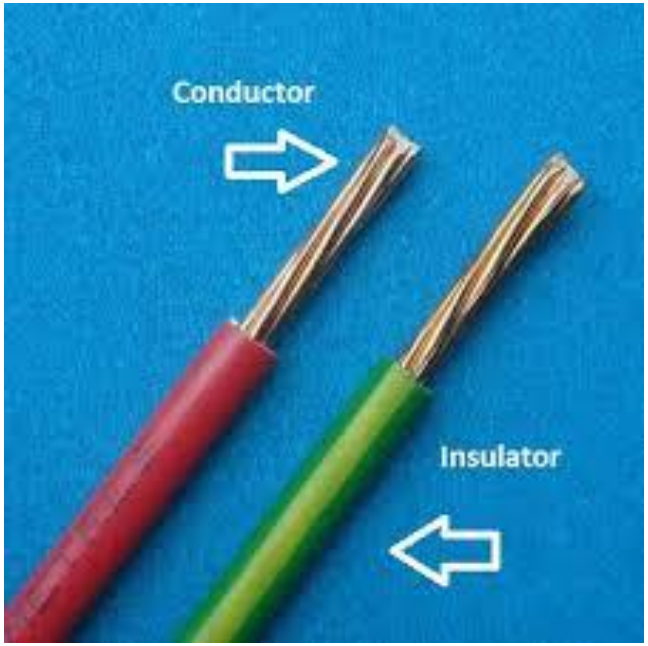
Charge and materials

Conductors and insulators

- A *conductor* permits the easy movement of charge through it. An *insulator* does not.
- Most metals are good conductors, while most nonmetals are insulators. (See Figure 21.6 at the right.)
- *Semiconductors* are intermediate in their properties between good conductors and good insulators.



Insulators



Conductors and insulators

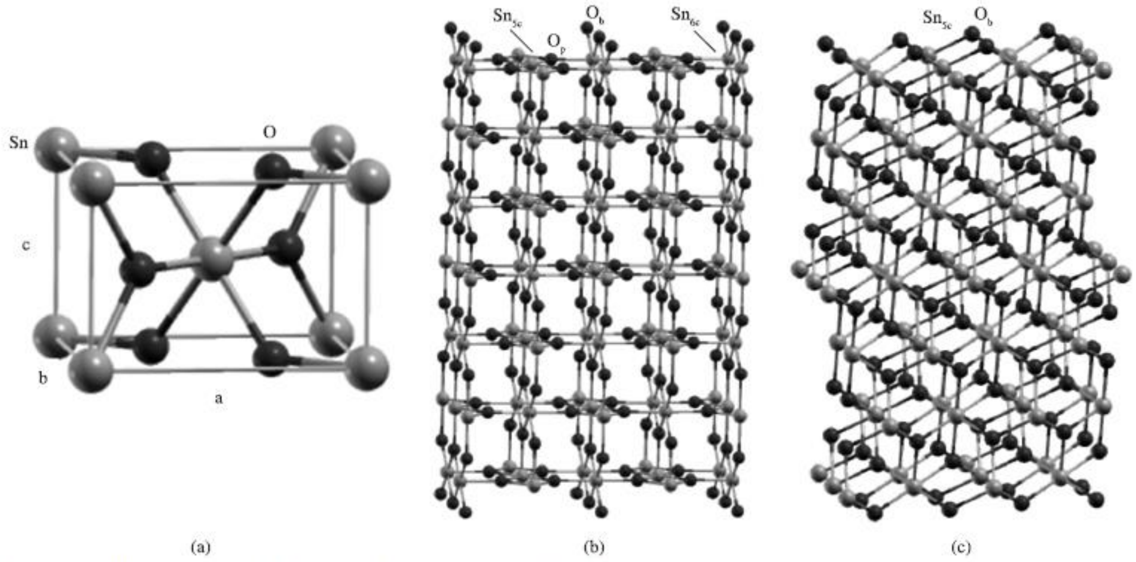
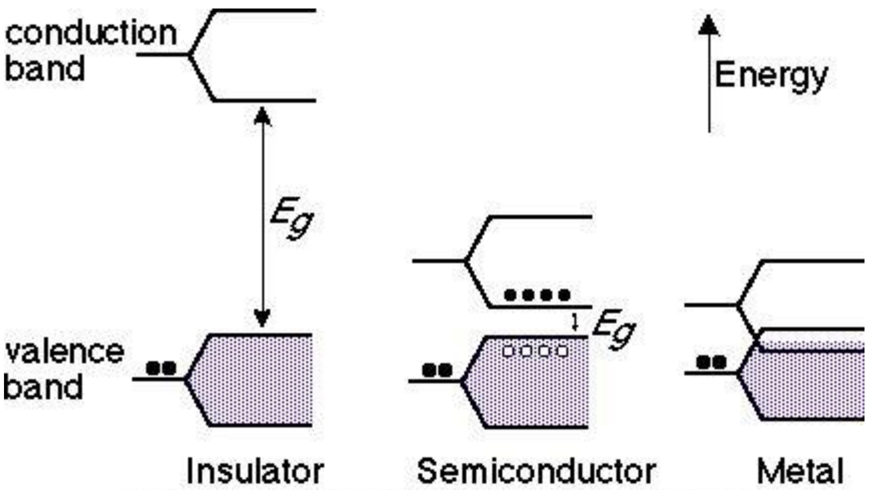


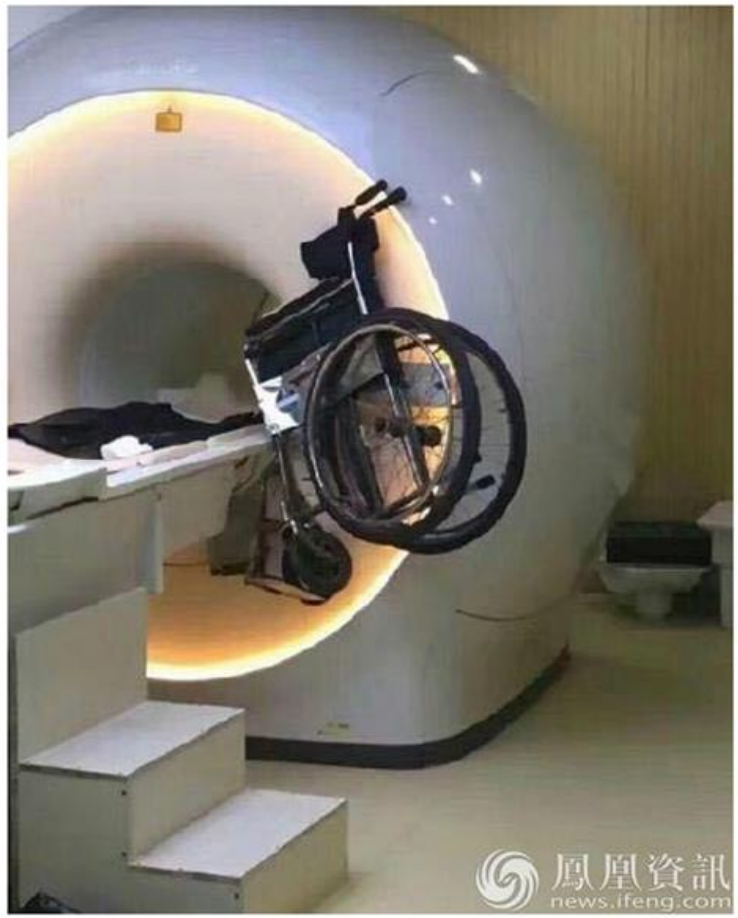
Figure 1. a) Rutile tetragonal unit cell; b) (110) surface structure; and c) (101) surface structure.



Superconductor

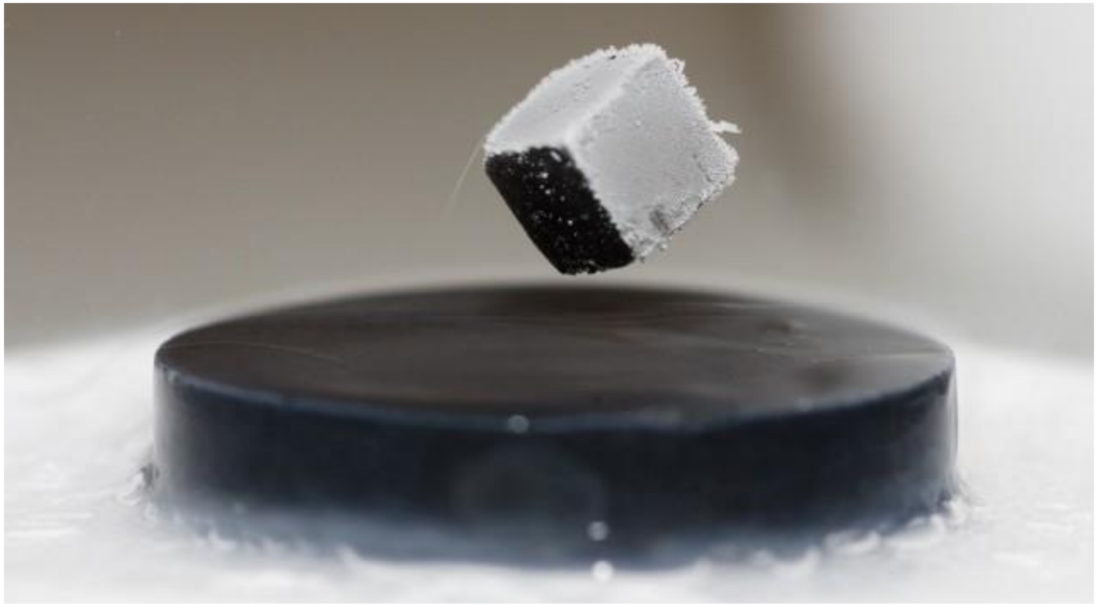
上海肺科医院核磁共振室惊人一幕：家属不听劝告把轮椅推进医院核磁共振房间被“亲吻”【3】

作者： 来源：凤凰网 2016年07月06日09:19

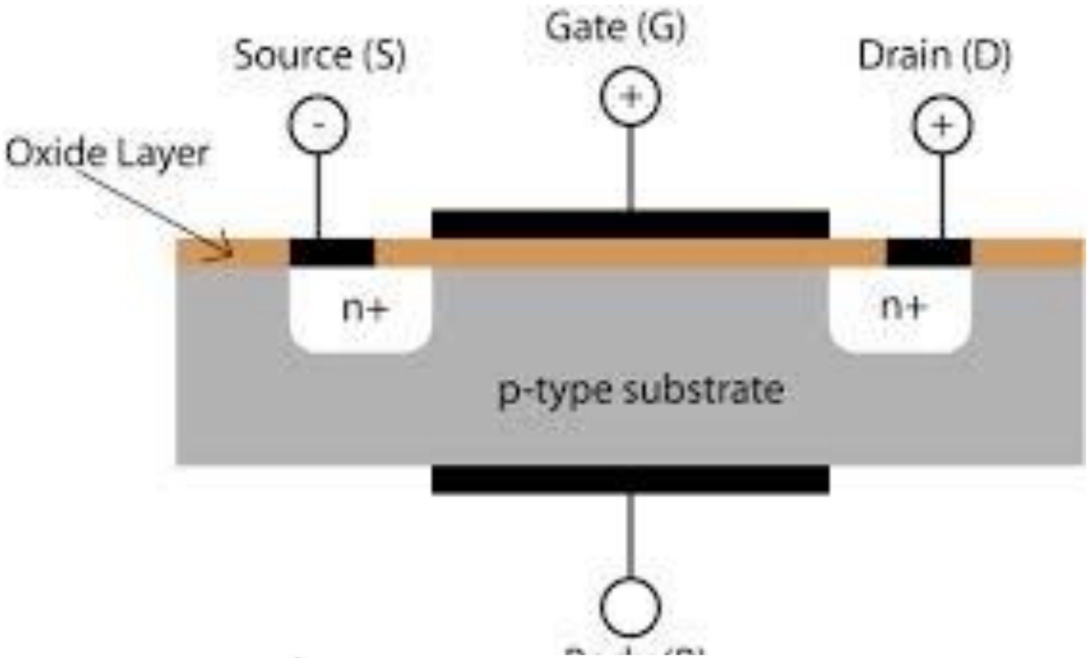


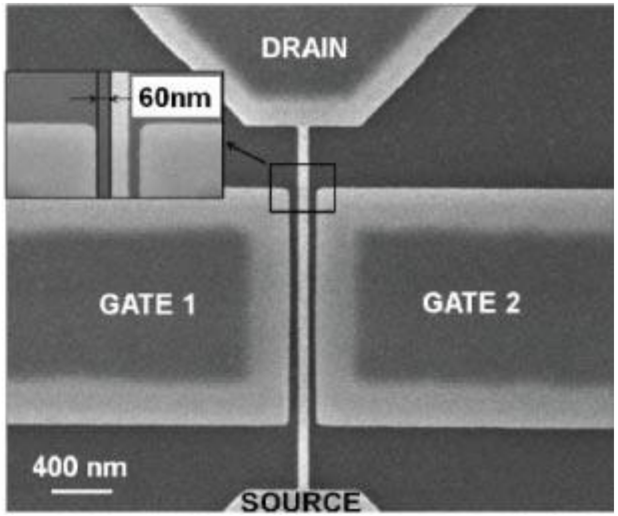
据东方网2016年7月5日报道：昨天，上海肺科医院核磁共振室内发生“惊人一幕”，一台轮椅“亲吻”上了核磁共振仪，网传仪器修理费将达
300万元。不过东方网记者今日获悉，300万元维修费的说法子虚乌有，这台仪器明后天就能继续使用。

