The University of Nottingham

UNITED KINGDOM · CHINA · MALAYSIA

Science A Physics

Lecture 9: The Electrical Force

Aims of today's lecture

1. What is the Electrical Force?
2. Static Electricity
3. Insulators, Conductors and Semiconductors
4. Charging Objects
5. Coulomb's Law

Previously

- You may recall that when we looked at the manifestations of force, we referred to the electrical force and the magnetic force.
- We said that these forces, like gravity, exert a long-range force.
- Let’s look at the first of these forces: the electrical force; what exactly is it?

1. What is the Electrical Force?

What is the Electrical Force?

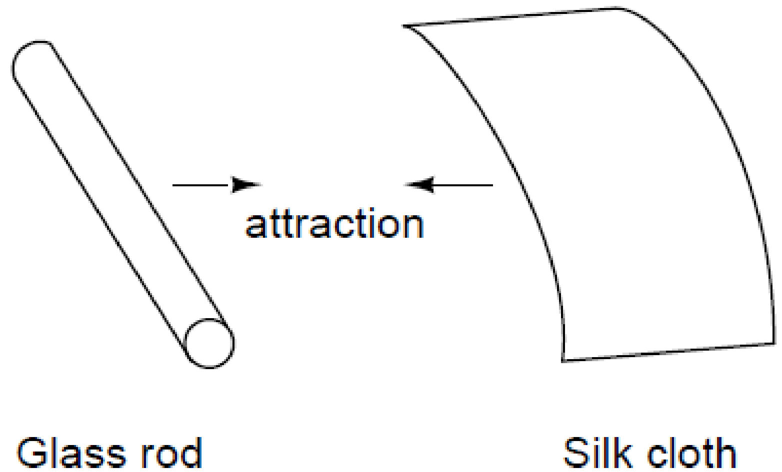
Q. What is the electrical force?

Thales

Amber

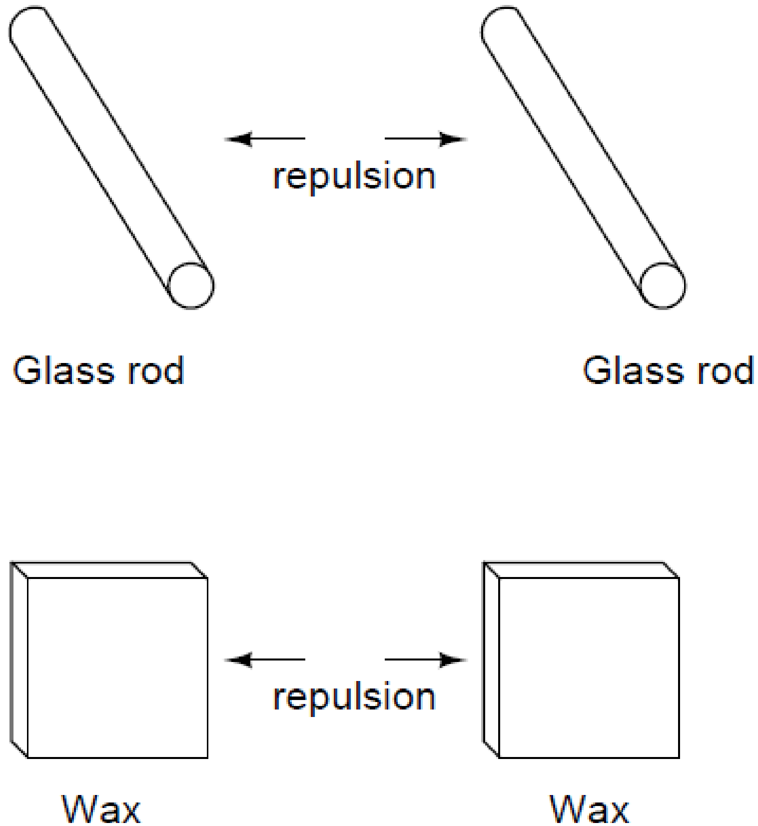
- Thales, the father of western philosophy, is the first known person to try and carry out systemic research into electricity.
- He observed, along with others, that when amber, the Latin word being ‘electrum’, was rubbed with a cloth, it could attract other objects, such as feathers. This was quite mysterious. Other materials, when rubbed, produced the same effect; let’s look at some more examples.

