Electromagnetic waves

FIZ102E: Electricity & Magnetism

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Contents

LEARNING GOALS

- The nature of electric charge, and how we know that electric charge is conserved.
- How objects become electrically charged.
- How to use Coulomb's law to calculate the electric force between charges.
- The distinction between electric force and electric field.
- How to calculate the electric field due to a collection of charges.
- How to use the idea of electric field lines to visualize and interpret electric fields.
- How to calculate the properties of electric dipoles.

Water makes life possible:
The cells of your body could not function without water
in which to dissolve essential biological molecules.
What electrical properties of water make it such a good solvent?

- What holds your body together?
- What keeps a skyscraper standing?
- What keeps a car on the road as it turns?
- What governs the electronics in computers?
- What provides the tension in a climbing rope?
- What enables the photosynthesis of plants?

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Answer: Electric forces

Atomic nucleus

- What holds the nucleus together?
- In a nucleus there are several protons, all of which are positive. Why don't they push themselves apart?
- In nuclei there are, in addition to electrical forces, non-electrical forces, called *nuclear forces*, which are greater than the electrical forces and which are able to hold the protons together in spite of the electrical repulsion.
- The nuclear forces, however, have a short range—their force falls off much more rapidly than $1/r^2$.

Four fundamental forces of Nature

- Gravity (long range)
- Electromagnetism (long range)
- Strong nuclear force (short range)
  (Holds protons together at the nucleus)
- Weak nuclear force (short range)
  (Responsible for beta-decay)

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All macroscopic phenomena are governed by gravity and EM forces!
Everything in your daily life other than gravity is electromagnetic!

The forces on a skier

Gravity versus normal force! But what is the origin of the normal force that the water applies?

The forces on a skier

The forces that hold atoms together to form solid matter, and that keep the atoms of solid objects from passing through each other, are fundamentally due to electric interactions between the charged particles within atoms.

The forces on a skier

Electric interactions between adjacent molecules give rise to the force of the water on the ski and the tension in the tow rope. Electric interactions also hold the atoms of the skier's body together. Only one wholly non-electric force acts on the skier: the force of gravity.

Notable effective forces of electrical origin:

What about other forces we learned in mechanics? Are they electromagnetic?

- Tension
- Normal Forces
- Compression
- Friction force
- Adhesive force of glue
- Most forces in chemistry & biology-the force in your muscles originate from the electrostatic binding energy ATP molecules.

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Applications

Technological
Computer microchips
Cell phones
Motors & generators

Biological
Heartbeat pacing
Nerve impulses
Osmosis through cell membranes

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Yet all are described by Maxwell equations-the laws of electromagnetism!

Maxwell's Equations

$$\oint \vec{\mathbf{E}} \cdot \mathrm{d}\vec{\mathbf{A}} = \frac{Q_{\mathrm{enc}}}{\epsilon_0}$$ Gauss' law

$$\oint \vec{\mathbf{E}} \cdot \mathrm{d}\vec{\mathbf{l}} = -\frac{\mathrm{d}}{\mathrm{d}t} \int \vec{\mathbf{B}} \cdot \mathrm{d}\vec{\mathbf{A}},$$ Faraday's law

$$\oint \vec{\mathbf{B}} \cdot \mathrm{d}\vec{\mathbf{A}} = 0,$$ Gauss's law for magnetism

$$\oint \vec{\mathbf{B}} \cdot \mathrm{d}\vec{\mathbf{l}} = \mu_0 i_{\mathrm{enc}} + \mu_0 \epsilon_0 \frac{\mathrm{d}}{\mathrm{d}t} \int \vec{\mathbf{E}} \cdot \mathrm{d}\vec{\mathbf{A}},$$ Gen. Ampere's law

Lorentz's Force

We find, *from experiment*, that the force that acts on a particular charge—no matter how many other charges there are or how they are moving—depends only on the *position* of that particular charge, on the *velocity* of the charge, and on the *amount* of charge.
Force acting on a charged particle given the $\vec{\mathbf{E}}$ & $\vec{\mathbf{B}}$ fields is

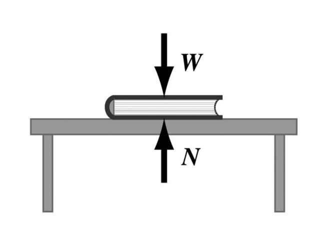
$$\vec{\mathbf{F}} = q(\vec{\mathbf{E}} + \vec{\mathbf{v}} \times \vec{\mathbf{B}})$$

where $\vec{\mathbf{v}}$ is the velocity of the particle.
We call $\vec{\mathbf{E}}$ the electric field and $\vec{\mathbf{B}}$ the magnetic field at the location of the charge. The important thing is that the electrical forces from all the other charges in the universe can be summarized by giving just these two vectors. Their values will depend on *where* the charge is, and may change with *time*.

Electromagnetism is much stronger than gravity

- The mass of the whole world is attracting the book to the center...

$$W = mg = m\frac{GM_{\text{Earth}}}{R^2_{\text{Earth}}}$$



- ...yet it takes only the normal force, N, applied by the desk to balance it.
- The origin of the normal force is electrical. It arises from electric forces between charged particles in the atoms of the book and in the atoms of the desk.