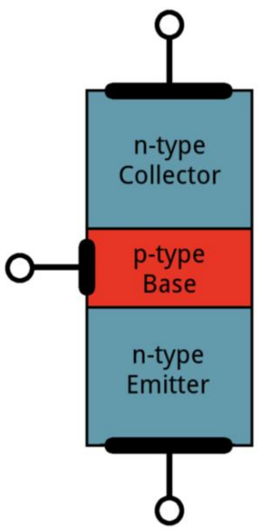
Superconductor

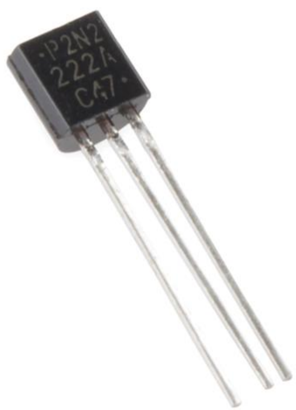


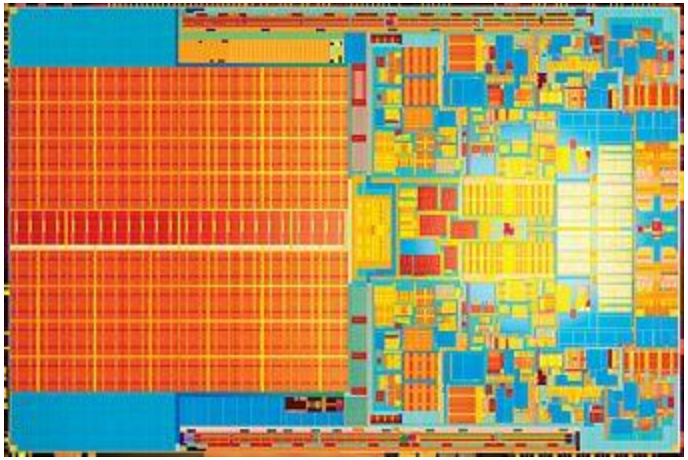
Semiconductor





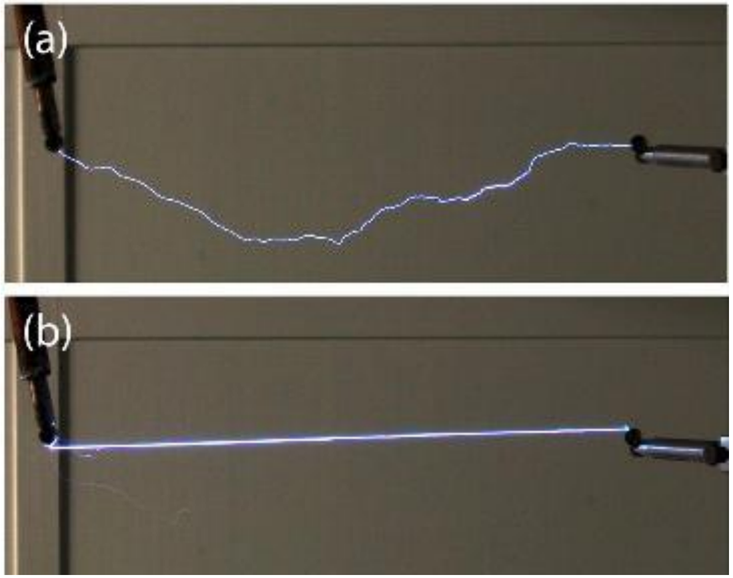


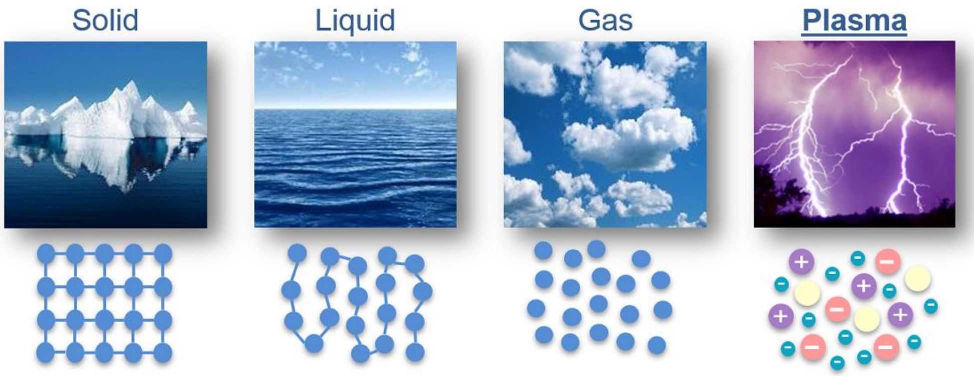




Insulators

Lightning Rod : from insulator to conductor

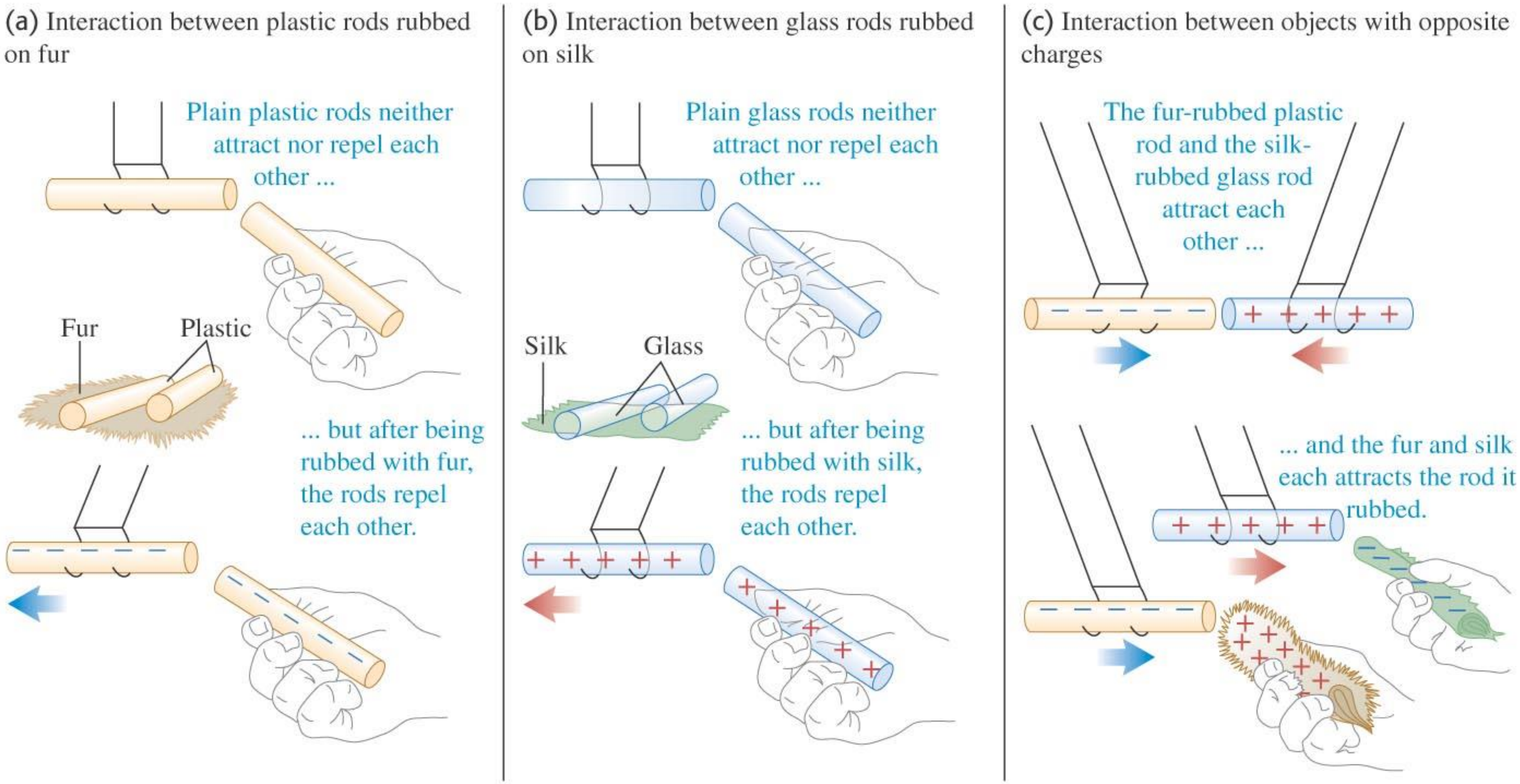




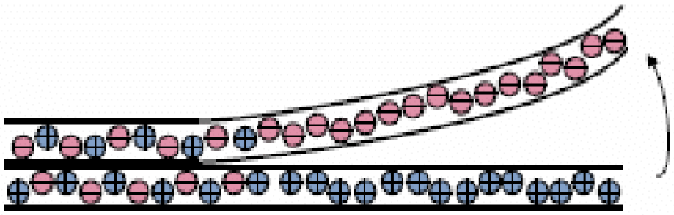
Charging

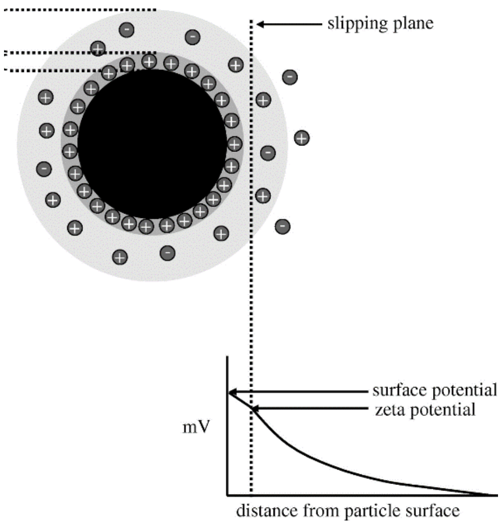
Electric charge: charging by friction

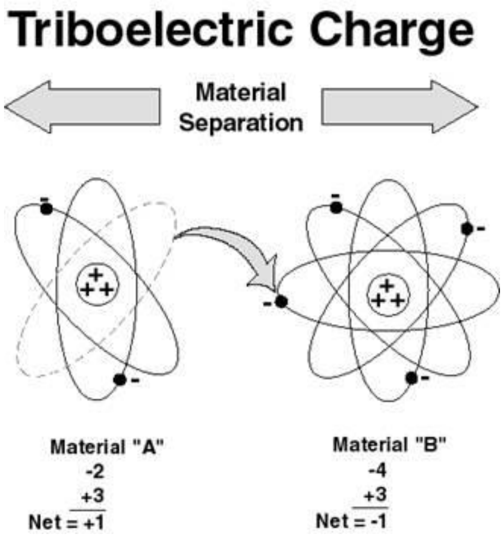
- Two positive or two negative charges repel each other. A positive charge and a negative charge attract each other.
- Figure 21.1 below shows some experiments in *electrostatics*.



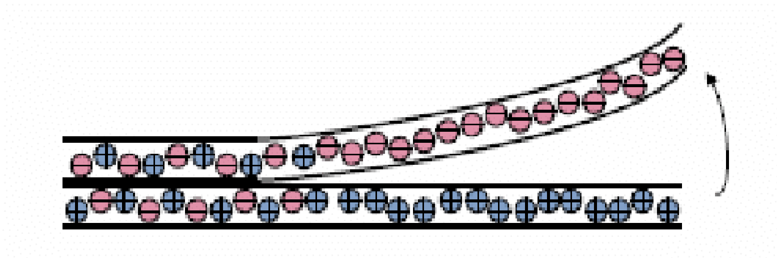
Electric charge: by touching

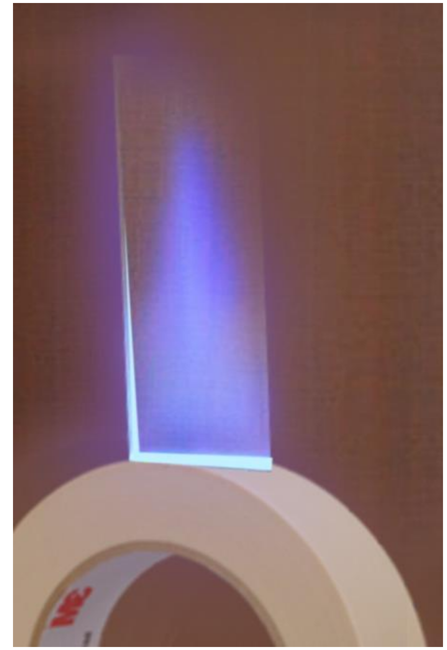


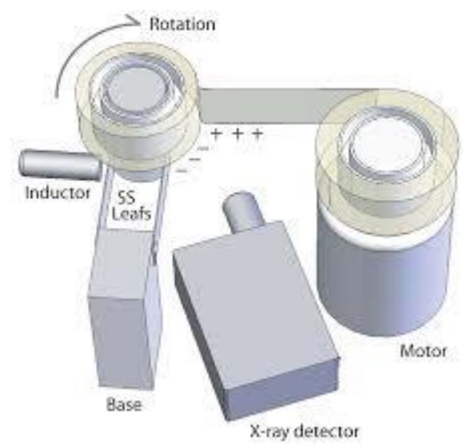




Electric charge: by touching

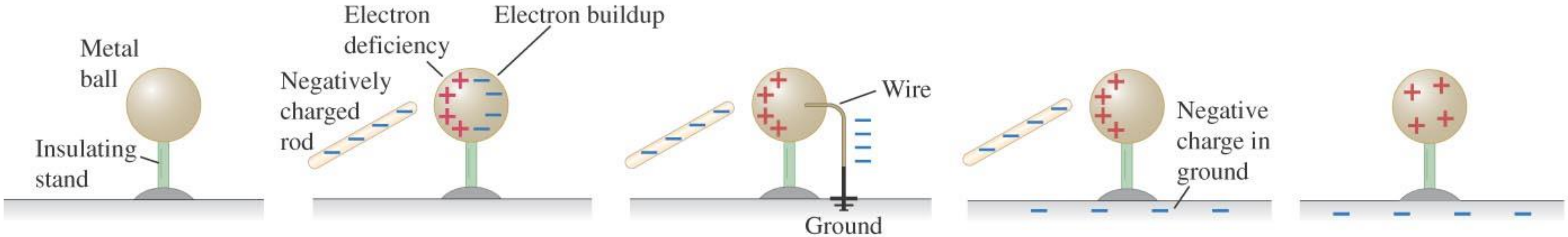






Charging by induction: consequence of force

- In Figure 21.7 below, the negative rod is able to charge the metal ball without losing any of its own charge. This process is called charging by *induction*.



(a) Uncharged metal ball

(b) Negative charge on rod repels electrons, creating zones of negative and positive **induced charge**.

(c) Wire lets electron build-up (induced negative charge) flow into ground.

(d) Wire removed; ball now has only an electron-deficient region of positive charge.

(e) Rod removed; electrons rearrange themselves, ball has overall electron deficiency (net positive charge).

Charging by induction

上 海 交 通 大 学 试 卷 (Paper A)

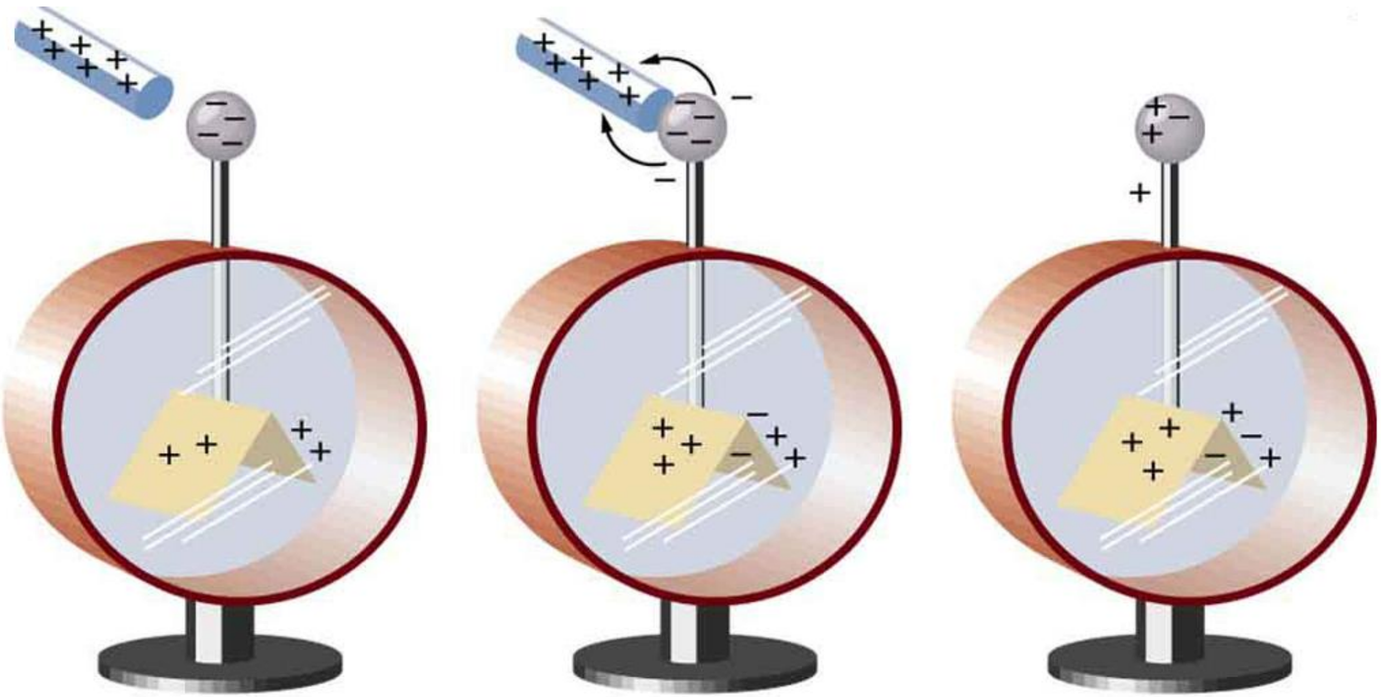
(2015 ~ 2016 Academic Year/ Fall Semester)

Class No. 240 Student No.______________ Name (Chinese) ____________________

Course Title VP240 Physics II __________ Grade ______________

1. (15%) An electroscope can measure the magnitude of electric charge on a body, even without touching, please explain the situation shown below: a positive charged rod is approaching the electroscope (without touching), two metallic thin films, connected to the top metal ball by a conducting rod, start to spread out. Draw a figure if necessary.

Charging by induction



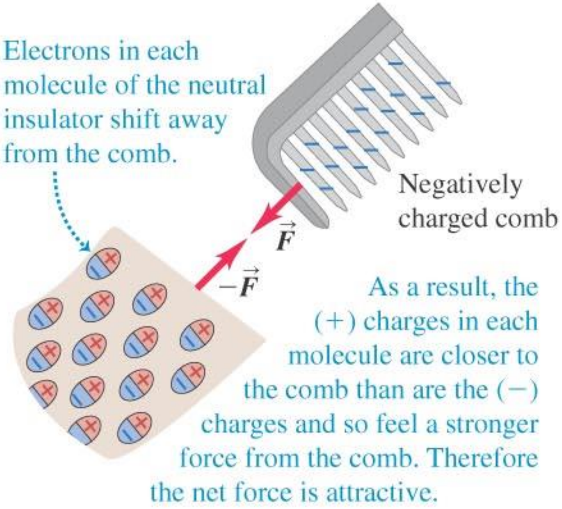
(a) (b) (c)

Electric forces on uncharged objects

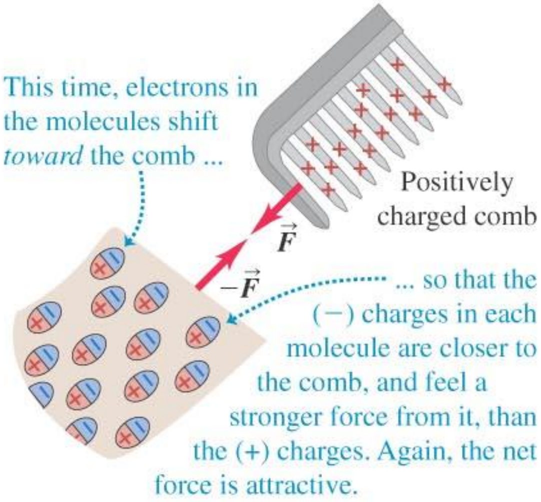
- The charge within an insulator can shift slightly. As a result, two neutral objects can exert electric forces on each other, as shown in Figure 21.8 below.