What is the Electrical Force?



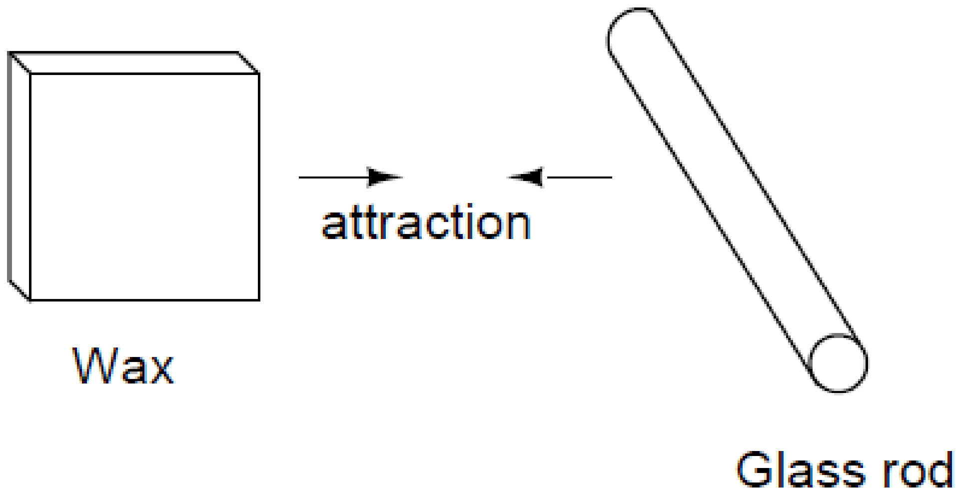
- After rubbing some silk against a piece of glass, the silk and glass tend to stick together, and there is also an attractive force between the materials when they are separated; **why?**

What is the Electrical Force?



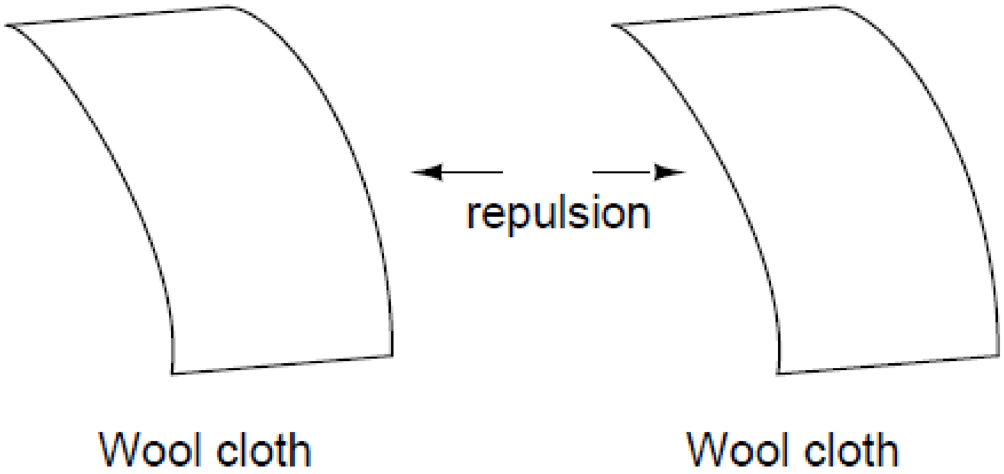
- Identical materials, after being rubbed with their respective cloths, can repel each other; **why?**

What is the Electrical Force?



- When a piece of glass rubbed with silk is exposed to a piece of wax rubbed with wool, the two materials can attract one another; **why?**

What is the Electrical Force?