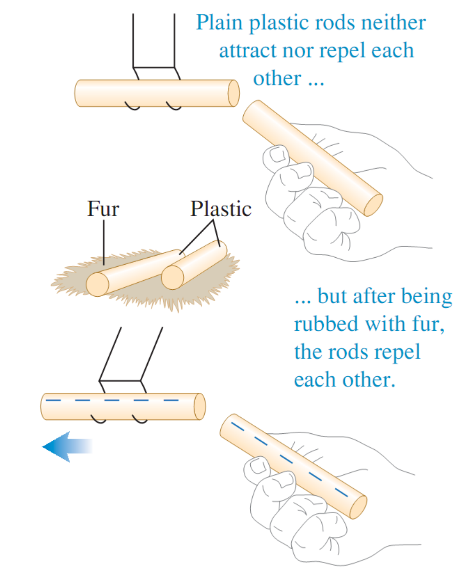
Why then the electric force does not dominate?

- If electrical forces are so strong why then the attraction between the Earth and the Moon is gravitational rather than electrical.
- Think that even a charge imbalance of one part in a million would result with electrical force dominating the gravitational force.
- Macroscopic matter is neutral to a very high precision, charge is balanced.
- Any charge imbalance leads to large restoring forces.
- Gravity is always attractive, but electric forces can be both attractive and repelling.

Electric Charge

- Electromagnetic interactions involve particles that have a property called electric charge.
- Electric charge is an attribute that is as fundamental as mass.
- Just as objects with mass are accelerated by gravitational forces, electrically charged objects are accelerated by electric forces.
- Electric currents are simply streams of charged particles flowing within wires in response to electric forces.
- Electrostatics is the study of the interactions between electric charges that are at *rest*.

Two kinds of charge

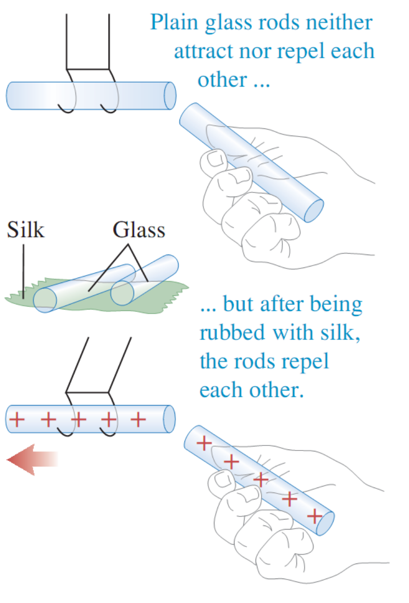


After we charge both plastic rods by rubbing them with the piece of fur, we find that the rods repel each other.
Because the process is the same in both cases they must have the same kind of charge.

Like charges repel.

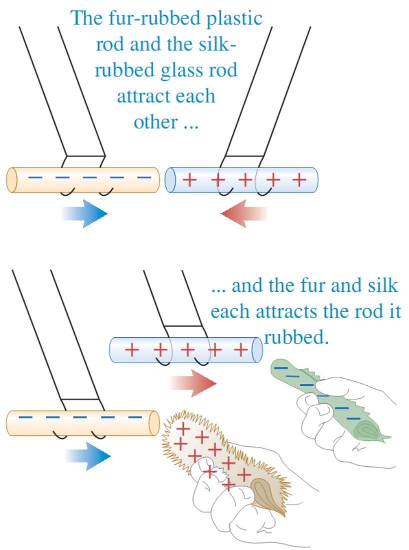
see http://www.youtube.com/watch?v=45AAI19_lsc

Two kinds of charge



When we rub glass rods with silk, the glass rods also become charged and *repel* each other.

Two kinds of charge



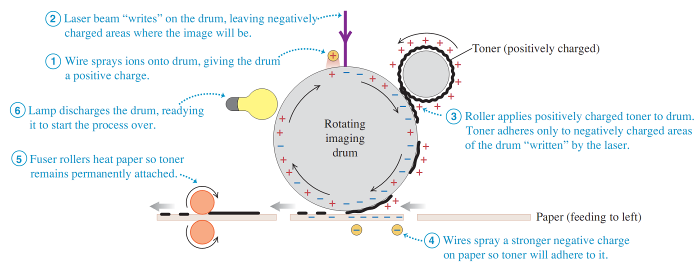
But a charged plastic rod attracts a charged glass rod; furthermore, the plastic rod and the fur attract each other, and the glass rod and the silk attract each other.

Two kinds of charge

- These experiments and many others like them have shown that there are exactly two kinds of electric charge.
- The kind on the plastic rod rubbed with fur and the kind on the glass rod rubbed with silk.
- Benjamin Franklin (1706–1790) suggested calling these two kinds of charge negative and positive, respectively, and these names are still used.
- The plastic rod and the silk have negative charge; the glass rod and the fur have positive charge.

Two positive charges or two negative charges repel each other.
A positive charge and a negative charge attract each other.

Laser Printer

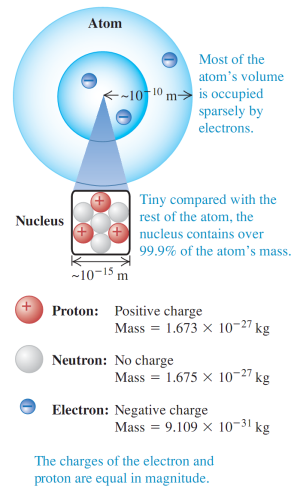


- The printer's light-sensitive imaging drum is given a positive charge.
- As the drum rotates, a laser beam shines on selected areas of the drum, leaving those areas with a negative charge.
- Positively charged particles of toner adhere only to the areas of the drum "written" by the laser.
- When a piece of paper is placed in contact with the drum, the toner particles stick to the paper and form an image.