(a) A charged comb picking up uncharged pieces of plastic

(b) How a negatively charged comb attracts an insulator

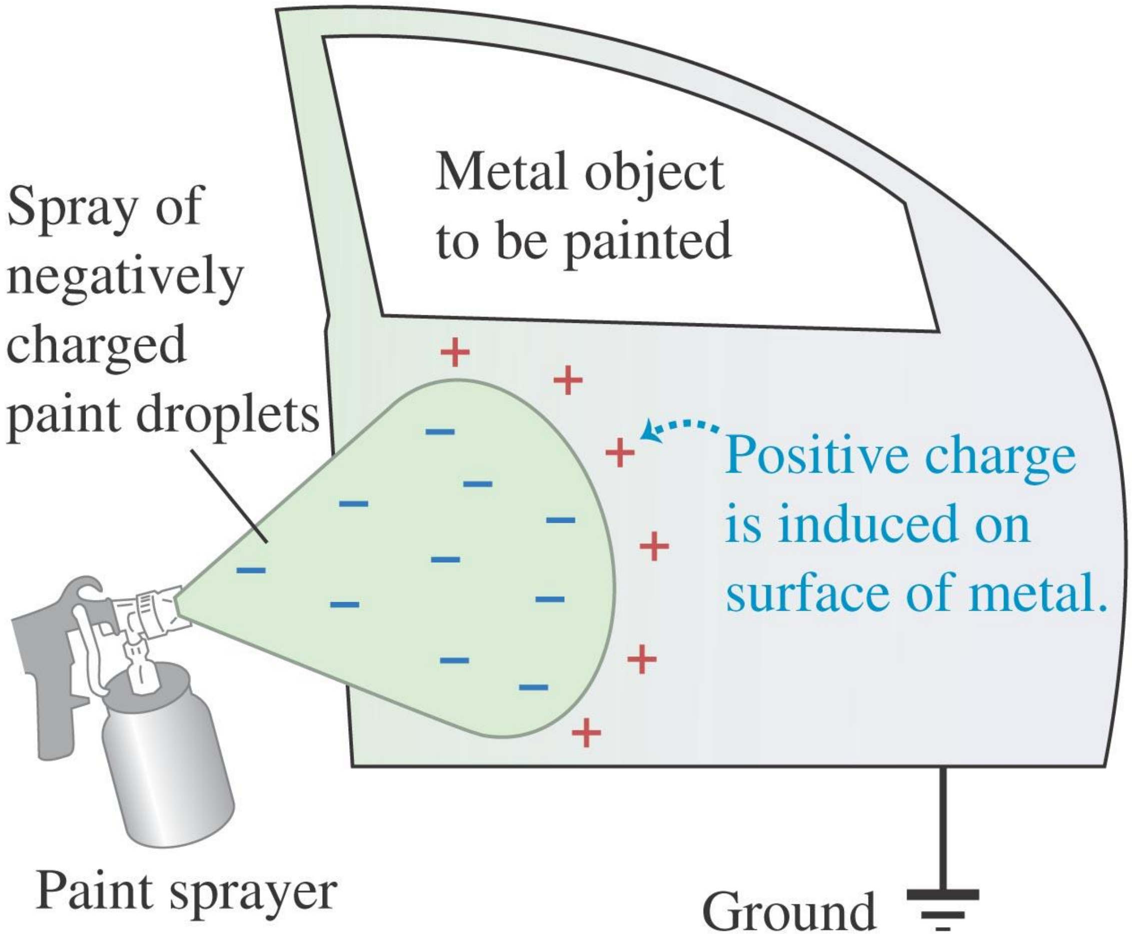


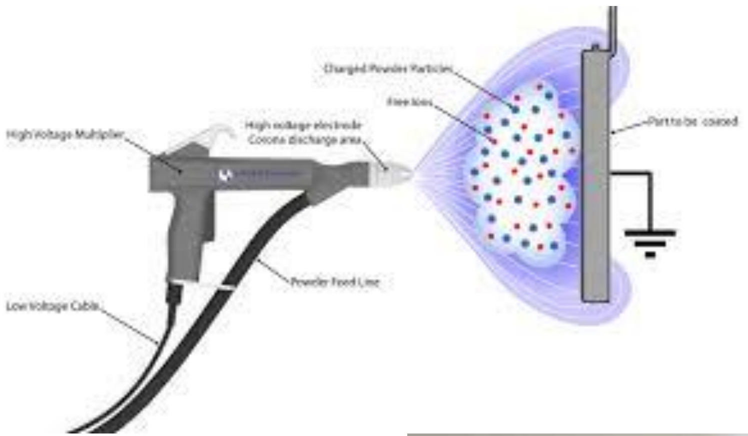
(c) How a positively charged comb attracts an insulator

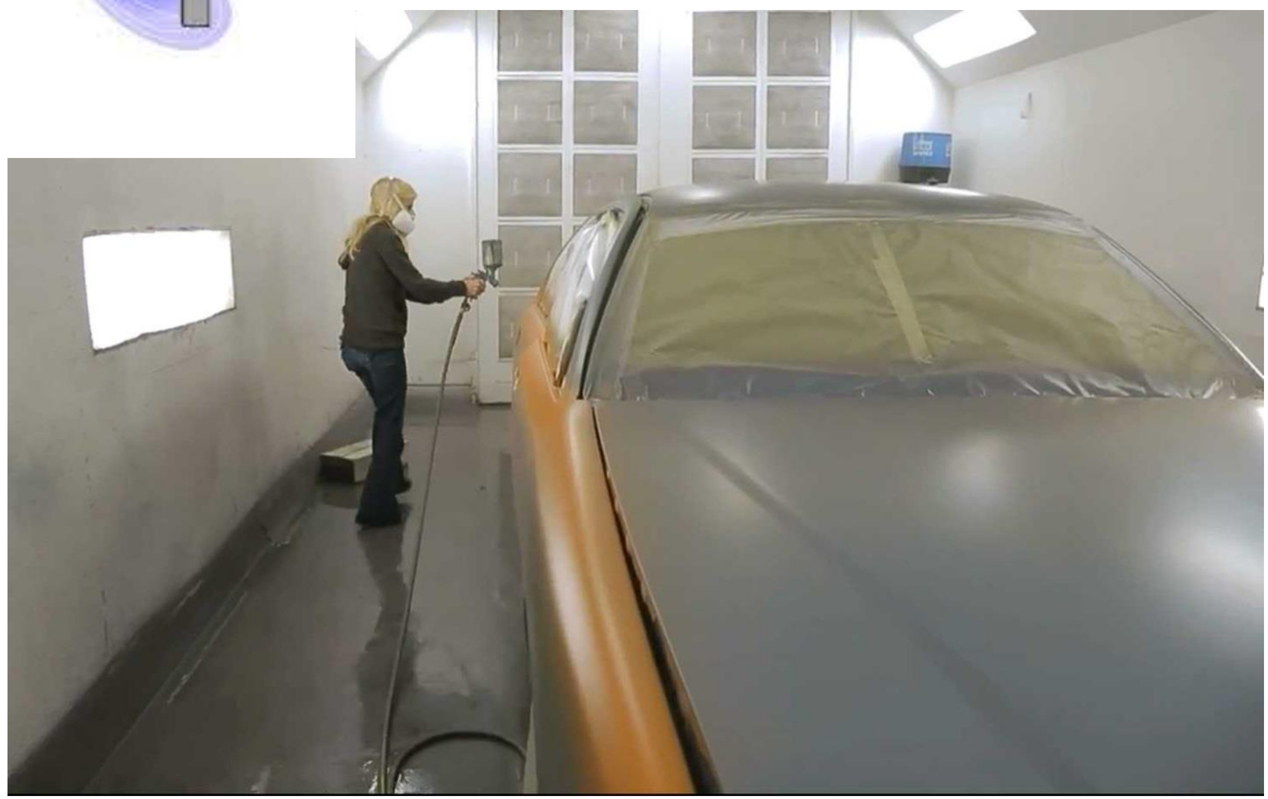


Electrostatic painting

- Induced positive charge on the metal object attracts the negatively charged paint droplets.

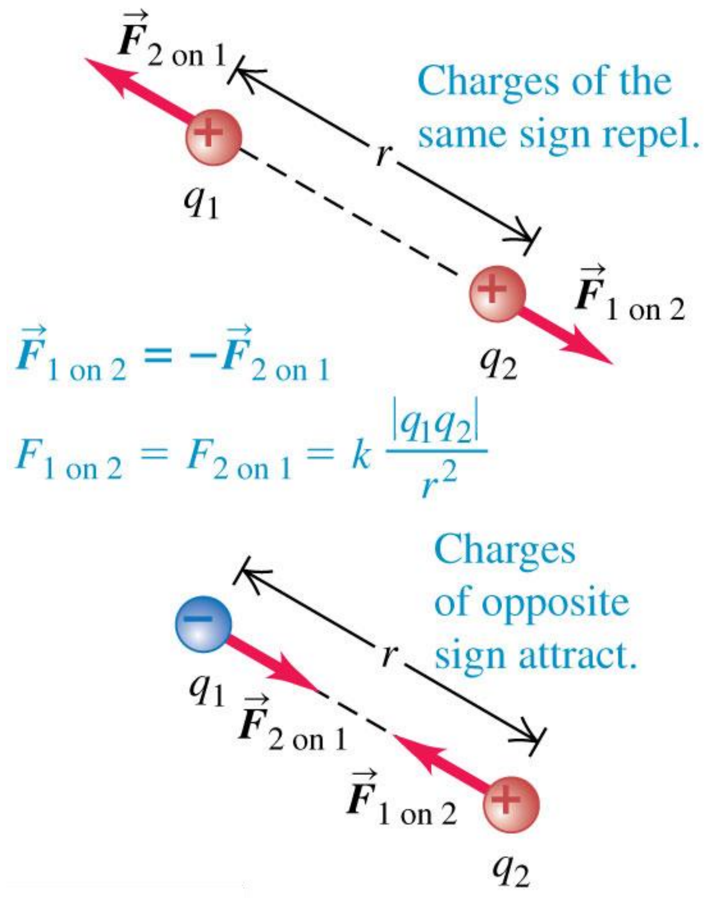



High Voltage Multiplier
High voltage electrode
Corona discharge area
Charged Powder Particles
Free Ions
Part to be coated
Powder Feed Line
Low Voltage Cable



Coulomb's law

- *Coulomb's Law*: The magnitude of the electric force between two point charges is directly proportional to the product of their charges and inversely proportional to the square of the distance between them. (See the figure at the right.)

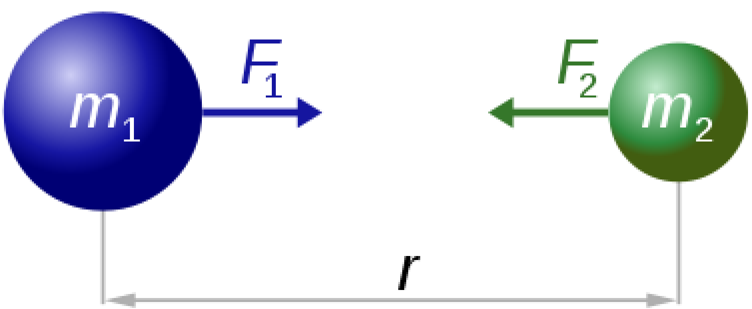


- Mathematically:
  $F = k|q_1 q_2|/r^2 = (1/4\pi\varepsilon_0)|q_1 q_2|/r^2$

Familiar ?

Newton's Law

Newton's Law Coulomb's law



$$F_1 = F_2 = G\frac{m_1 \times m_2}{r^2}$$

Coulomb's law

$$F = k|q_1 q_2|/r^2$$

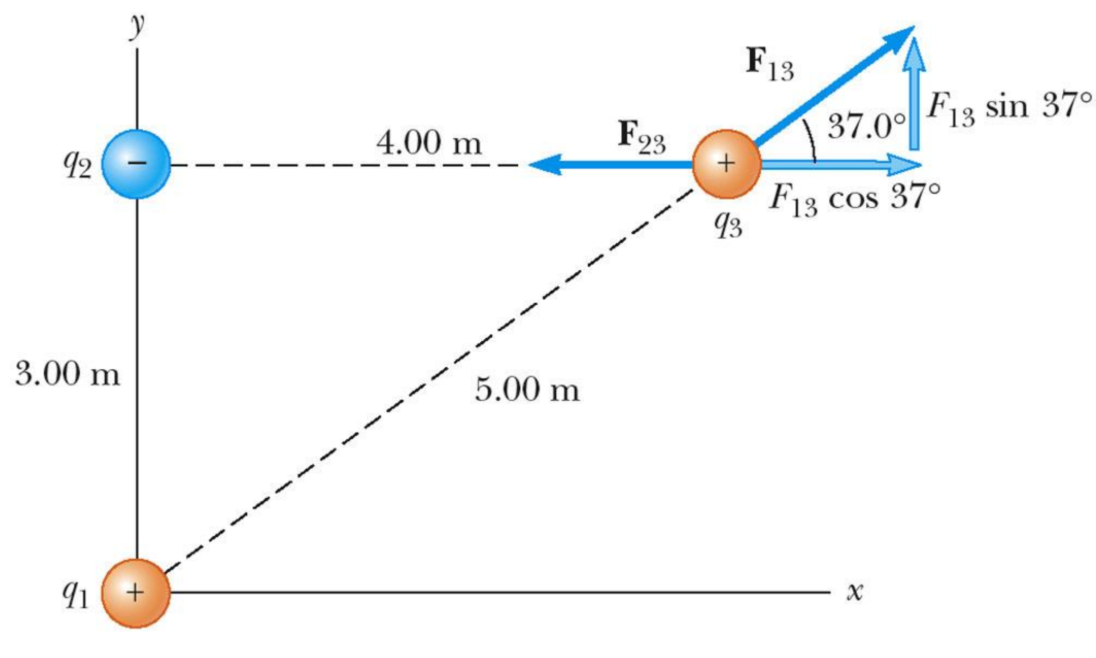
The Superposition Principle

The resultant force on any one charge equals the vector sum of the forces exerted by the other individual charges that are present.

- Remember to add the forces as *vectors*

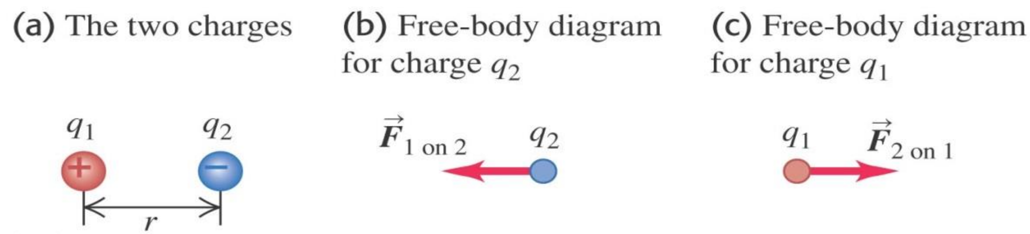
Superposition Principle Example

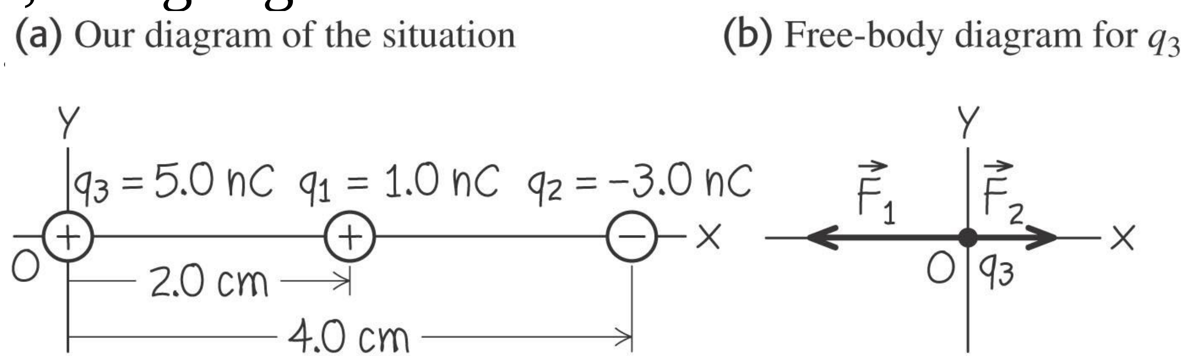
- The force exerted by q_1 on q_3 is $\vec{\mathbf{F}}_{13}$
- The force exerted by q_2 on q_3 is $\vec{\mathbf{F}}_{23}$
- The *total force* exerted on q_3 is the vector sum of $\vec{\mathbf{F}}_{13}$ and $\vec{\mathbf{F}}_{23}$



Force between charges along a line

- Read Problem-Solving Strategy 21.1.
- two charges, using Figure 21.12 at the right.
- Follow Example 21.3 for three charges, using Figure 21.13 below.





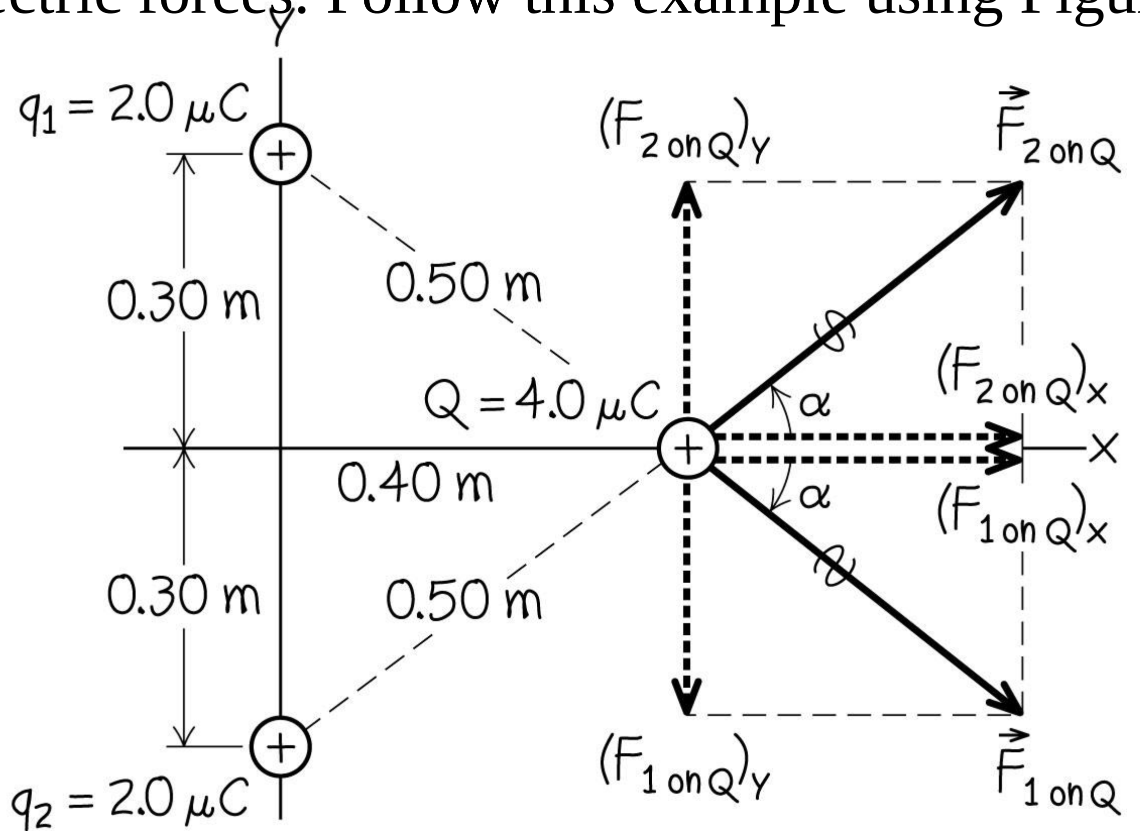
$$F_{1 \text{ on } 3} = \frac{1}{4\pi\epsilon_0}\frac{|q_1 q_3|}{r^2}$$
$$= (9.0 \times 10^9\ \text{N}\cdot\text{m}^2/\text{C}^2)\frac{(1.0 \times 10^{-9}\ \text{C})(5.0 \times 10^{-9}\ \text{C})}{(0.020\ \text{m})^2}$$
$$= 1.12 \times 10^{-4}\ \text{N} = 112\ \mu\text{N}$$

$$F_{2 \text{ on } 3} = \frac{1}{4\pi\epsilon_0}\frac{|q_2 q_3|}{r^2}$$
$$= (9.0 \times 10^9\ \text{N}\cdot\text{m}^2/\text{C}^2)\frac{(3.0 \times 10^{-9}\ \text{C})(5.0 \times 10^{-9}\ \text{C})}{(0.040\ \text{m})^2}$$
$$= 8.4 \times 10^{-5}\ \text{N} = 84\ \mu\text{N}$$

$$F_x = -112\ \mu\text{N} + 84\ \mu\text{N} = -28\ \mu\text{N}$$

Vector addition of electric forces

- Example 21.4 shows that we must use vector addition when adding electric forces. Follow this example using Figure 21.14 below.