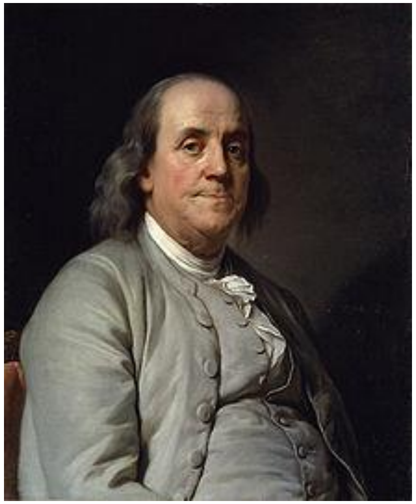


- **Conclusion:** **whatever change** takes place to make these materials attract or repel one another appears **invisible.**

Q. What is this invisible change?

A. Some experimenters thought that **invisible fluids** were being transferred from one object to another, making the objects attract or repel each other.

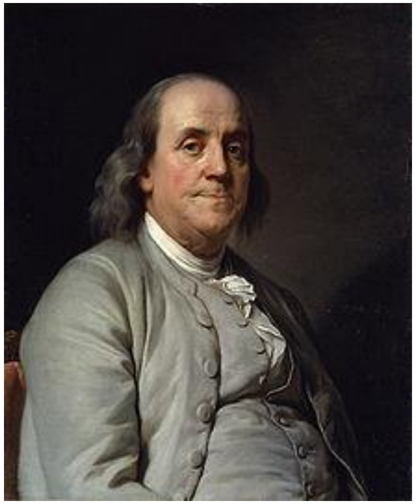
What is the Electrical Force?



Benjamin Franklin (1706-1790)

- Benjamin came to the conclusion that there was only one fluid exchanged between rubbed objects, and that the **two different changes** were nothing more than either an excess or a deficiency of that one fluid.

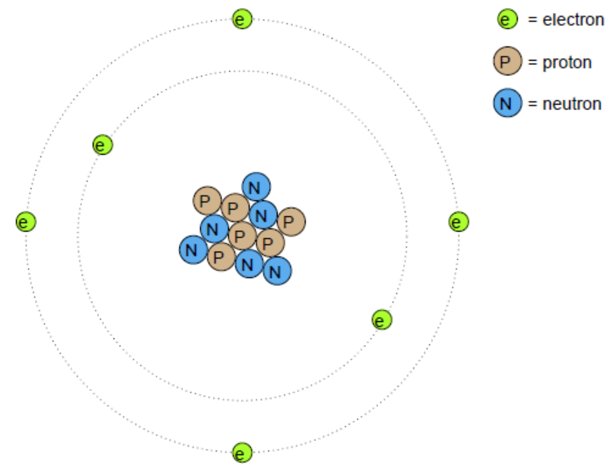
What is the Electrical Force?



Benjamin Franklin (1706-1790)

- An object with a deficiency of fluid was said to be negatively changed, while an object that had a surplus of this fluid was said to be positively changed.
- This above definition was not fully correct, however.

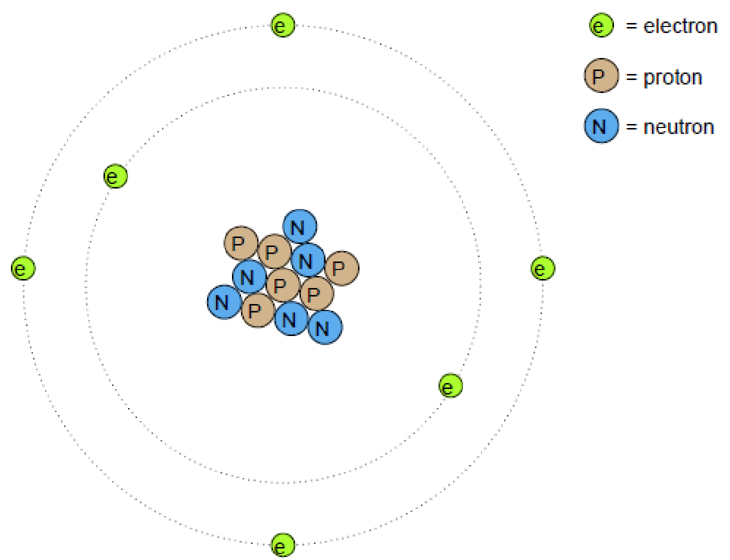
What is the Electrical Force?