Constituents of matter

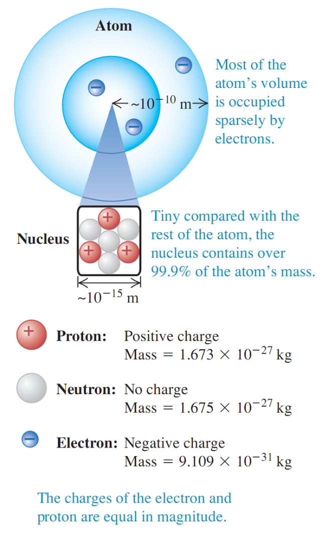
- What, then, actually happens to the rod when you charge it?
- The structure of atoms can be described in terms of three particles: the negatively charged electron, the positively charged proton, and the uncharged neutron.
- The proton and neutron are combinations of other entities called quarks.
- Quarks have charges of $\pm\frac{1}{3}$ and $\frac{2}{3}$ times the electron charge.
- Isolated quarks have not been observed, and there are theoretical reasons to believe that it is impossible in principle to observe a quark in isolation.

Distribution of particles in an atom



- The protons and neutrons in an atom make up a small, very dense core called the nucleus, with dimensions of the order of 10^{-15} m.
- Surrounding the nucleus are the electrons, extending out to distances of the order of 10^{-10} m from the nucleus.
- If an atom were a few kilometers across, its nucleus would be the size of a tennis ball. (Most of the atom is empty.)

Forces between particles in an atom



- The negatively charged electrons are held within the atom by the electric forces.
- The protons and neutrons are held within stable atomic nuclei by the strong nuclear force that overcomes the electric repulsion of the protons.
- The strong nuclear force has a short range, and its effects do not extend far beyond the nucleus.

The masses of particles in an atom

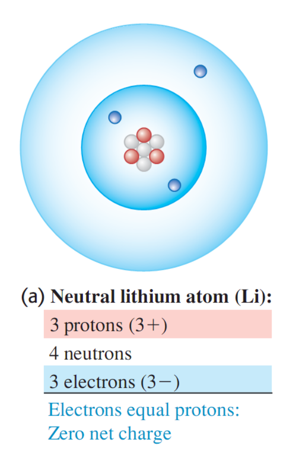
The masses of the individual particles, to the precision that they are presently known, are

- Mass of electron $= m_\mathrm{e} = 9.10938215(45) \times 10^{-31}$ kg
- Mass of proton $= m_\mathrm{p} = 1.672621637(83) \times 10^{-27}$ kg
- Mass of neutron $= m_\mathrm{n} = 1.674927211(84) \times 10^{-27}$ kg

- The mass of proton is 1836 times greater than electron.
- Over 99.9 per-cent of the mass of any atom is concentrated in its nucleus.
- The mass of proton and neutron are very similar but not exactly the same:

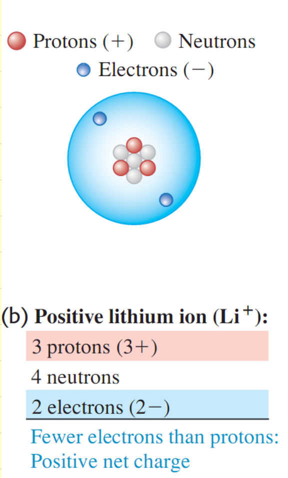
$$m_\mathrm{n} - m_\mathrm{p} = 2.5 m_\mathrm{e}$$

Neutral atom



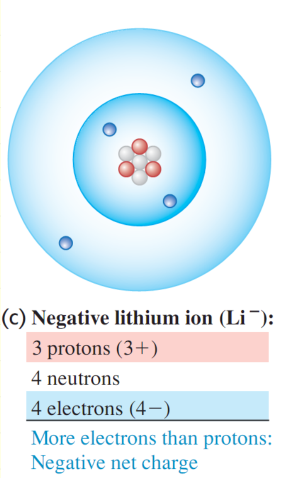
- The negative charge of the electron has (within experimental error) exactly the same magnitude as the positive charge of the proton.
- In a neutral atom the number of electrons equals the number of protons in the nucleus, and the net electric charge (the algebraic sum of all the charges) is exactly zero.
- The number of protons or electrons in a neutral atom of an element is called the atomic number of the element.

Positive ion



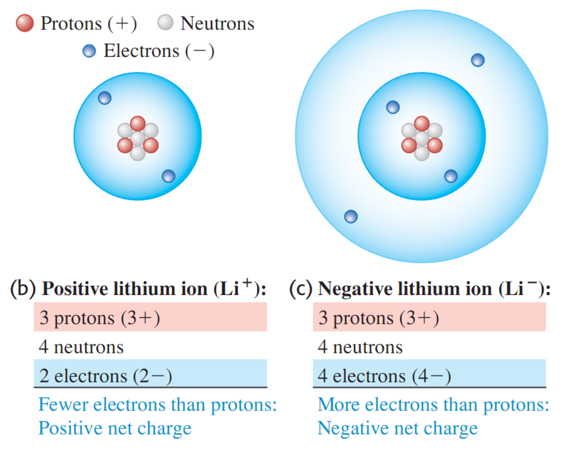
If one or more electrons are removed from an atom, what remains is called a positive ion.