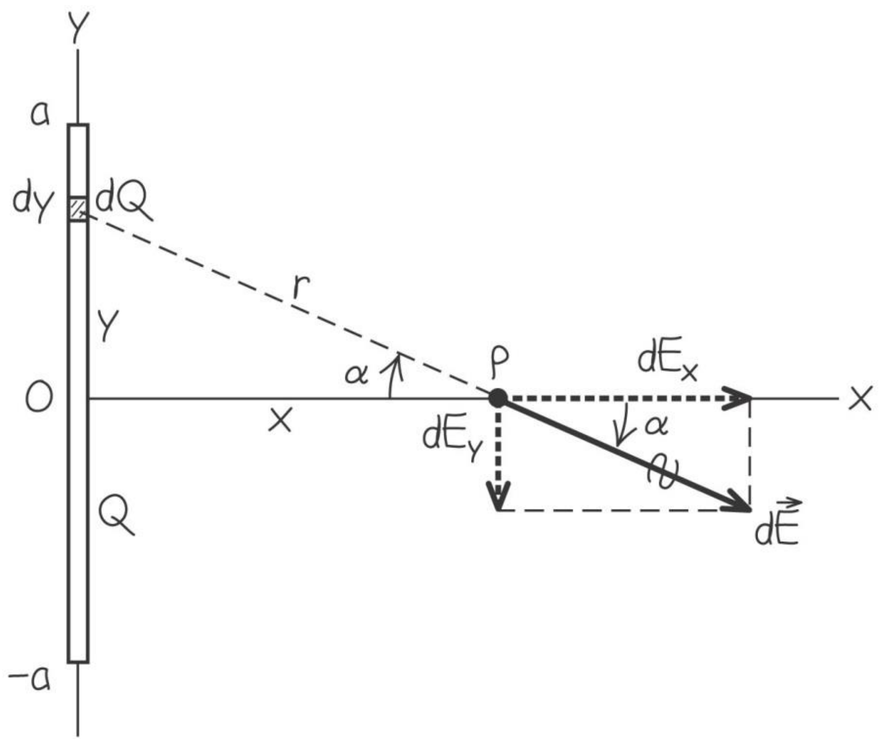
$$F_{1\text{ or }2\text{ on }Q} = (9.0 \times 10^9\ \mathrm{N \cdot m^2/C^2}) \times \frac{(4.0 \times 10^{-6}\ \mathrm{C})(2.0 \times 10^{-6}\ \mathrm{C})}{(0.50\ \mathrm{m})^2} = 0.29\ \mathrm{N}$$

The x-components of the two forces are equal:

$$(F_{1\text{ or }2\text{ on }Q})_x = (F_{1\text{ or }2\text{ on }Q})\cos\alpha = (0.29\ \mathrm{N})\frac{0.40\ \mathrm{m}}{0.50\ \mathrm{m}} = 0.23\ \mathrm{N}$$

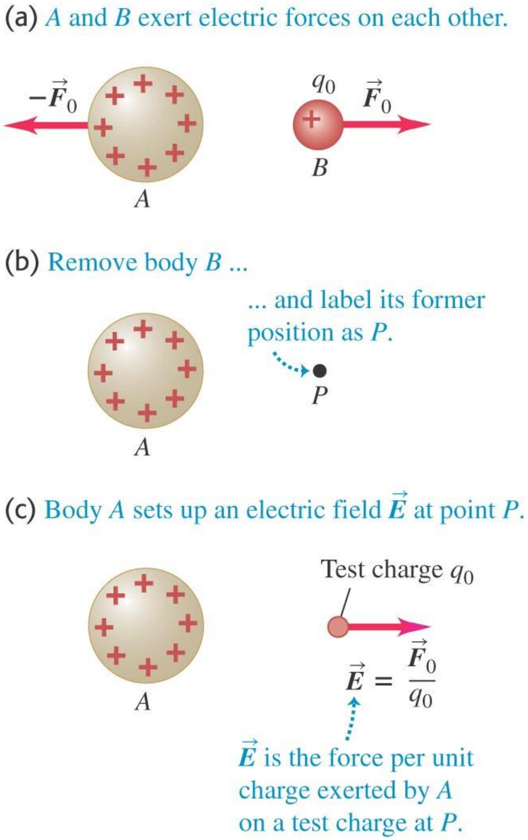
Field of a charged line segment

- Follow Example 21.10 and Figure 21.24 below.



Electric field

- A charged body produces an *electric field* in the space around it (see Figure 21.15 at the lower left).
- We use a small *test charge* q_0 to find out if an electric field is present (see Figure 21.16 at the lower right).



Electric field

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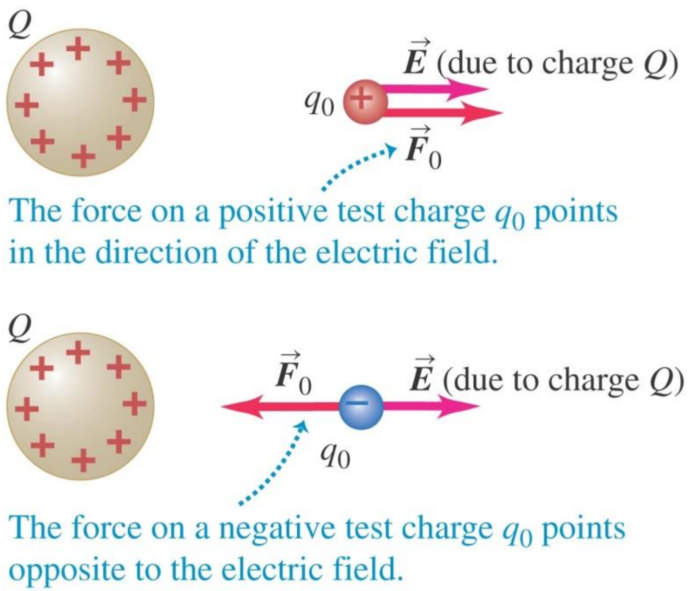
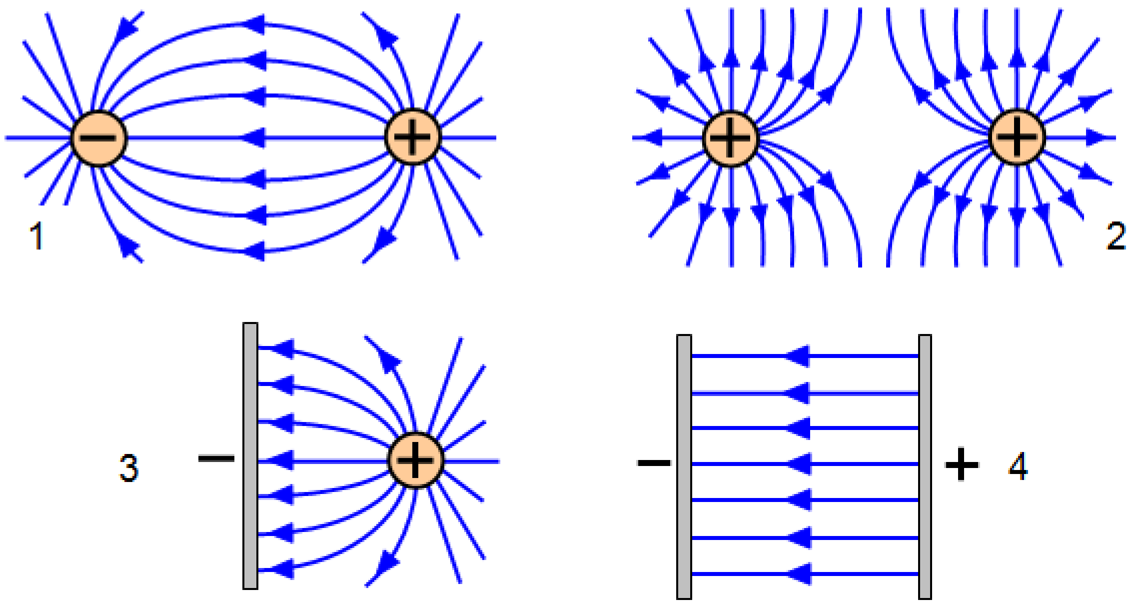


$$\vec{E} = \frac{\vec{F}_0}{q_0}$$ (definition of electric field as electric force per unit charge)

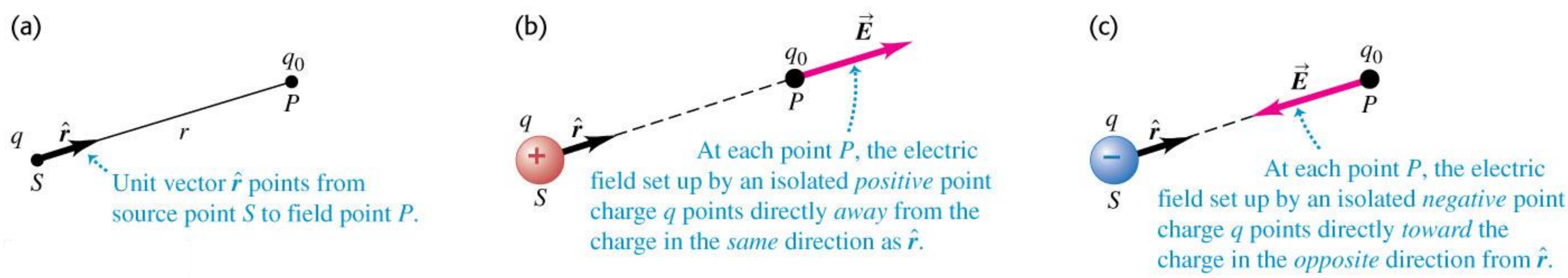
Electric field

- A charged body produces an *electric field* in the space around it (see Figure 21.15 at the lower left).
- We use a small *test charge* q_0 to find out if an electric field is present (see Figure 21.16 at the lower right).



Definition of the electric field

- Follow the definition in the text of the electric field using Figure 21.17 below.



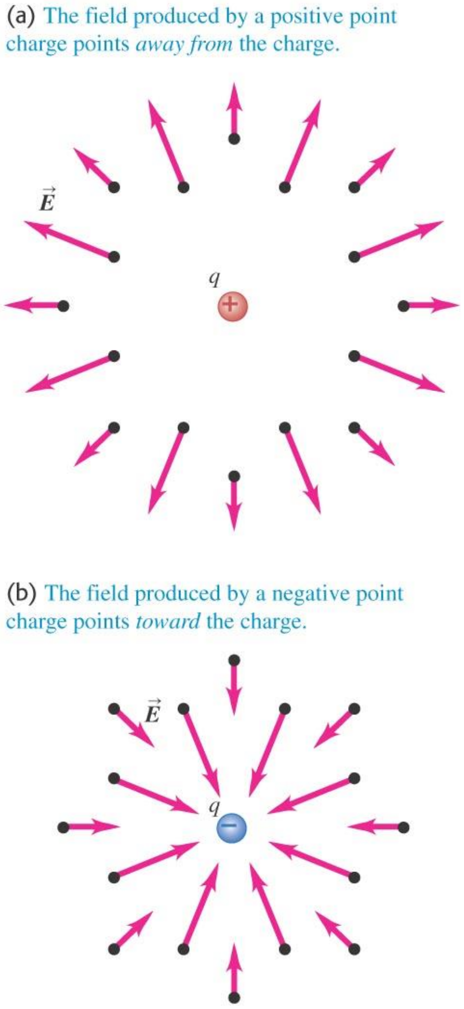
$$F_0 = \frac{1}{4\pi\epsilon_0}\frac{|qq_0|}{r^2}$$

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

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

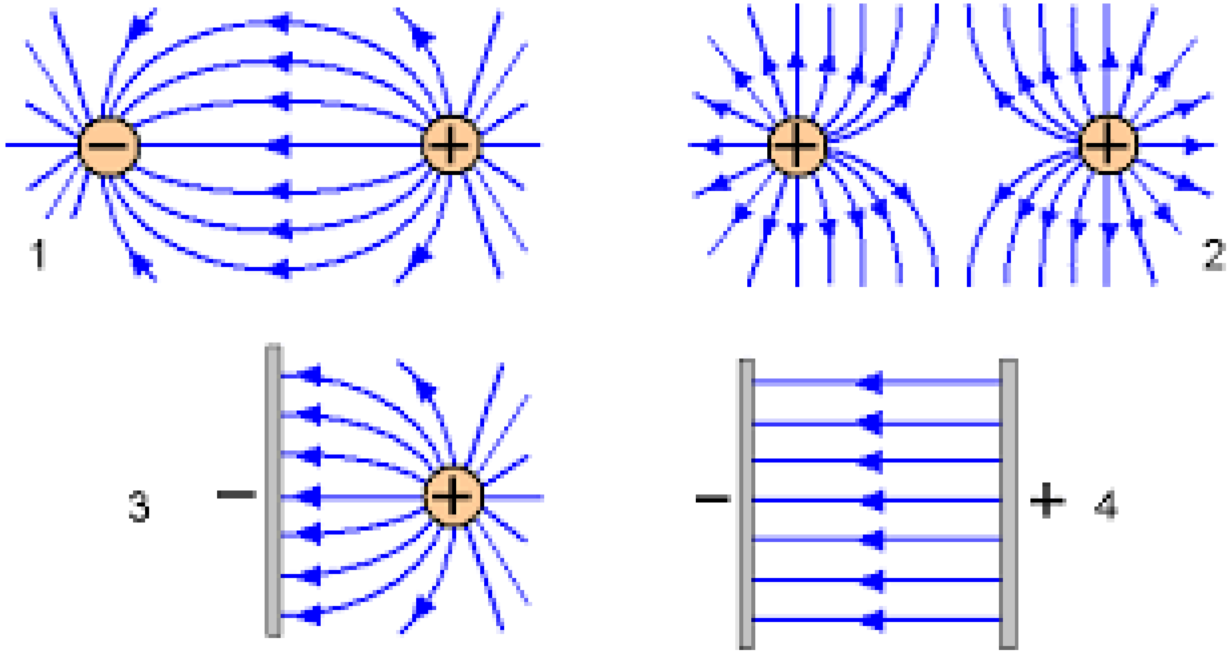
Electric field of a point charge

- Follow the discussion in the text of the electric field of a point charge, using Figure 21.18 at the right.
- Follow Example 21.5 to calculate the magnitude of the electric field of a single point charge.



$$\vec{E} = \frac{1}{4\pi\epsilon_0}\frac{q}{r^2}\hat{r} \qquad \text{(electric field of a point charge)} \qquad (21.7)$$

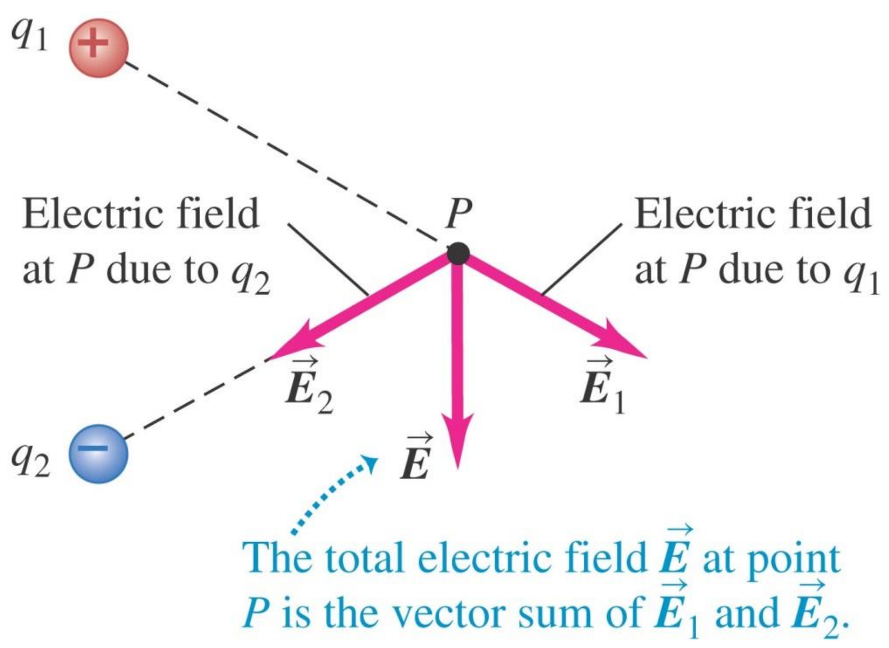
Electric field: typical distribution



http://www.falstad.com/emstatic/index.html

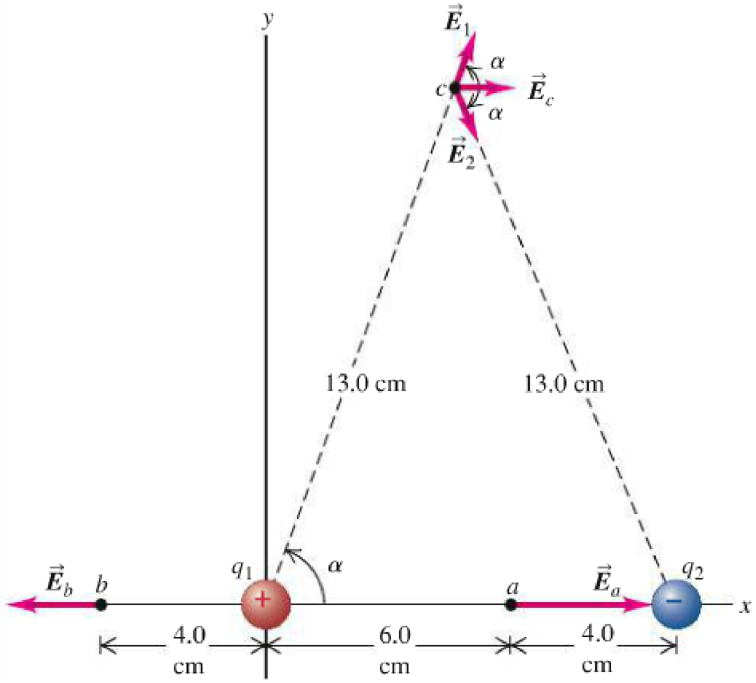
Superposition of electric fields

- The total electric field at a point is the vector sum of the fields due to all the charges present. (See Figure 21.21 below right.)
- Review Problem-Solving Strategy 21.2.
- Follow Example 21.8 for an electric dipole. Use Figure 21.22 below.