- It was discovered much later that this fluid was actually composed of extremely small bits of matter called **electrons**, so named in honour of the Greek/Latin word for amber.

- We now know that all matter is composed of extremely small 'building-blocks' known as atoms, and that these atoms are composed of particles known as protons, neutrons and electrons.

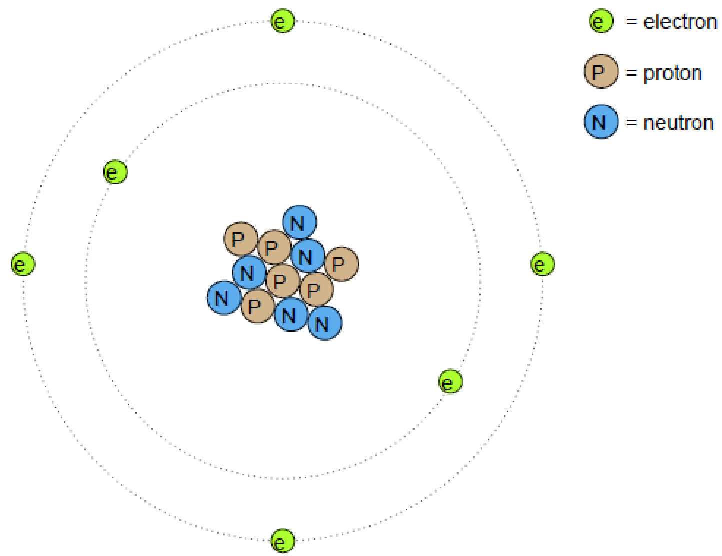
What is the Electrical Force?



- If we were able to look at an atom, we would see that it is composed mostly of empty space.

- An atom of any material has a characteristic number of protons and neutrons, which determines that material's identity.

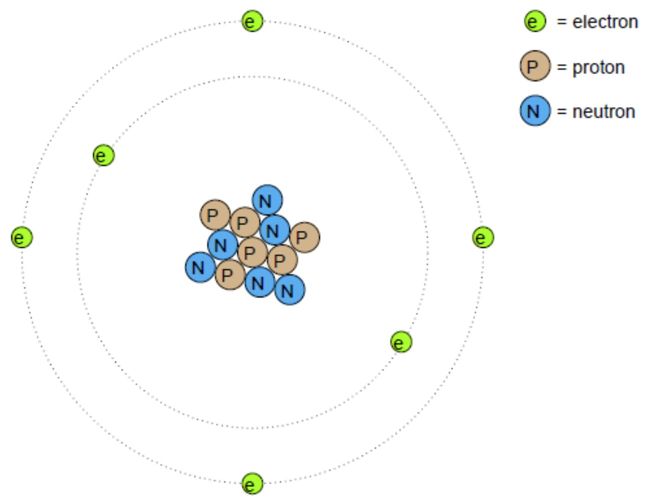
What is the Electrical Force?



- If a material is **uncharged**, its number of electrons is always equal to its number of protons.

- Electrons have significantly more freedom to move around in an atom than either protons or neutrons. They can even be displaced entirely from the atom.

What is the Electrical Force?