Negative ion



A negative ion is an atom that has gained one or more electrons.

Ionization



This gain or loss of electrons is called ionization.

Ionization

- When the total number of protons in a macroscopic body equals the total number of electrons, the total charge is zero and the body as a whole is electrically neutral.
- To give a body an excess negative charge, we may either add negative charge to a neutral body or remove positive charges from that body.
- Similarly, we can create an excess positive charge by either adding positive charge or removing negative charge.
- In most cases, negatively charged (and highly mobile) electrons are added or removed, and a "positively charged body" is one that has lost some of its normal complement of electrons.
- When we speak of the charge of a body, we always mean its net charge. The net charge is always a very small fraction (typically no more than 10^{-12}) of the total positive charge or negative charge in the body.

Why electrons not fall into protons?

If this electrical force is so strong, why don't the protons and electrons just get on top of each other?
The answer has to do with the quantum effects. If we try to confine electrons in a region that is very close to the protons, then according to the *uncertainty principle* they must have some momentum which is larger the more we try to confine them. It is this motion, required by the laws of *quantum mechanics*, that keeps the electrical attraction from bringing the charges any closer together.

What holds a negatively charged electron together?

- electron has no nuclear forces
- If an electron is all made of one kind of substance, each part should repel the other parts.
- Why, then, doesn't it fly apart? But does the electron have "parts"?
- Perhaps we should say that the electron is just a point and that electrical forces only act between different point charges, so that the electron does not act upon itself.

Principle of conservation of charge

The algebraic sum of all the electric charges in any closed system is constant.

Ex: If we rub together a plastic rod and a piece of fur, both initially uncharged, the rod acquires a negative charge (since it takes electrons from the fur) and the fur acquires a positive charge of the same magnitude (since it has lost as many electrons as the rod has gained). Hence the total electric charge on the two bodies together does not change.

In any charging process, charge is not created or destroyed; it is merely transferred from one body to another.

Conservation of charge is thought to be a universal conservation law. No experimental evidence for any violation of this principle has ever been observed.

A natural unit for charge

The magnitude of charge of the electron or proton is a natural unit of charge.

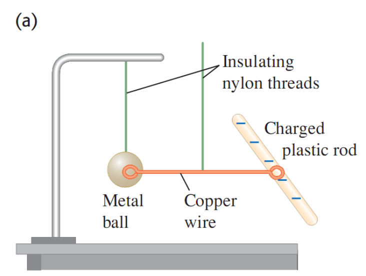
- Every observable amount of electric charge is always an integer multiple of this basic unit
  $\rightarrow$ charge is quantized.
- The charge on any macroscopic body is always either zero or an integer multiple (negative or positive) of the electron charge.
- A familiar example of quantization is money. When you pay cash for an item in a store, you have to do it in one-cent increments. Cash can't be divided into amounts smaller than one cent, and electric charge can't be divided into amounts smaller than the charge of one electron or proton.

End of Lecture 1

Conductors, Insulators, and Induced Charges

- Some materials permit electric charge to move easily from one region of the material to another, while others do not.
- Conductors permit the easy movement of charge through them, while insulators do not.
- Metals like copper are good conductors.
- Nylon, glass, wood are good insulators.
- Within a solid metal such as copper, one or more valance electrons in each atom become detached and can move freely throughout the material.
- In an insulator there are no, or very few, free electrons, and electric charge cannot move freely through the material.
- Some materials called semiconductors are intermediate in their properties between good conductors and good insulators.

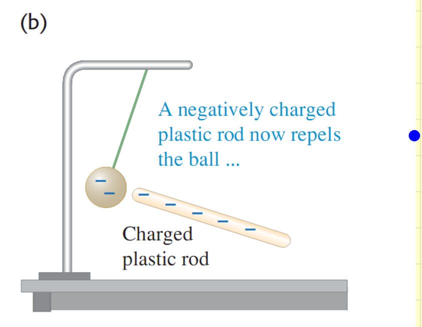
Charging by Conduction



The wire conducts charge from the negatively charged plastic rod to the metal ball.

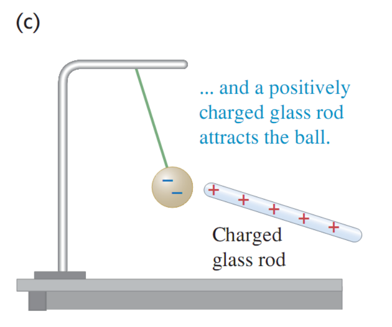
- Charging a metal ball using a copper wire and an electrically charged plastic rod.
- Copper is a good conductor of electricity;
- nylon is a good insulator.
- The copper wire conducts charge between the metal ball and the charged plastic rod to charge the ball negatively.

Charging by Conduction



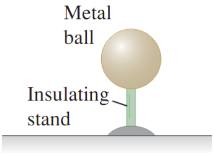
- Once the ball is charged negatively, the metal ball is repelled by a negatively charged plastic rod.

Charging by Conduction



- Once the ball is charged negatively, the metal ball is attracted to a positively charged glass rod.