Superposition of electric fields

21.22 Electric field at three points, a, b, and c, set up by charges q_1 and q_2, which form an electric dipole.



(a) At a, $\vec{E}_{1a}$ and $\vec{E}_{2a}$ are both directed to the right, so

$$\vec{E}_a = E_{1a}\hat{\imath} + E_{2a}\hat{\imath} = (9.8 \times 10^4\ \text{N/C})\hat{\imath}$$

(b) At b, $\vec{E}_{1b}$ is directed to the left and $\vec{E}_{2b}$ is directed to the right, so

$$\vec{E}_b = -E_{1b}\hat{\imath} + E_{2b}\hat{\imath} = (-6.2 \times 10^4\ \text{N/C})\hat{\imath}$$

(c) Figure 21.22 shows the directions of $\vec{E}_1$ and $\vec{E}_2$ at c. Both vectors have the same x-component:

$$E_{1cx} = E_{2cx} = E_{1c}\cos\alpha = (6.39 \times 10^3\ \text{N/C})\left(\tfrac{5}{13}\right)$$
$$= 2.46 \times 10^3\ \text{N/C}$$

From symmetry, E_{1y} and E_{2y} are equal and opposite, so their sum is zero. Hence

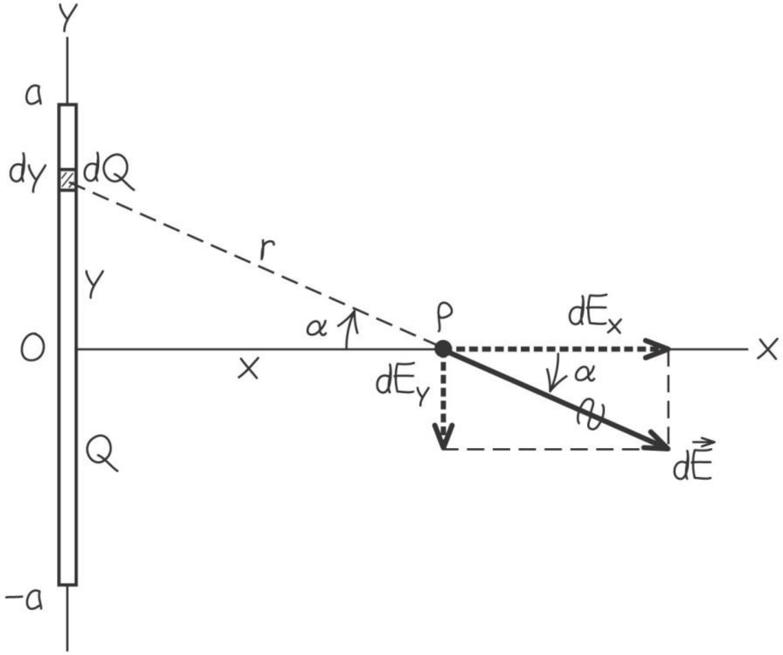
$$\vec{E}_c = 2(2.46 \times 10^3\ \text{N/C})\hat{\imath} = (4.9 \times 10^3\ \text{N/C})\hat{\imath}$$

EVALUATE: We can also find $\vec{E}_c$ using Eq. (21.7) for the field of a point charge. The displacement vector $\vec{r}_1$ from q_1 to point c is $\vec{r}_1 = r\cos\alpha\,\hat{\imath} + r\sin\alpha\,\hat{\jmath}$. Hence the unit vector that points from q_1 to point c is $\hat{r}_1 = \vec{r}_1/r = \cos\alpha\,\hat{\imath} + \sin\alpha\,\hat{\jmath}$. By symmetry, the unit vector that points from q_2 to point c has the opposite x-component but the same y-component: $\hat{r}_2 = -\cos\alpha\,\hat{\imath} + \sin\alpha\,\hat{\jmath}$. We can now use Eq. (21.7) to write the fields $\vec{E}_{1c}$ and $\vec{E}_{2c}$ at c in vector form, then find their sum. Since $q_2 = -q_1$ and the distance r to c is the same for both charges,

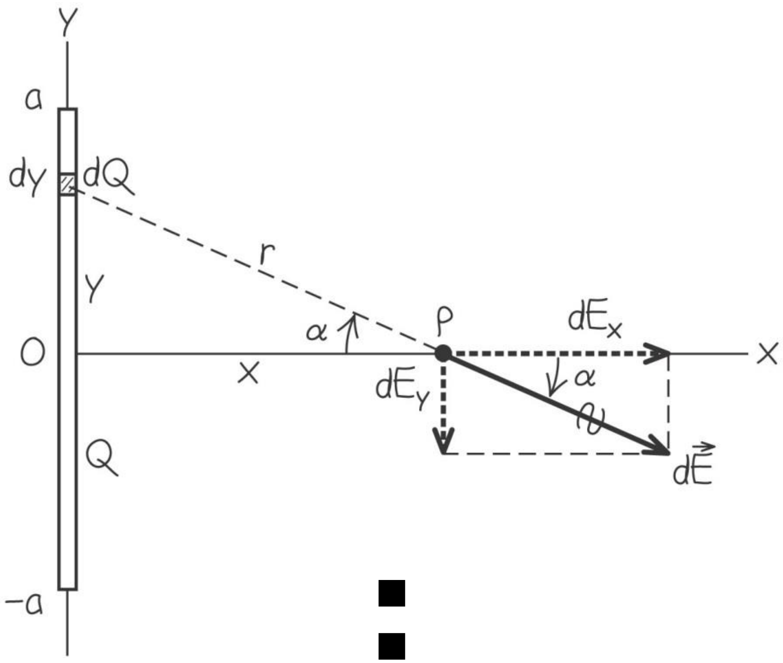
$$\vec{E}_c = \vec{E}_{1c} + \vec{E}_{2c} = \frac{1}{4\pi\epsilon_0}\frac{q_1}{r^2}\hat{r}_1 + \frac{1}{4\pi\epsilon_0}\frac{q_2}{r^2}\hat{r}_2$$
$$= \frac{1}{4\pi\epsilon_0 r^2}(q_1\hat{r}_1 + q_2\hat{r}_2) = \frac{q_1}{4\pi\epsilon_0 r^2}(\hat{r}_1 - \hat{r}_2)$$
$$= \frac{1}{4\pi\epsilon_0}\frac{q_1}{r^2}(2\cos\alpha\,\hat{\imath})$$
$$= 2(9.0 \times 10^9\ \text{N}\cdot\text{m}^2/\text{C}^2)\frac{12 \times 10^{-9}\ \text{C}}{(0.13\ \text{m})^2}\left(\tfrac{5}{13}\right)\hat{\imath}$$
$$= (4.9 \times 10^3\ \text{N/C})\hat{\imath}$$

This is the same as we calculated in part (c).

Field of a charged line segment: Dividing



Field of a charged line segment: Dividing

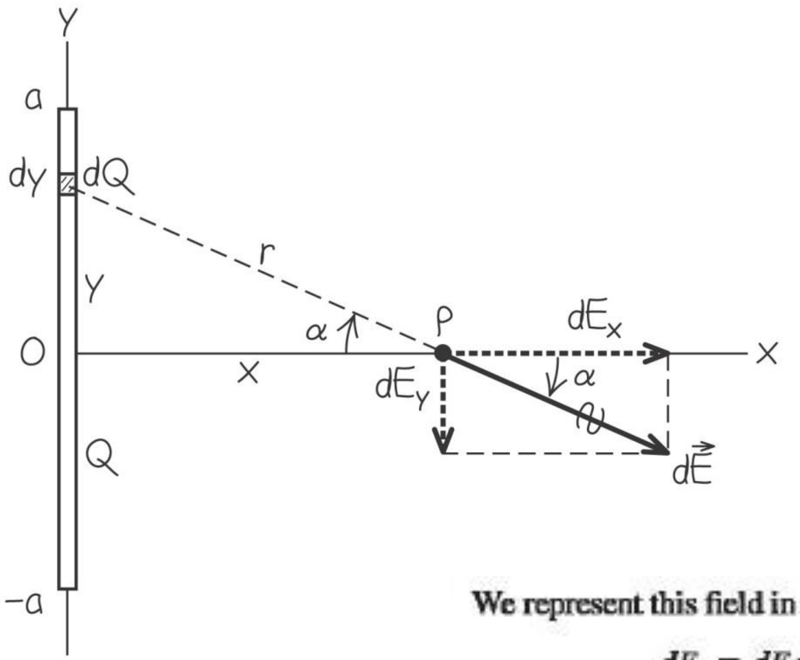


$$dQ = \lambda dy = \frac{Q\,dy}{2a}$$

The distance r from this segment to P is $(x^2 + y^2)^{1/2}$, so the magnitude of field dE at P due to this segment is

$$dE = \frac{1}{4\pi\epsilon_0}\frac{dQ}{r^2} = \frac{Q}{4\pi\epsilon_0}\frac{dy}{2a(x^2 + y^2)}$$

Field of a charged line segment: decomposing



We represent this field in terms of its x- and y-components:

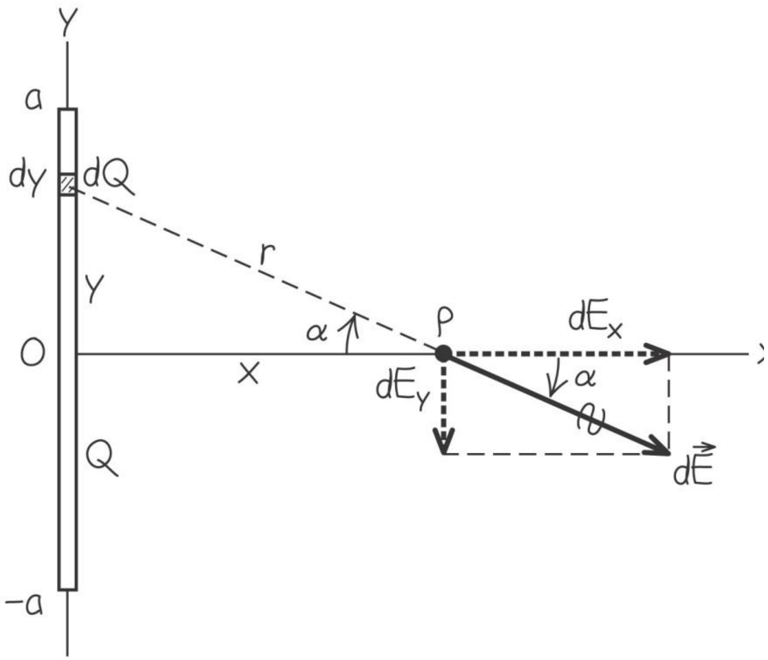
$$dE_x = dE\cos\alpha \qquad dE_y = -dE\sin\alpha$$

We note that $\sin\alpha = y/(x^2+y^2)^{1/2}$ and $\cos\alpha = x/(x^2+y^2)^{1/2}$; combining these with the expression for dE, we find

$$dE_x = \frac{Q}{4\pi\epsilon_0}\frac{x\,dy}{2a(x^2+y^2)^{3/2}}$$

$$dE_y = -\frac{Q}{4\pi\epsilon_0}\frac{y\,dy}{2a(x^2+y^2)^{3/2}}$$

Field of a charged line segment : summing



To find the total field components E_x and E_y, we integrate these expressions, noting that to include all of Q, we must integrate from $y = -a$ to $y = +a$. We invite you to work out the details of the integration; an integral table is helpful. The final results are

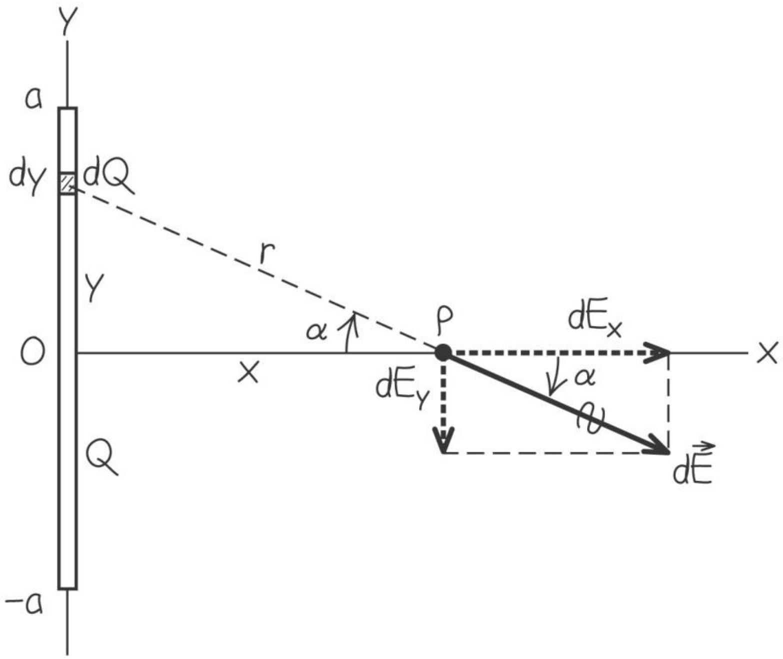
$$E_x = \frac{1}{4\pi\epsilon_0}\frac{Qx}{2a}\int_{-a}^{a}\frac{dy}{(x^2+y^2)^{3/2}} = \frac{Q}{4\pi\epsilon_0}\frac{1}{x\sqrt{x^2+a^2}}$$

$$E_y = -\frac{1}{4\pi\epsilon_0}\frac{Q}{2a}\int_{-a}^{a}\frac{y\,dy}{(x^2+y^2)^{3/2}} = 0$$

or, in vector form,

$$\vec{E} = \frac{1}{4\pi\epsilon_0}\frac{Q}{x\sqrt{x^2+a^2}}\hat{\imath} \qquad (21.9)$$

Field of a charged line segment

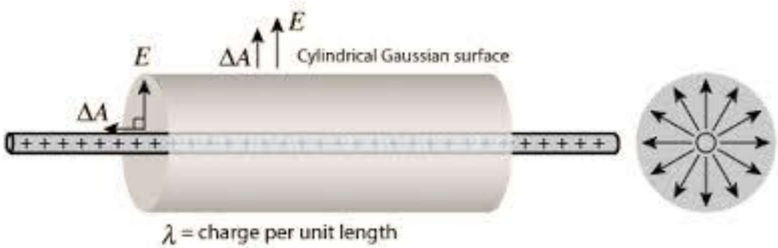


$$\vec{E} = \frac{1}{4\pi\epsilon_0}\frac{Q}{x\sqrt{x^2+a^2}}\hat{\imath}$$

$x \gg a,$ $$\vec{E} = \frac{1}{4\pi\epsilon_0}\frac{Q}{x^2}\hat{\imath}$$

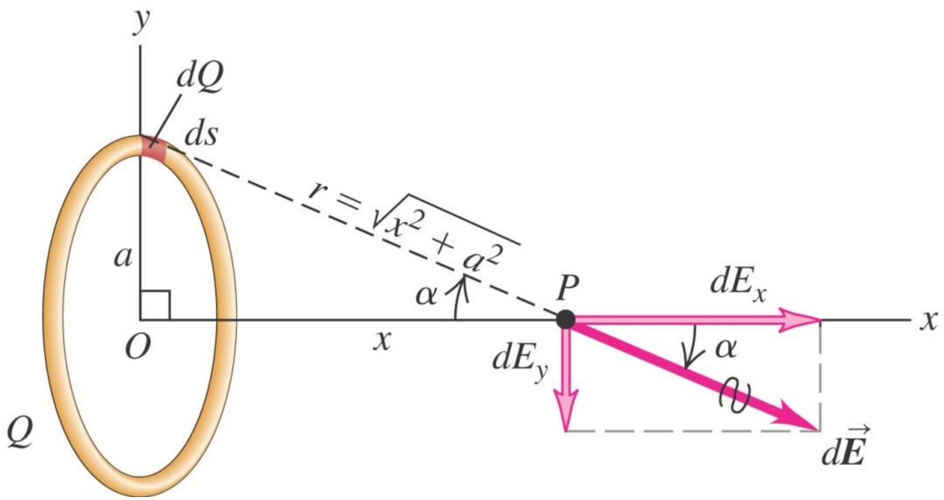
$$\vec{E} = \frac{1}{4\pi\epsilon_0}\frac{q}{r^2}\hat{r} \quad \text{(electric field of a point charge)} \quad (21.7)$$

the linear charge density $\lambda = Q/2a$.