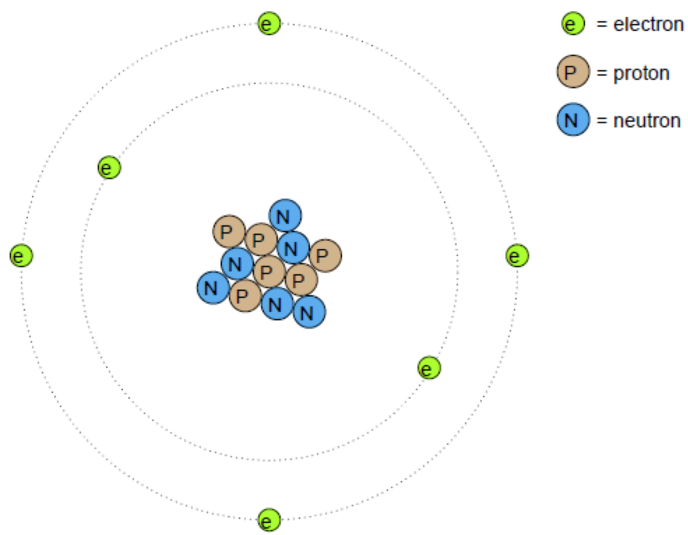


- If electrons become displaced entirely from the atoms of a particular material, the material still retains the visible appearance of its original identity, but an important **imbalance between protons and electrons** occurs.

N.B.

It is this imbalance that is responsible for the visible attraction or repulsion between objects that we observe after they have been rubbed.

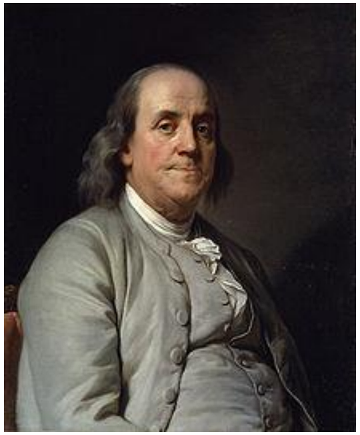
What is the Electrical Force?



- The process of electrons arriving or leaving is exactly what happens when certain combinations of materials are rubbed together: **electrons from the atoms of one material are forced by the rubbing to leave their respective atoms and transfer over to the atoms of the other material**.

N.B. In other words, electrons are like the fluid hypothesised by Franklin.

What is the Electrical Force?

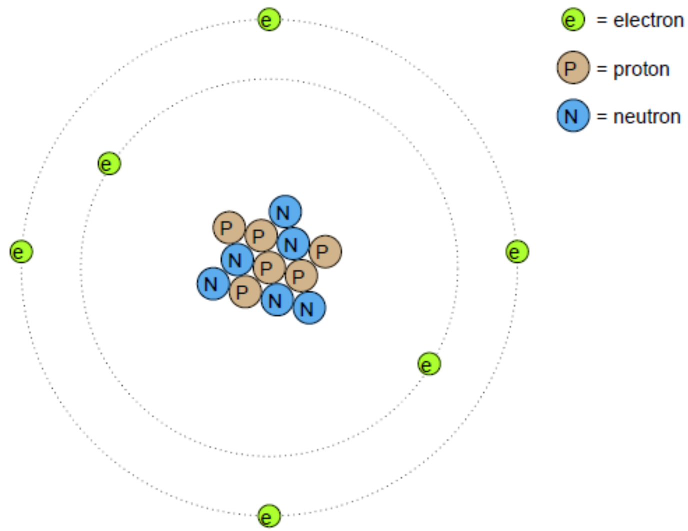


Benjamin Franklin (1706-1790)

- **Franklin's idea:** an object with a deficiency of fluid was said to be negatively changed, while an object that had a surplus of this fluid was said to be positively changed.

- **More Correct:** an object whose atoms have received a surplus of electrons is said to be **negatively charged**, while an object whose atoms are lacking electrons is said to be **positively charged**.

What is the Electrical Force?