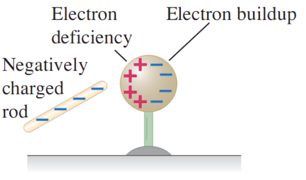
Charging by Induction



(a) Uncharged metal ball

Now consider an uncharged metal ball supported on an insulating stand.

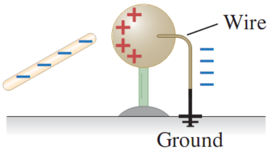
Charging by Induction



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

- When you bring a negatively charged rod near it, **without actually touching it**, the free electrons in the metal ball are repelled by the excess electrons on the rod, and they shift toward the right, away from the rod.
- They cannot escape from the ball because the supporting stand and the surrounding air are insulators.
- So we get excess negative charge at the right surface of the ball and a deficiency of negative charge at the left surface. These excess charges are called induced charges.

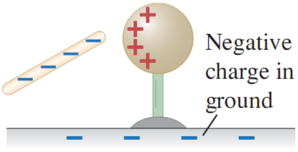
Charging by Induction



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

- What happens if, while the plastic rod is nearby, you touch one end of a conducting wire to the right surface of the ball and the other end to the earth?
- The earth is a conductor, and it is so large that it can act as a practically infinite source of extra electrons or sink of unwanted electrons.
- Some of the negative charge flows through the wire to the earth.

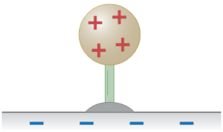
Charging by Induction



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

Now suppose you disconnect the wire

Charging by Induction



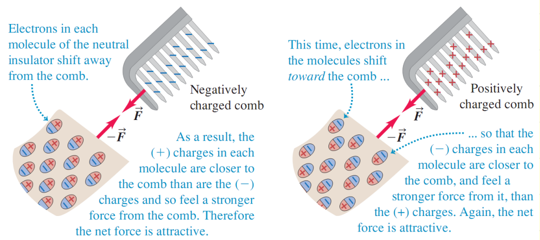
(e) Rod removed; electrons rearrange themselves, ball has overall electron deficiency (net positive charge).

- ...and then remove the rod;
- a net positive charge is left on the ball.
- The charge on the negatively charged rod has not changed during this process.
- The earth acquires a negative charge that is equal in magnitude to the induced positive charge remaining on the ball.

Electric Forces on Uncharged Objects

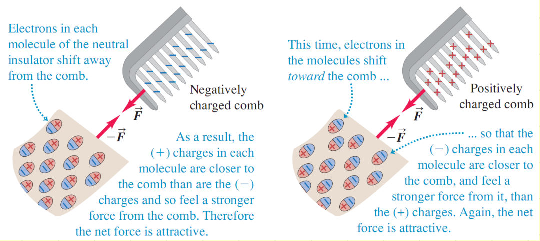
A charged body can exert forces even on objects that are not charged themselves.

Electric Forces on Uncharged Objects



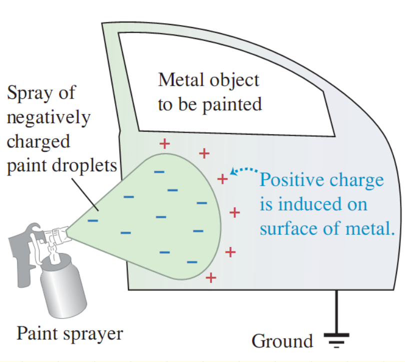
- This interaction is an induced-charge effect.
- Even in an insulator, electric charges can shift back and forth a little when there is charge nearby.
- The negatively charged plastic comb causes a slight shifting of charge within the molecules of the neutral insulator, an effect called polarization.

Electric Forces on Uncharged Objects



- The positive and negative charges in the material are present in equal amounts, ...
- ...but the positive charges are closer to the plastic comb...
- ...and so feel an attraction that is stronger than the repulsion felt by the negative charges, giving a net attractive force.

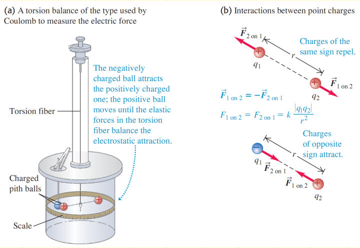
Application: The electrostatic painting process



- A metal object to be painted is connected to the earth ("ground").
- the paint droplets are given an electric charge as they exit the sprayer nozzle.
- Induced charges of the opposite sign appear in the object as the droplets approach.
- They attract the droplets to the surface.
- This process minimizes overspray from clouds of stray paint particles and gives a particularly smooth finish.

End of Lecture 2

Coulomb's Law



- Charles Augustin de Coulomb (1736-1806) studied the interaction forces of charged particles in detail in 1784.
- He used a torsion balance.
- Point charges are charged bodies that are very small compared with the distance r between them.
- Electric force is inversely proportional to distance squared: $F \propto 1/r^2$.
- Force also depends on the quantity of charge on each body, q_1 and q_2 as $F \propto q_1 q_2$.
- Thus

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

Fundamental Electric Constants

- The value of the proportionality constant in Coulomb's law depends on the system of units used.
- We always will use SI units.
- The SI unit of electric charge is called one coulomb (1 C).
- In SI unites

$$k = 8.987551787 \times 10^9 \,\mathrm{N\,m^2/C^2} \cong 9 \times 10^9 \,\mathrm{N\,m^2/C^2}$$

- A closely related constant is the speed of light in vacuum

$$c = 2.99792458 \times 10^8 \,\mathrm{m/s}.$$

- The numerical value of k is defined in terms of c as

$$k = (10^{-7} \,\mathrm{N\,s^2/C^2})c^2$$

- check if k has the right units.