$a \gg x$ $$\vec{E} = \frac{1}{2\pi\epsilon_0}\frac{\lambda}{x\sqrt{(x^2/a^2)+1}}\hat{\imath} \qquad \vec{E} = \frac{\lambda}{2\pi\epsilon_0 x}\hat{\imath}$$

Field of a ring of charge



To calculate E_x, note that the square of the distance r from a ring segment to the point P is $r^2 = x^2 + a^2$. Hence the magnitude of this segment's contribution $d\vec{E}$ to the electric field at P is

$$dE = \frac{1}{4\pi\epsilon_0}\frac{dQ}{x^2 + a^2}$$

Using $\cos\alpha = x/r = x/(x^2 + a^2)^{1/2}$, the x-component dE_x of this field is

$$dE_x = dE\cos\alpha = \frac{1}{4\pi\epsilon_0}\frac{dQ}{x^2 + a^2}\frac{x}{\sqrt{x^2 + a^2}} = \frac{1}{4\pi\epsilon_0}\frac{x\,dQ}{(x^2 + a^2)^{3/2}}$$

To find the *total* x-component E_x of the field at P, we integrate this expression over all segments of the ring:

$$E_x = \int \frac{1}{4\pi\epsilon_0}\frac{x\,dQ}{(x^2 + a^2)^{3/2}}$$

Since x does not vary as we move from point to point around the ring, all the factors on the right side except dQ are constant and can be taken outside the integral. The integral of dQ is just the total charge Q, and we finally get

$$\vec{E} = E_x\hat{\imath} = \frac{1}{4\pi\epsilon_0}\frac{Qx}{(x^2 + a^2)^{3/2}}\hat{\imath} \tag{21.8}$$

Field due to arc of charge

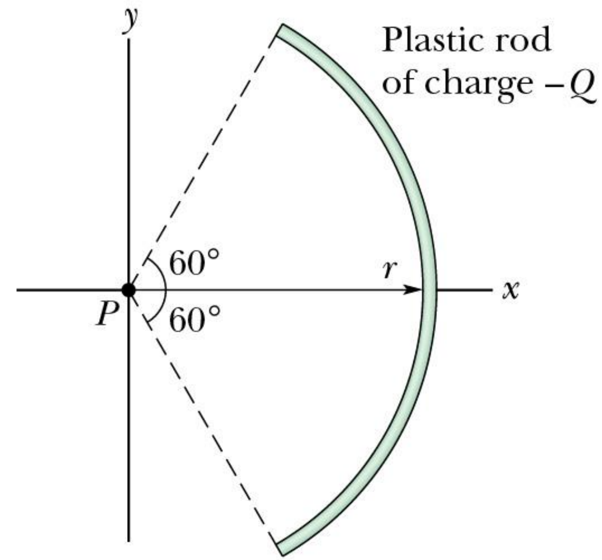
$$E_y = \int_{-L/2}^{L/2} dE_y = 0$$

$$dE_x = k\, dq \cos\theta / r^2$$
$$= k\,\lambda\, ds \cos\theta / r^2$$

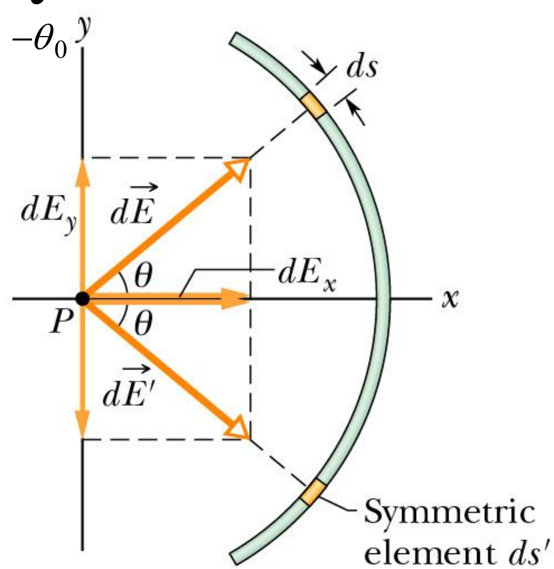
$s = r\,\theta$, $ds = r\, d\theta$

$$E_x = k\lambda \int_{-L/2}^{L/2} r\,d\theta \cos\theta / r^2 = k\lambda / r \int_{-\theta_0}^{\theta_0} d\theta \cos\theta$$

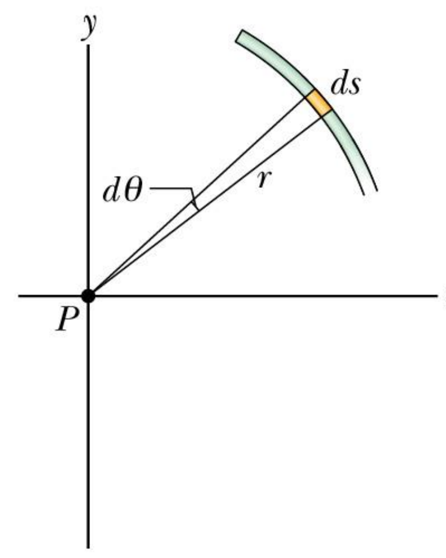
$$E_x = \frac{2k\lambda}{r}\sin\theta_0$$



(a)



(b)



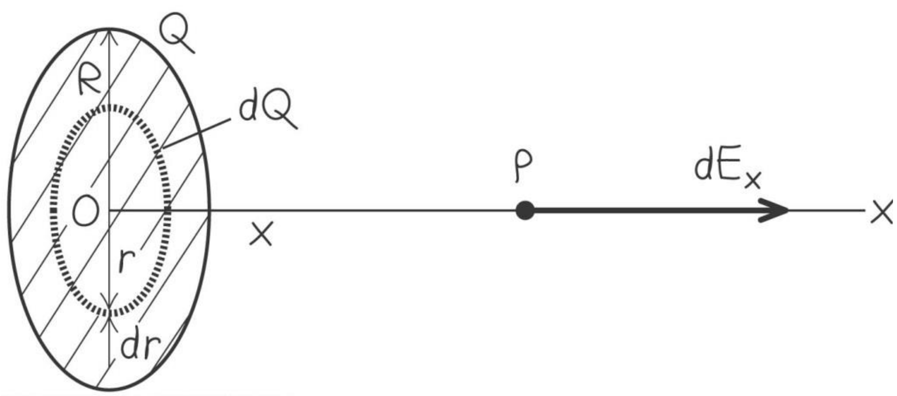
(c)

What is the field at the center of a circle of charge?

Ans. 0

Field of a uniformly charged disk

- Follow Example 21.11 using Figure 21.25 below.



EXECUTE: A typical ring has charge dQ, inner radius r, and outer radius $r + dr$ (Fig. 21.26). Its area dA is approximately equal to its width dr times its circumference $2\pi r$, or $dA = 2\pi r\,dr$. The charge per unit area is $\sigma = dQ/dA$, so the charge of the ring is $dQ = \sigma\,dA = \sigma\,(2\pi r\,dr)$, or

$$dQ = 2\pi\sigma r\,dr$$

We use this in place of Q in the expression for the field due to a ring found in Example 21.10, Eq. (21.8), and also replace the ring radius a with r. The field component dE_x at point P due to charge dQ is

$$dE_x = \frac{1}{4\pi\epsilon_0}\frac{dQ}{r^2} = \frac{1}{4\pi\epsilon_0}\frac{(2\pi\sigma r\,dr)x}{(x^2 + r^2)^{3/2}}$$

To find the total field due to all the rings, we integrate dE_x over r from $r = 0$ to $r = R$ (*not* from $-R$ to R):

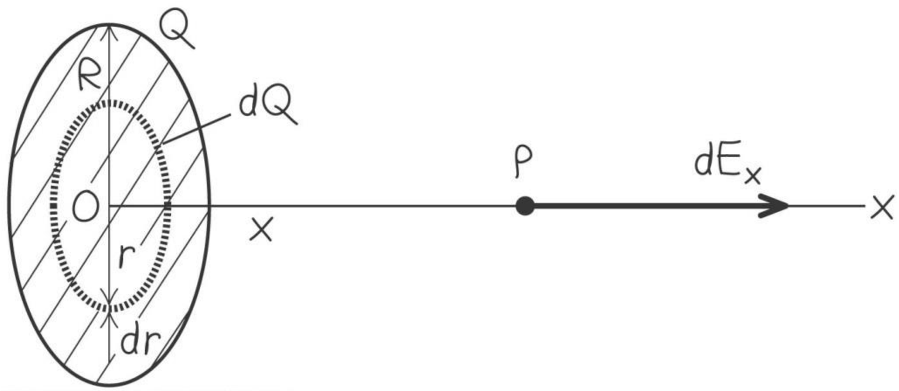
$$E_x = \int_0^R \frac{1}{4\pi\epsilon_0}\frac{(2\pi\sigma r\,dr)x}{(x^2 + r^2)^{3/2}} = \frac{\sigma x}{2\epsilon_0}\int_0^R \frac{r\,dr}{(x^2 + r^2)^{3/2}}$$

the substitution $z = x^2 + r^2$. We'll let you work out the details; the result is

$$E_x = \frac{\sigma x}{2\epsilon_0}\left[-\frac{1}{\sqrt{x^2 + R^2}} + \frac{1}{x}\right] = \frac{\sigma}{2\epsilon_0}\left[1 - \frac{1}{\sqrt{(R^2/x^2) + 1}}\right] \qquad (21.11)$$

Field of a uniformly charged disk

- Follow Example 21.11 using Figure 21.25 below.

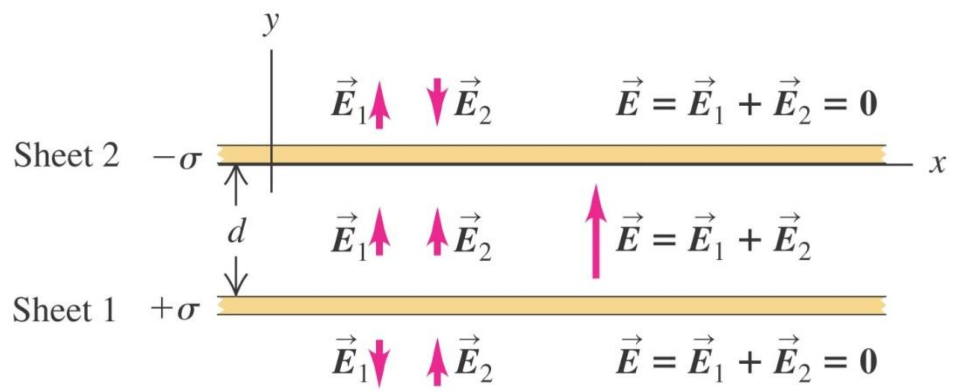


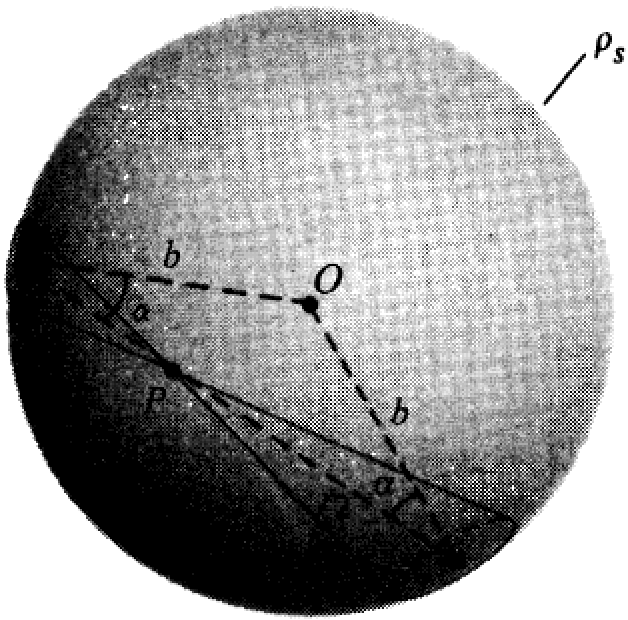
(charge per unit area) is constant. In the limit that R is much larger than the distance x of the field point from the disk, the term $1/\sqrt{(R^2/x^2) + 1}$ in Eq. (21.11) becomes negligibly small, and we get

$$E = \frac{\sigma}{2\epsilon_0} \tag{21.12}$$

Field of two oppositely charged infinite sheets

- Follow Example 21.12 using Figure 21.26 below.





es ds_1 and ds_2 is, from Eq. (3–12),

$$dE = \frac{\rho_s}{4\pi\epsilon_0}\left(\frac{ds_1}{r_1^2} - \frac{ds_2}{r_2^2}\right).$$

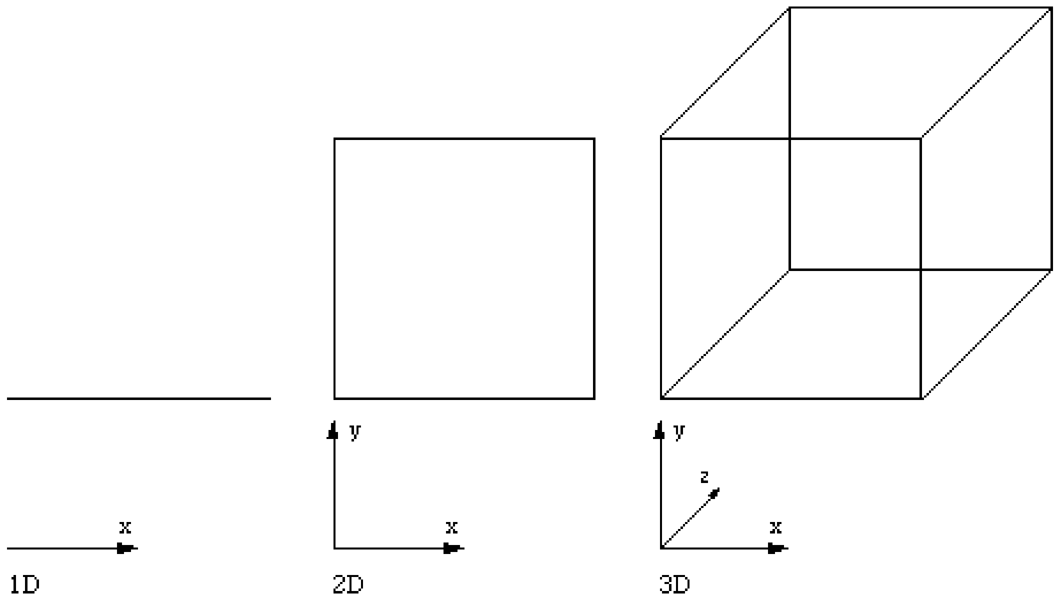
ngle $d\Omega$ equals

$$d\Omega = \frac{ds_1}{r_1^2}\cos\alpha = \frac{ds_2}{r_2^2}\cos\alpha.$$

expressions of dE and $d\Omega$, we find that

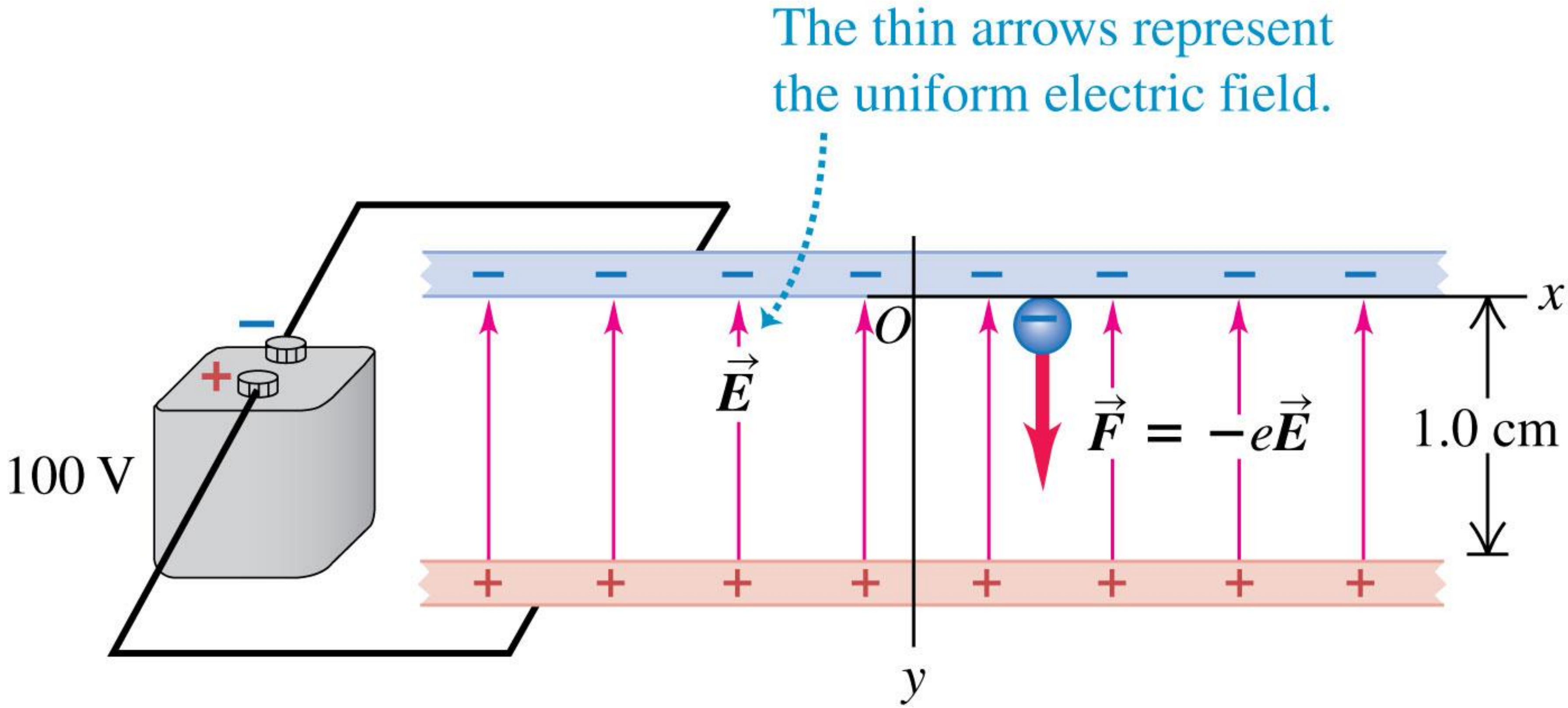
$$dE = \frac{\rho_s}{4\pi\epsilon_0}\left(\frac{d\Omega}{\cos\alpha} - \frac{d\Omega}{\cos\alpha}\right) = 0.$$

Field of 1D-3D problems



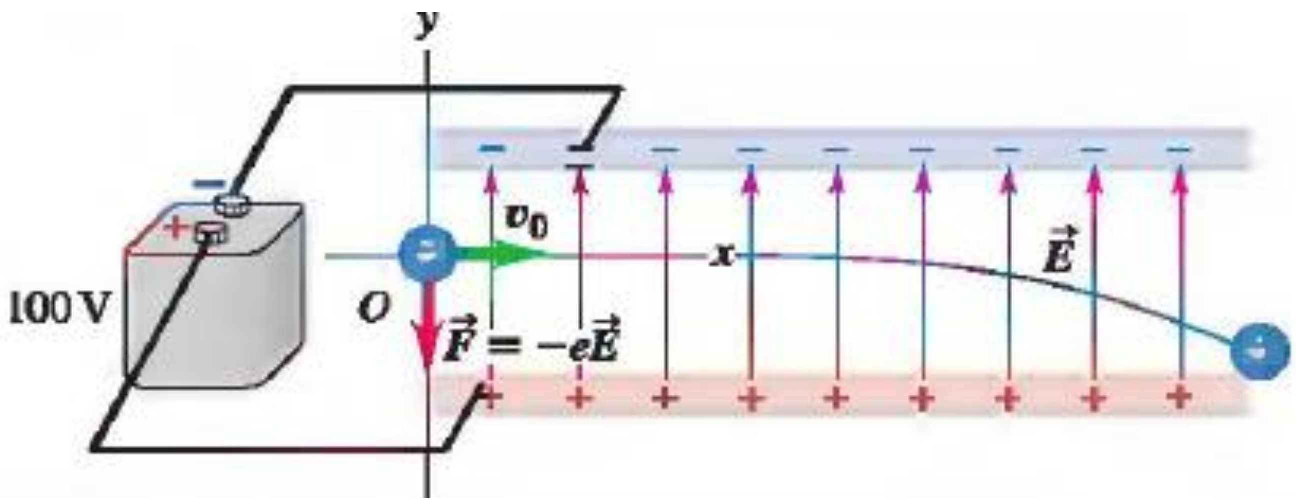
Electron in a uniform field

- Example 21.7 requires us to find the force on a charge that is in a known electric field. Follow this example using Figure 21.20 below.