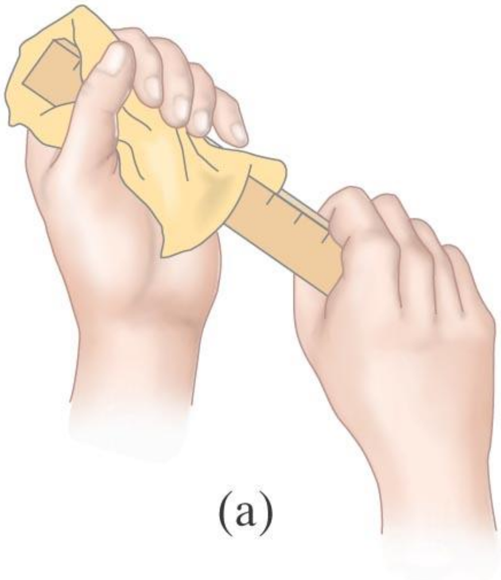


- The result of an imbalance of this fluid (electrons) between objects is called **static electricity**.

N.B. It is called **static electricity** because the displaced electrons tend to remain stationary after being moved from one material to another; let's have a look at this type of electricity in more detail.

2. Static Electricity

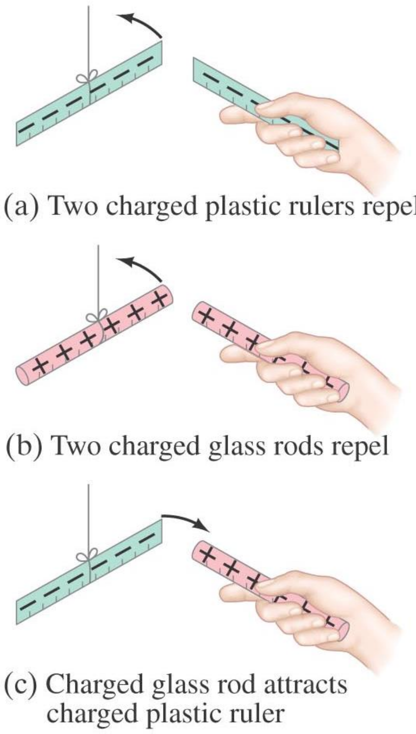
Static Electricity



(a)

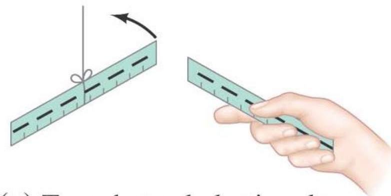
- An object can become ‘charged’ as a result of rubbing, and is said to possess a net electric charge.
- There are two types of electric charge.
- The two types of charge are either referred to as positive charge or negative charge.

Static Electricity

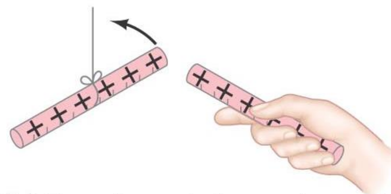


- Franklin set the charge on the rubbed glass to be positive charge, and the charge on the rubbed plastic ruler to be negative.
- Each type of charge repels the same type, but attracts the opposite type. That is: **unlike charges attract; like charges repel.**

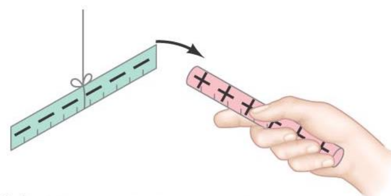
Static Electricity



(a) Two charged plastic rulers repel



(b) Two charged glass rods repel



(c) Charged glass rod attracts charged plastic ruler

- The **law of conservation of charge**: the net amount of electric charge produced in any process (such as rubbing glass with a cloth) is zero.
- In other words, no net electric charge can be created or destroyed.