Permittivity of free space

- In SI units we usually write

$$k = \frac{1}{4\pi\epsilon_0}$$

- This simplifies many formulas that we later will encounter.
- Permittivity of free space

$$\epsilon_0 = 8.854187817 \times 10^{-12}\,\mathrm{C}^2/\mathrm{N\,m}^2$$

Fundamental unit of charge

- The most fundamental unit of charge is the magnitude of the charge of an electron or a proton

$$e = 1.6021764871402 \times 10^{-19}\,\mathrm{C}$$

- Coulomb is a very large unit. Two charges of 1 C separated by 1 m would apply each other a force of 9×10^{9} N.
- Typical values of charge are $1\ \mu\mathrm{C} = 10^{-6}\,\mathrm{C}$ and $1\ \mathrm{nC} = 10^{-9}\,\mathrm{C}$.

Superposition of Forces

- Coulomb's law describes only the interaction of two point charges.
- Experiments show that when two charges exert forces simultaneously on a third charge, the total force acting on that charge is the vector sum of the forces that the two charges would exert individually.
- The principle of superposition of forces holds for any number of charges.

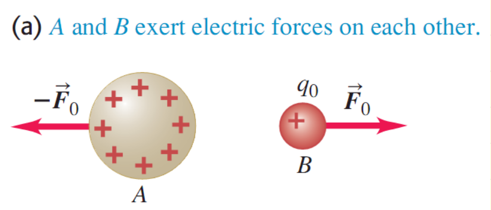
Action-at-a-distance force

- When two electrically charged particles in empty space interact, how does each one know the other is there?
- an “action-at-a-distance” force?
- a force that acts across empty space without needing any matter to transmit it through the intervening space.
- Gravity can also be thought of as an “action-at-a-distance” force.

Electric Field

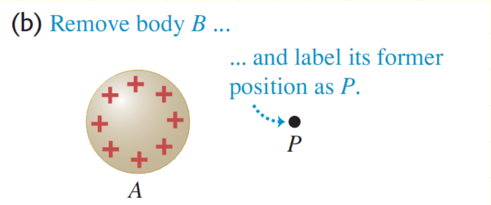
- It is possible to formulate Coulomb's law by using the concept of electric field.
- First envision that body A, as a result of the charge that it carries, somehow modifies the properties of the space around it.
- Then body B, as a result of the charge that it carries, senses how space has been modified at its position.
- The response of body B is to experience the force $\vec{F}_0$.

Electric Field



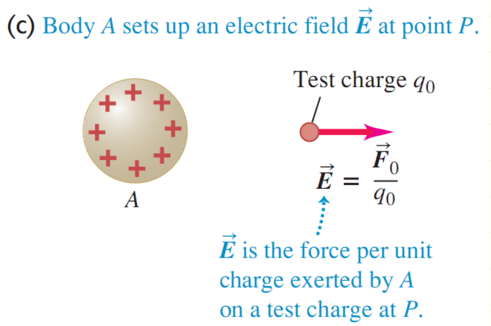
Consider two charged particles exerting a force on each other

Electric Field



consider body by*B* itself:
We remove body and label its former position as point *P*.

Electric Field



- We say that the charged body A produces or causes an electric field at point P and at all other points in the neighborhood.
- This electric field is present at even if there is no charge at P.
- it is a consequence of the charge on body A only.
- If a point charge q_0 is then placed at point P, it experiences the force $\vec{F}_0$.

- A single charge produces an electric field in the surrounding space, but this electric field cannot exert a net force on the charge that created it.
- a body cannot exert a net force on itself. (If this wasn't true, you would be able to lift yourself to the ceiling by pulling up on your belt!)

The electric force on a charged body is exerted by the electric field created by other charged bodies.

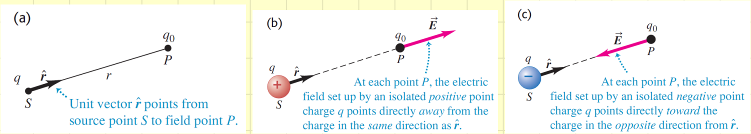
- To find out experimentally whether there is an electric field at a particular point, we place a small charged body, which we call a test charge, at the point.
- If the test charge experiences an electric force, then there is an electric field at that point. This field is produced by charges other than q_0.
- We define the electric field $\vec{E}$ at a point as the electric force $\vec{F}_0$ experienced by a test charge q_0 at the point, divided by the charge q_0.
- That is, the electric field at a certain point is equal to the electric force per unit charge experienced by a charge at that point:

$$\vec{E} = \lim_{q_0 \to 0} \frac{\vec{F}_0}{q_0}$$

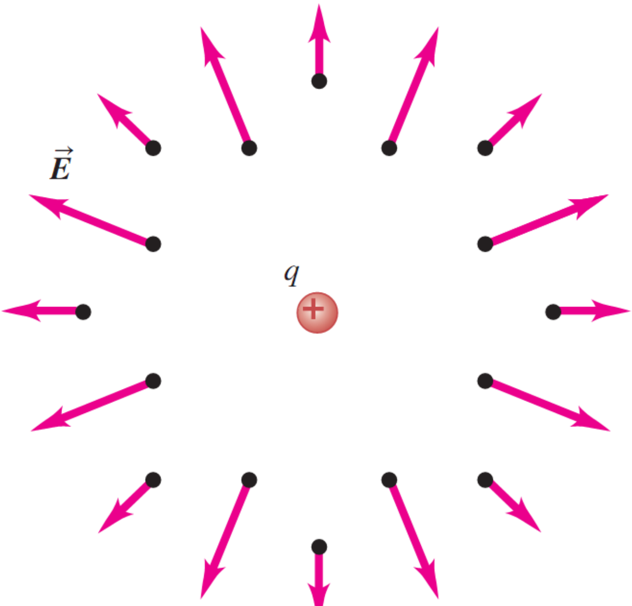
The electric field $\vec{E}$ or electric force per unit charge, is useful because it does not depend on the charge of the body on which the electric force is exerted.

Electric Field of a Point Charge

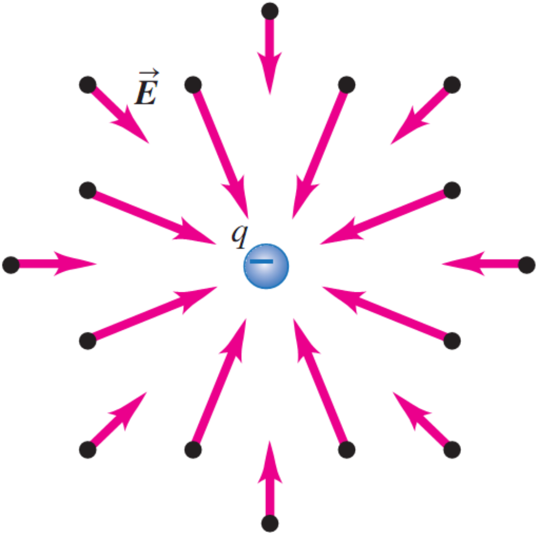
- If the source distribution is a point charge q, it is easy to find the electric field that it produces.
- We call the location of the charge the source point.
- we call the point P where we are determining the field the field point.
- we define a unit vector $\hat{r}$ that points along the line from source point to field point.


(a)
q_0
P
q
$\hat{r}$
r
S
Unit vector $\hat{r}$ points from source point S to field point P.
(b)
$\vec{E}$
q_0
P
q
$\hat{r}$
+
S
At each point P, the electric field set up by an isolated *positive* point charge q points directly *away* from the charge in the *same* direction as $\hat{r}$.
(c)
q_0
$\vec{E}$
P
q
$\hat{r}$
−
S
At each point P, the electric field set up by an isolated *negative* point charge q points directly *toward* the charge in the *opposite* direction from $\hat{r}$.

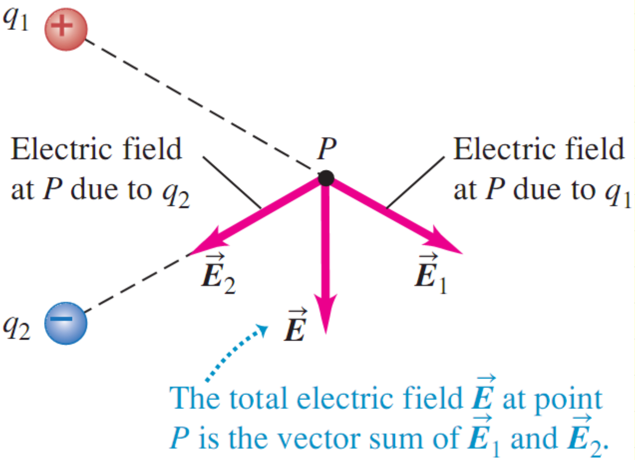
(a) The field produced by a positive point charge points *away from* the charge.



(b) The field produced by a negative point charge points *toward* the charge.