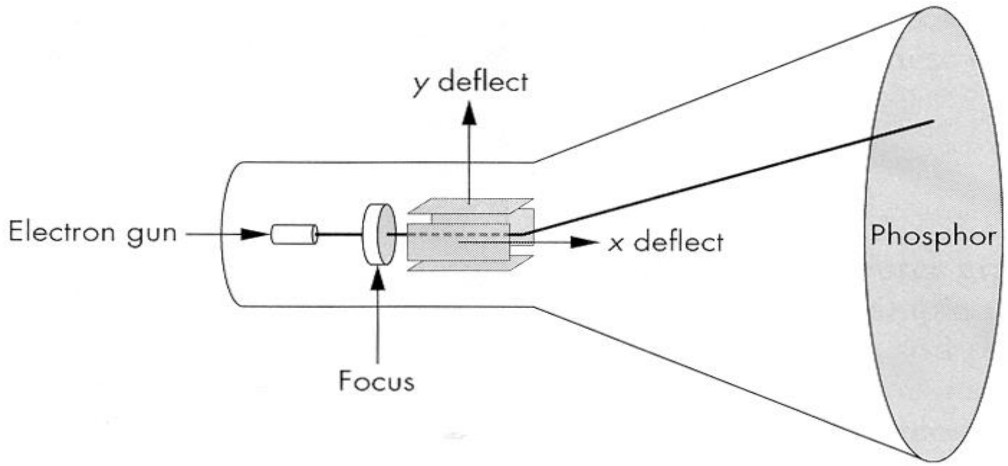


Electron in a uniform field

- Example 21.7 requires us to find the force on a charge that is in a known electric field. Follow this example using Figure 21.20 below.

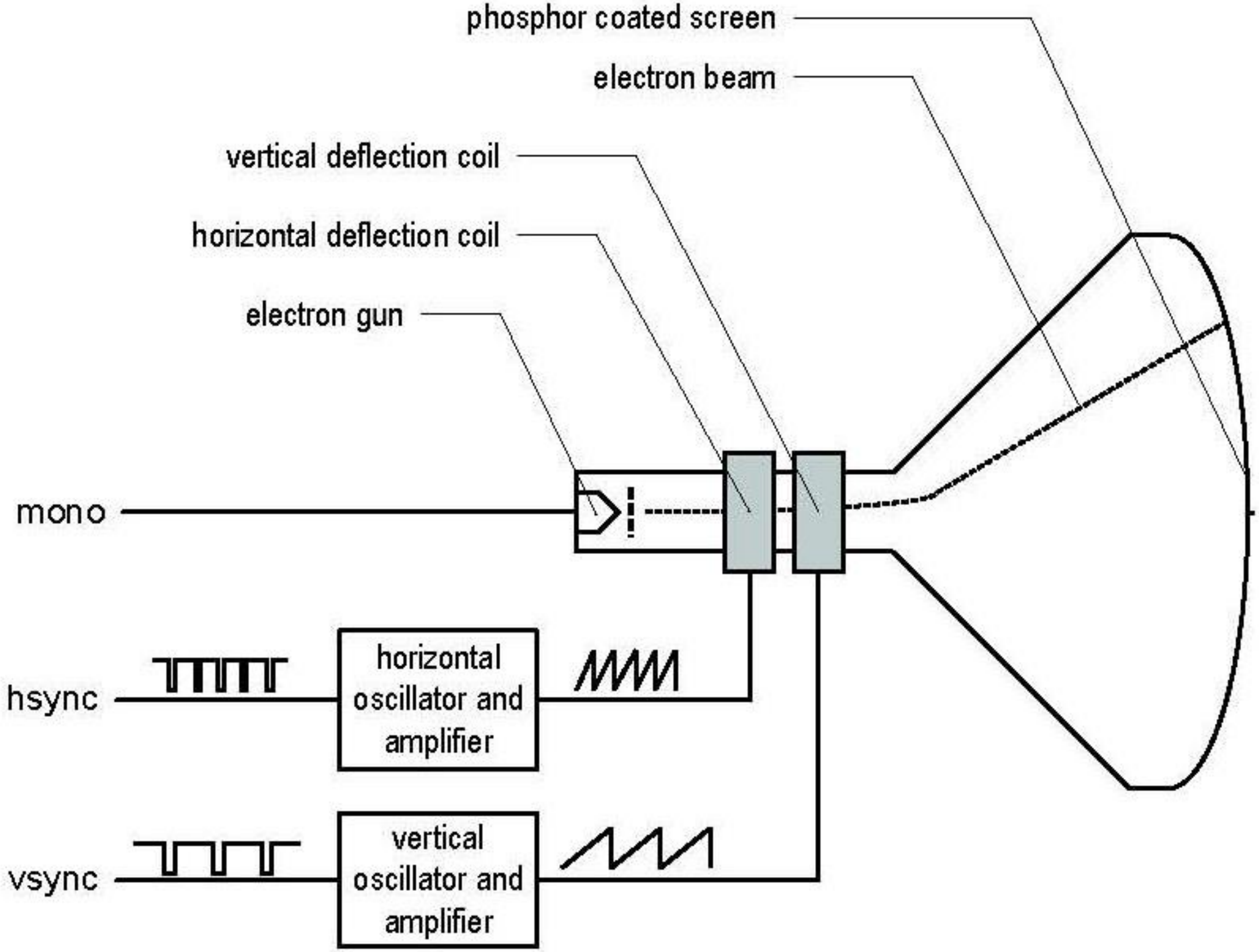


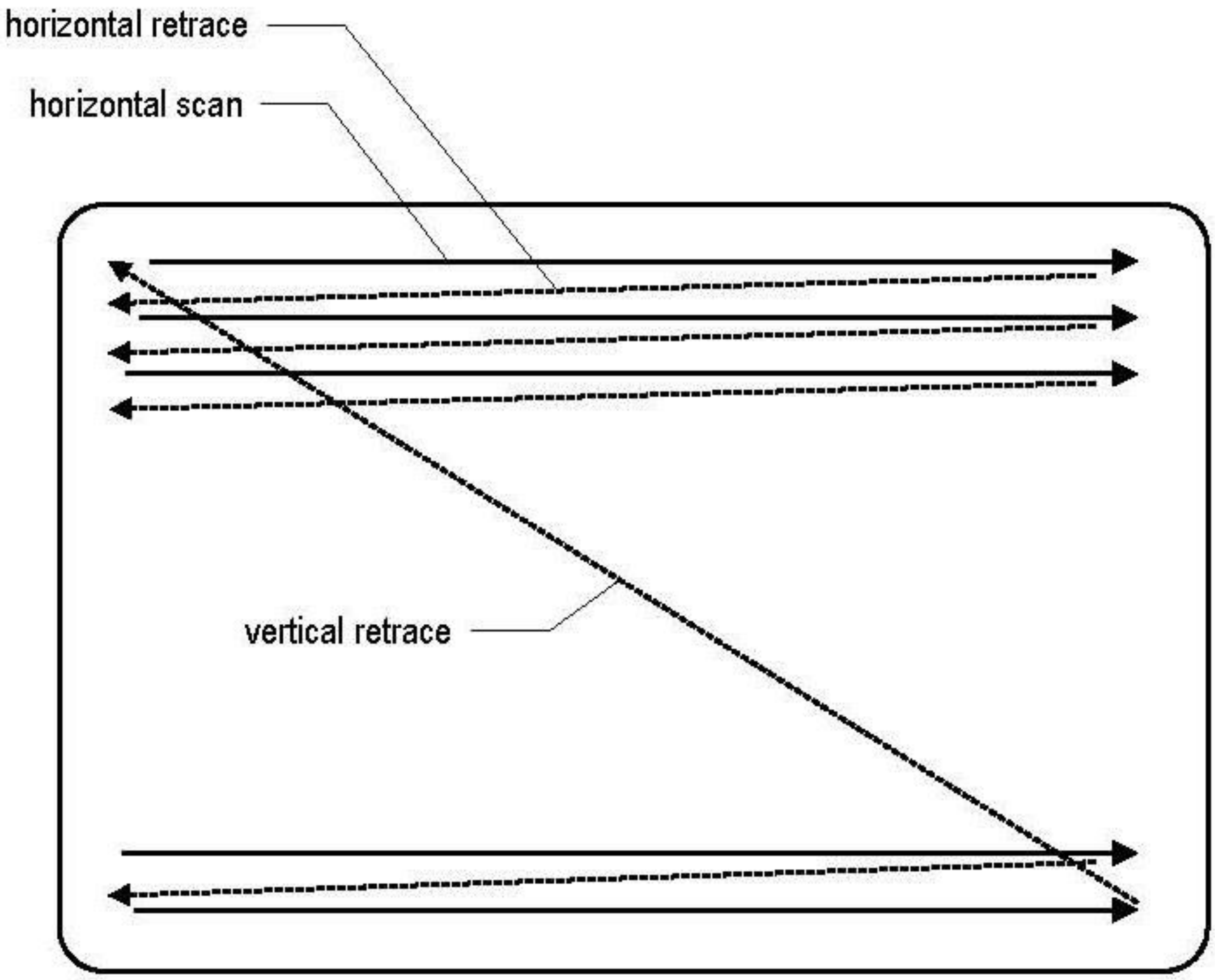
Cathode ray tubes (CRTs)



Consists of:

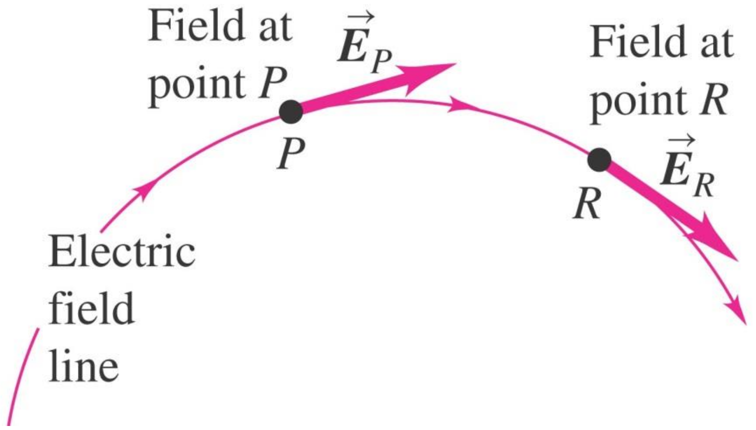
- electron gun
- electron focusing lens
- deflection plates/coils
- electron beam
- anode with phosphor coating


phosphor coated screen
electron beam
vertical deflection coil
horizontal deflection coil
electron gun
mono
hsync
horizontal oscillator and amplifier
vsync
vertical oscillator and amplifier


horizontal retrace
horizontal scan
vertical retrace

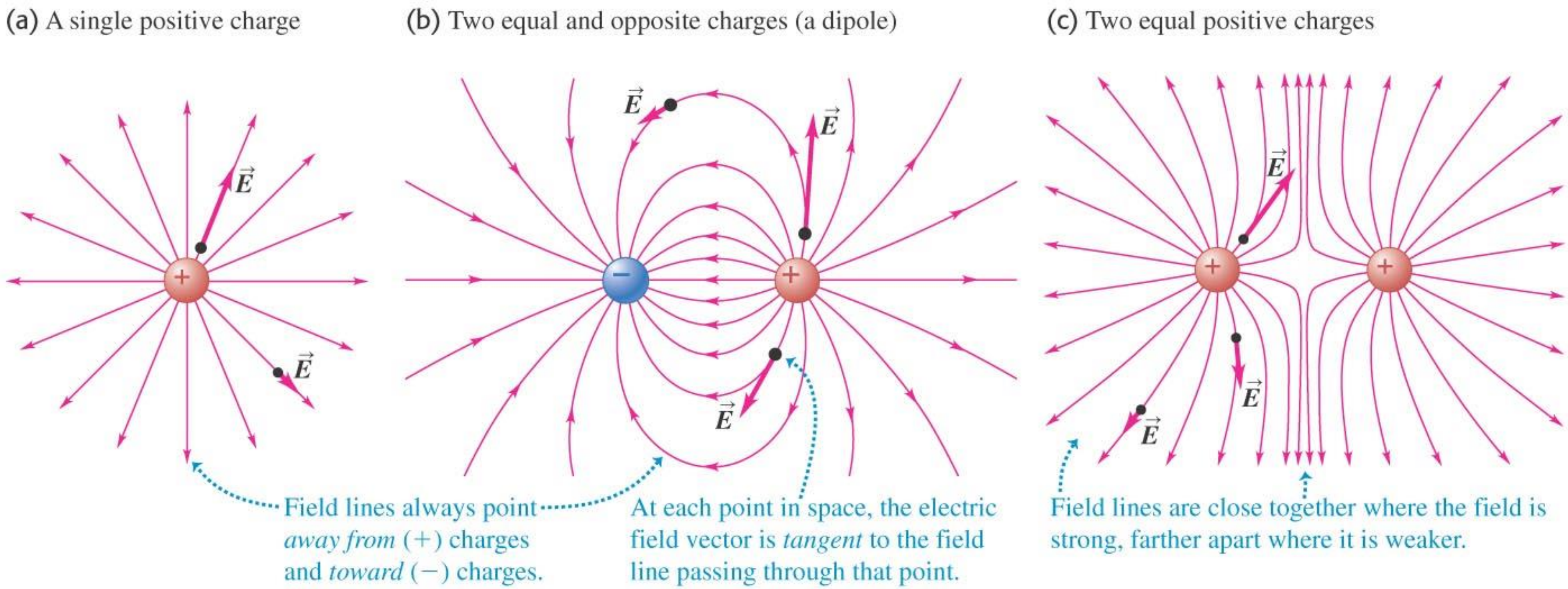
Electric field lines

- An *electric field line* is an imaginary line or curve whose tangent at any point is the direction of the electric field vector at that point. (See Figure 21.27 below.)



Electric field lines of point charges

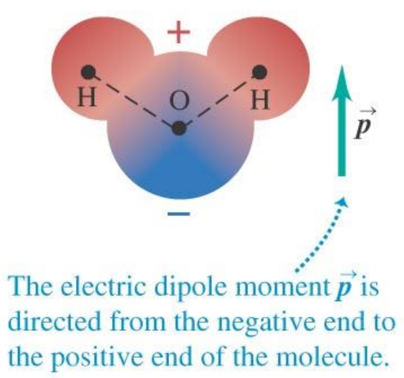
- Figure 21.28 below shows the electric field lines of a single point charge and for two charges of opposite sign and of equal sign.



Electric dipoles

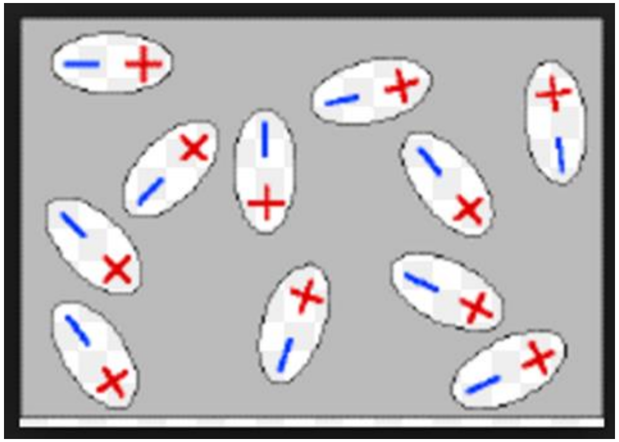
- An *electric dipole* is a pair of point charges having equal but opposite sign and separated by a distance.
- Figure 21.30 at the right illustrates the water molecule, which forms an electric dipole.