Static Electricity

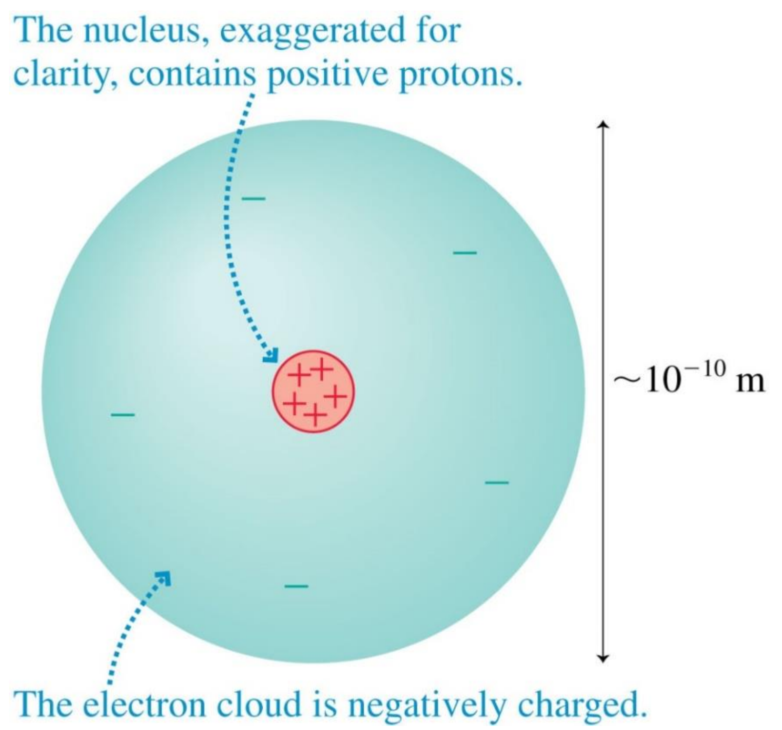
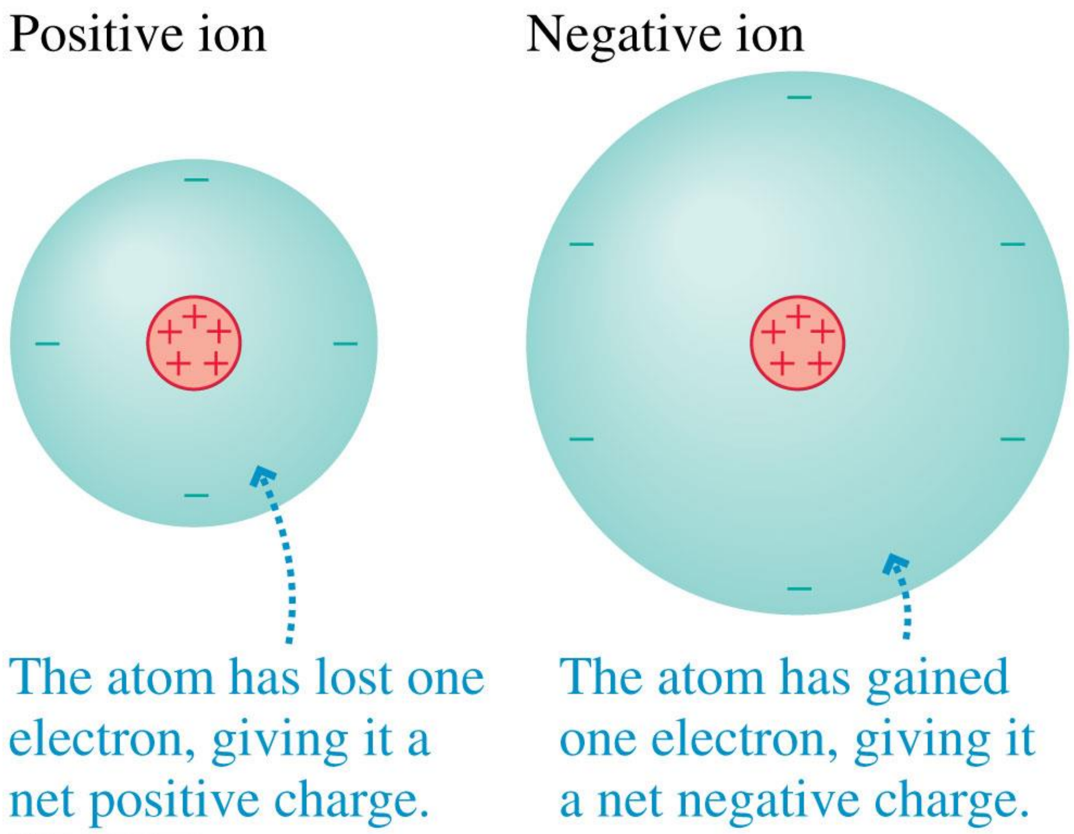