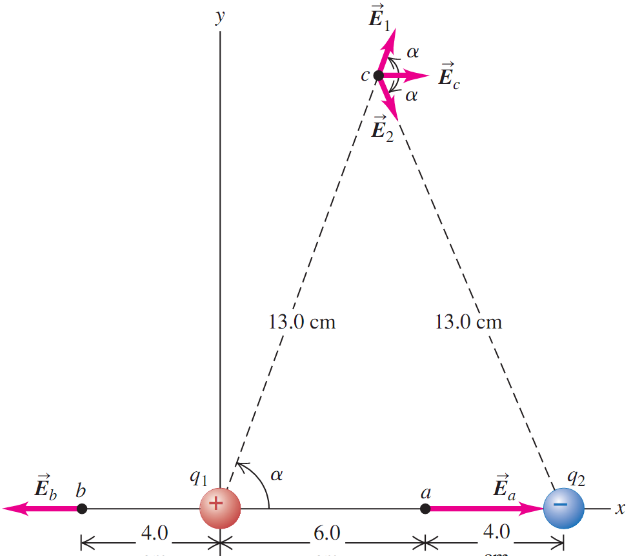


21.21 Illustrating the principle of superposition of electric fields.

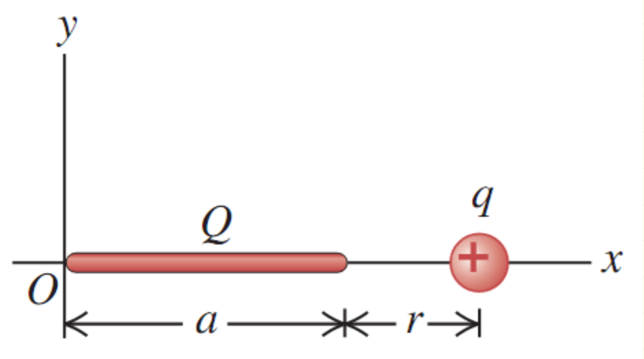


Electric Field of a Dipole

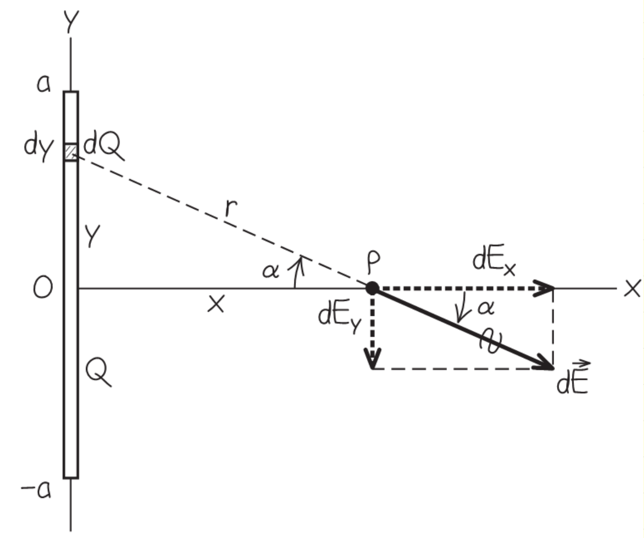
21.22 Electric field at three points, a, b, and c, set up by charges q_1 and q_2, which form an electric dipole.



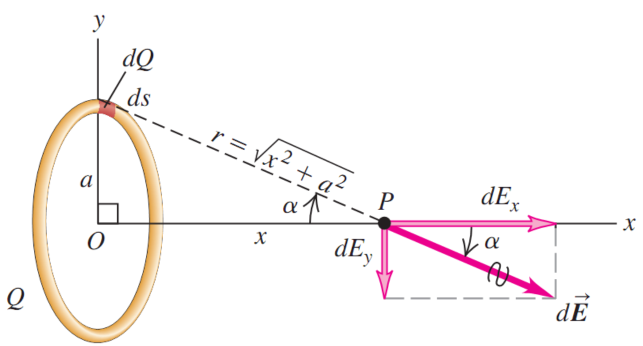
Electric Field of line of charge



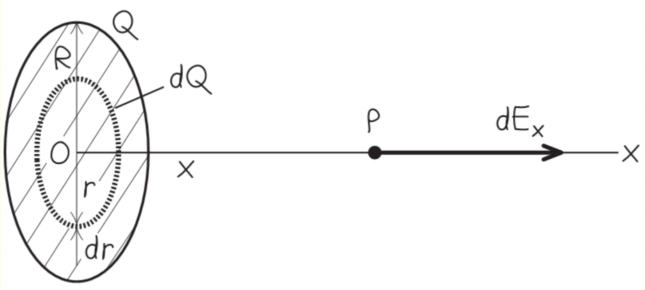
Electric Field of line of charge



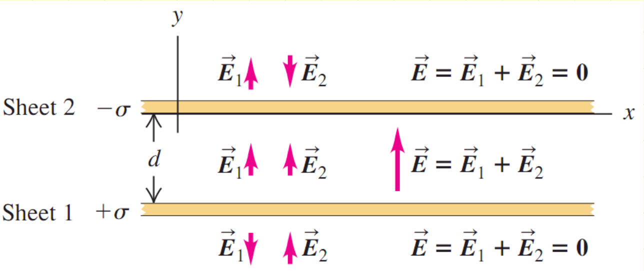
Electric Field of ring of charge



Electric Field of disk of charge



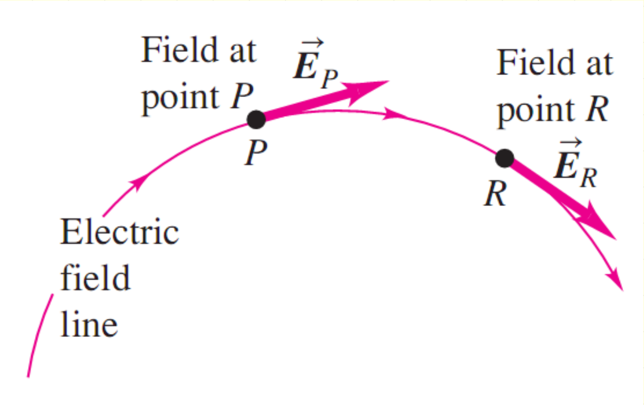
Field of two oppositely charged infinite sheets



Electric Field Lines

- We can not see electric fields directly.
- Electric field lines help for visualizing electric fields.
- An electric field line is an imaginary line or curve drawn through a region of space so that its tangent at any point is in the direction of the electric-field vector at that point.

Electric Field Lines



End of Lecture 3