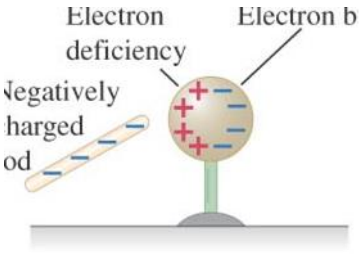
(a) A water molecule, showing positive charge as red and negative charge as blue



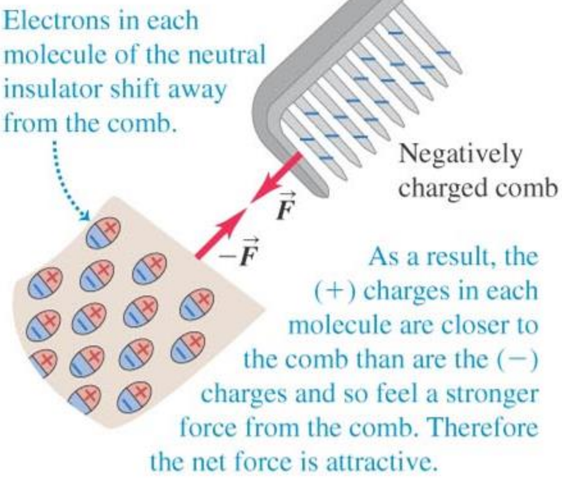
(b) Various substances dissolved in water

Electric dipoles





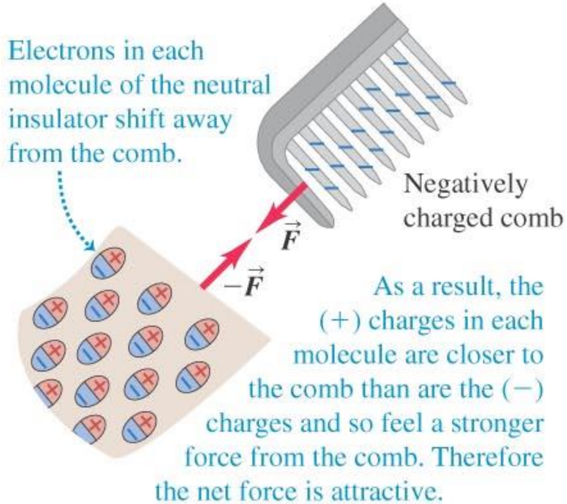
(b) How a negatively charged comb attracts an insulator



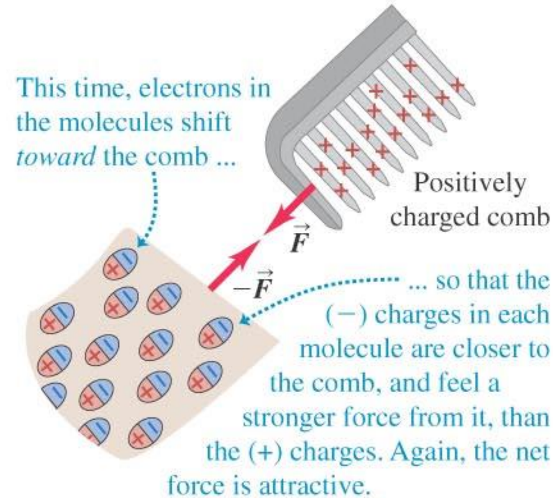
Magnetism and certain metals

(a) A charged comb picking up uncharged pieces of plastic

(b) How a negatively charged comb attracts an insulator



(c) How a positively charged comb attracts an insulator



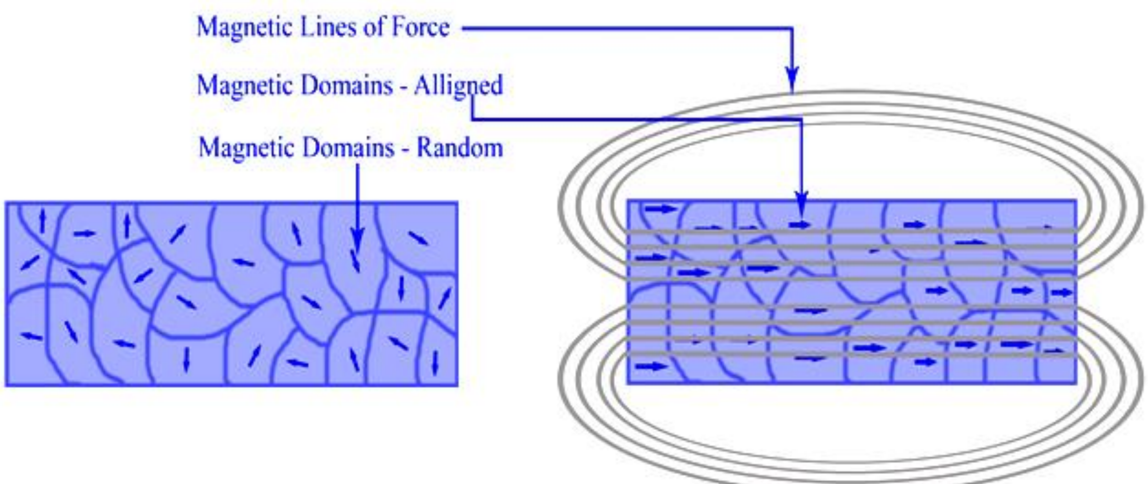
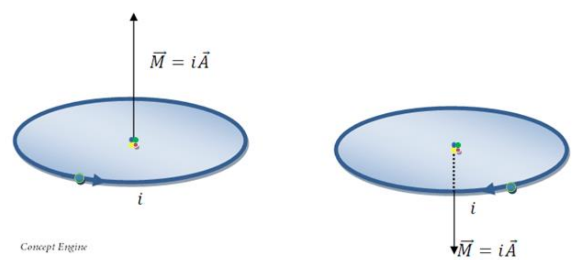
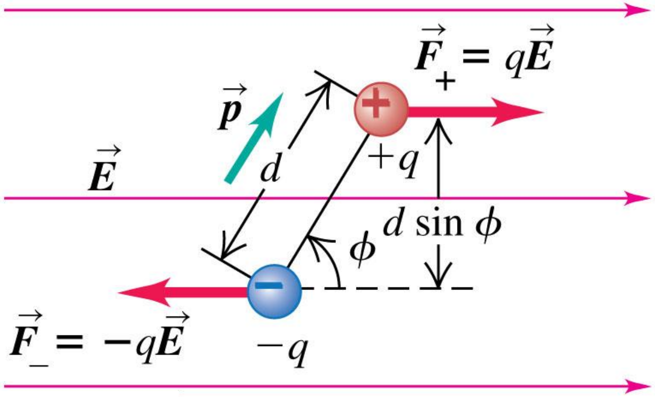


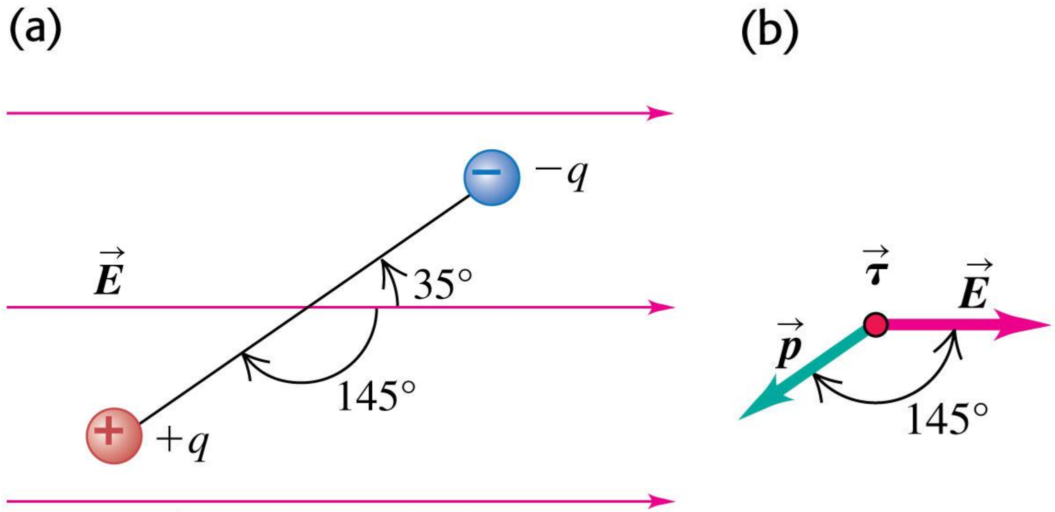
Fig. Ferromagnetism (a) Unmagnetized Material (b) Magnetized Material



Force and torque on a dipole

- Figure 21.31 below left shows the force on a dipole in an electric field.
- Follow the discussion of force, torque, and potential energy in the text.
- Follow Example 21.13 using Figure 21.32 below right.

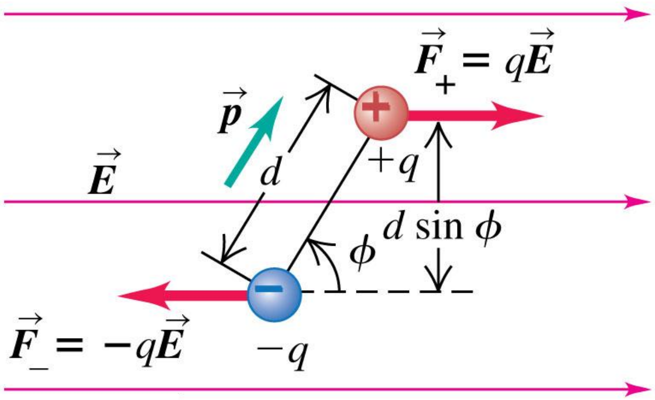




Force and torque on a dipole

angle between the electric field $\vec{E}$ and the dipole axis be ϕ; then the lever arm for both $\vec{F}_+$ and $\vec{F}_-$ is $(d/2)\sin\phi$. The torque of $\vec{F}_+$ and the torque of $\vec{F}_-$ both have the same magnitude of $(qE)(d/2)\sin\phi$, and both torques tend to rotate the dipole clockwise (that is, $\vec{\tau}$ is directed into the page in Fig. 21.31). Hence the magnitude of the net torque is twice the magnitude of either individual torque:

$$\tau = (qE)(d\sin\phi) \qquad (21.13)$$



electric dipole moment, denoted by p:

$$p = qd \qquad \text{(magnitude of electric dipole moment)}$$

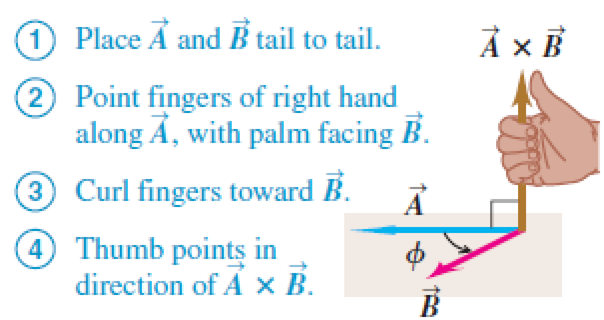
$$\tau = pE\sin\phi \qquad \text{(magnitude of the torque on an electric dipole)} \qquad (21.15)$$

$$\vec{\tau} = \vec{p} \times \vec{E} \qquad \text{(torque on an electric dipole, in vector form)} \qquad (21.16)$$

the vector product $\vec{A} \times \vec{B}$,

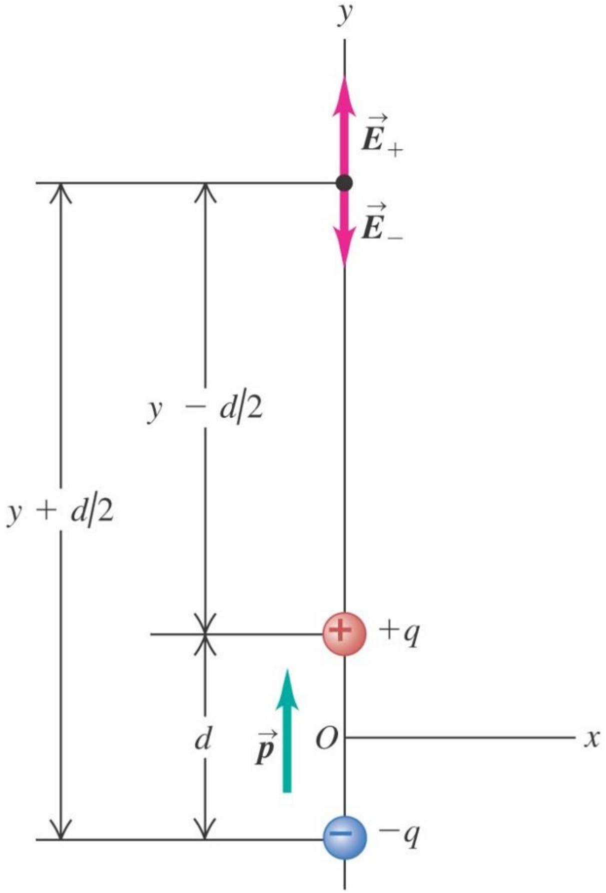
$$C = AB\sin\phi \qquad \text{(magnitude of the vector (cross) product of } \vec{A} \text{ and } \vec{B}\text{)}$$

(a) Using the right-hand rule to find the direction of $\vec{A} \times \vec{B}$



Electric field of a dipole

- Follow Example 21.14 using Figure 21.33.



EXECUTE: The total y-component E_y of electric field from the two charges is

$$E_y = \frac{q}{4\pi\epsilon_0}\left[\frac{1}{(y - d/2)^2} - \frac{1}{(y + d/2)^2}\right]$$
$$= \frac{q}{4\pi\epsilon_0 y^2}\left[\left(1 - \frac{d}{2y}\right)^{-2} - \left(1 + \frac{d}{2y}\right)^{-2}\right]$$

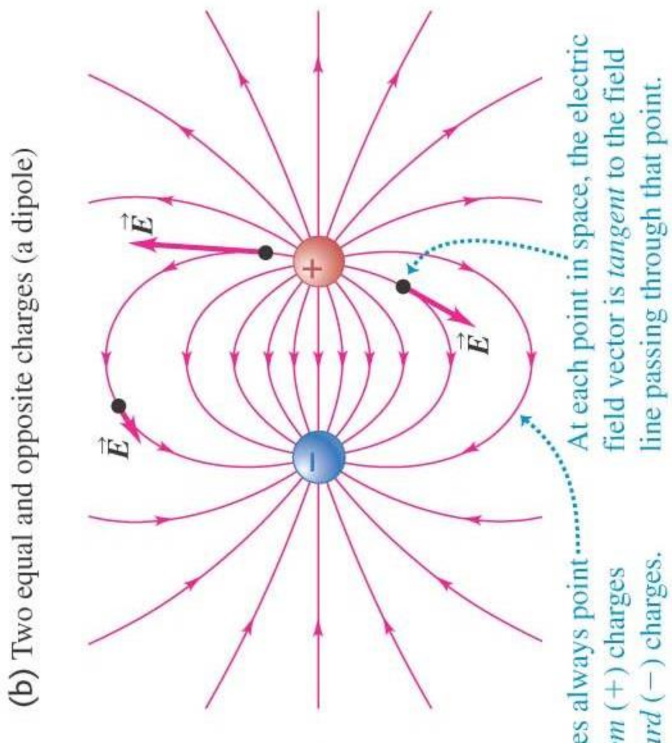
We used this same approach in Example 21.8 (Section 21.5). Now the approximation: When we are far from the dipole compared to its size, so $y \gg d$, we have $d/2y \ll 1$. With $n = -2$ and with $d/2y$ replacing x in the binomial expansion, we keep only the first two terms (the terms we discard are much smaller). We then have

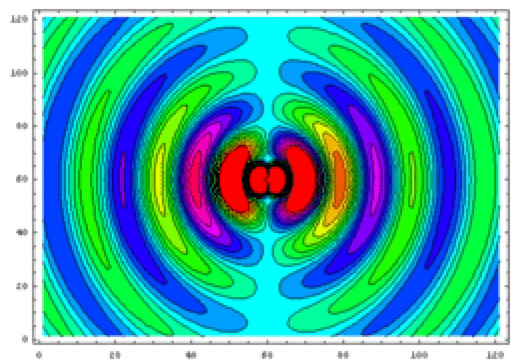
$$\left(1 - \frac{d}{2y}\right)^{-2} \cong 1 + \frac{d}{y} \quad \text{and} \quad \left(1 + \frac{d}{2y}\right)^{-2} \cong 1 - \frac{d}{y}$$

Hence E_y is given approximately by

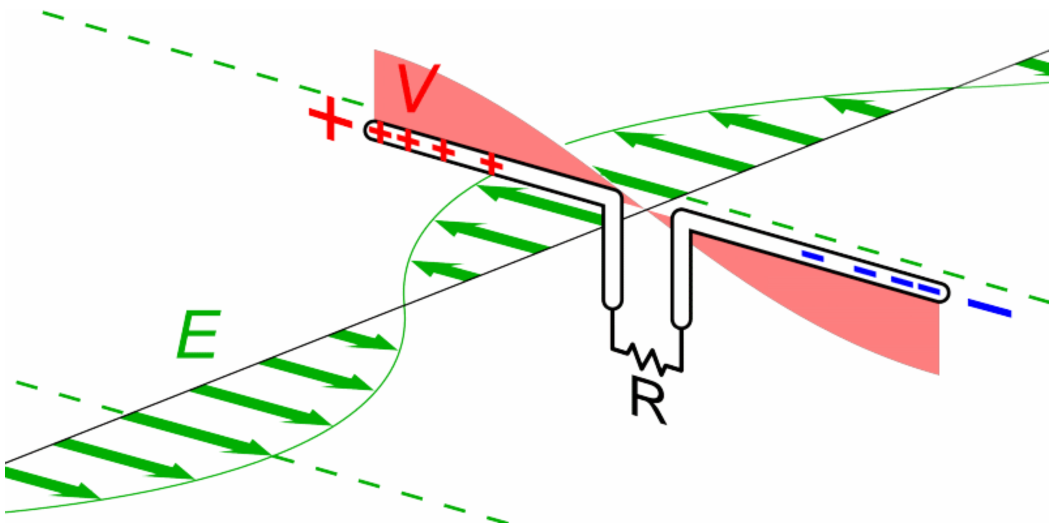
$$E_y \cong \frac{q}{4\pi\epsilon_0 y^2}\left[1 + \frac{d}{y} - \left(1 - \frac{d}{y}\right)\right] = \frac{qd}{2\pi\epsilon_0 y^3} = \frac{p}{2\pi\epsilon_0 y^3}$$

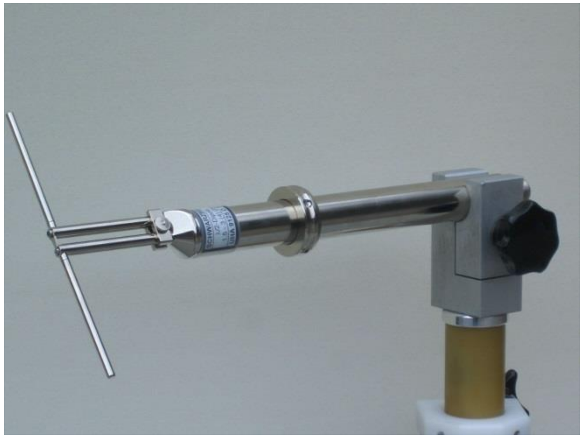
Electric field lines of point charges

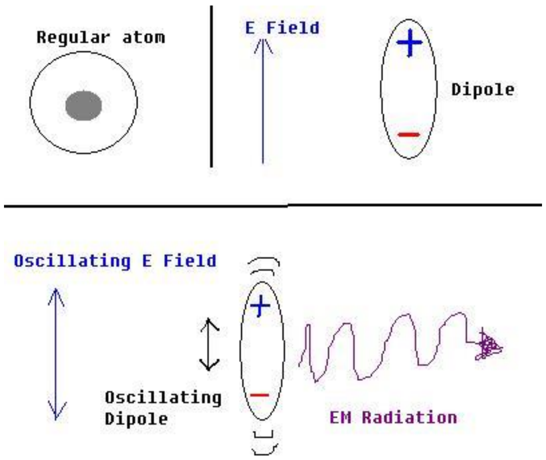


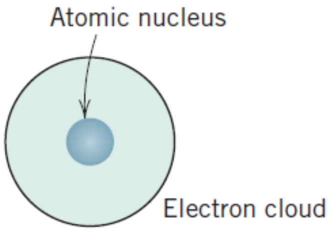


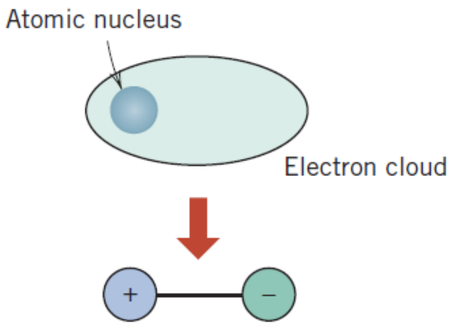
Electric field lines of point charges











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