TABLE 25.1 Protons and electrons

Particle	Mass (kg)	Charge
Proton	1.67×10^{-27}	$+e$
Electron	9.11×10^{-31}	$-e$

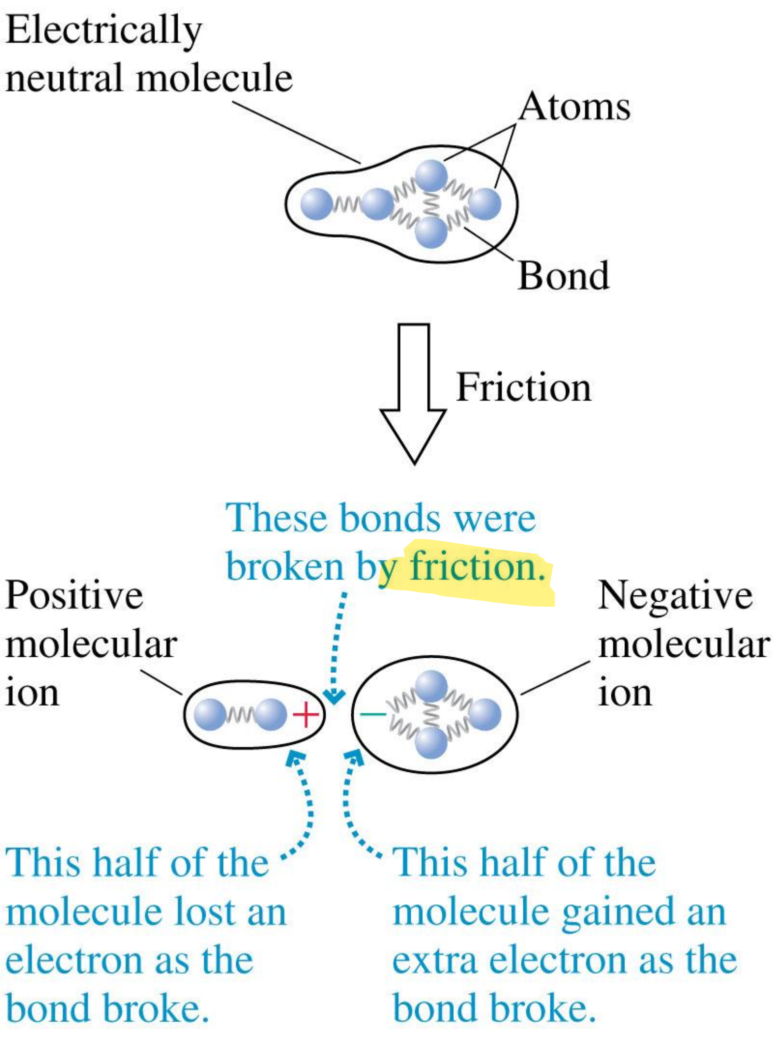
Static Electricity



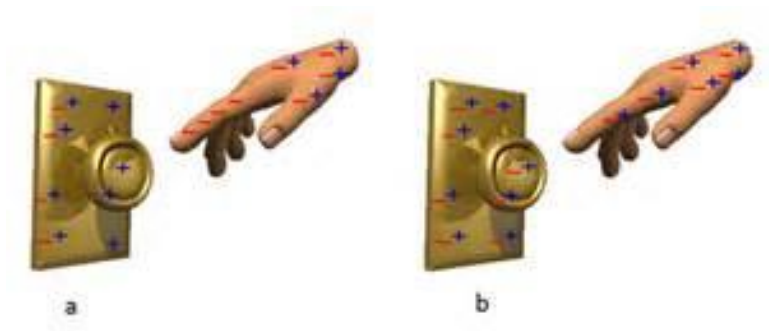
- The process of removing an electron from the electron cloud of an atom, or adding an electron to it, is called **ionization.**

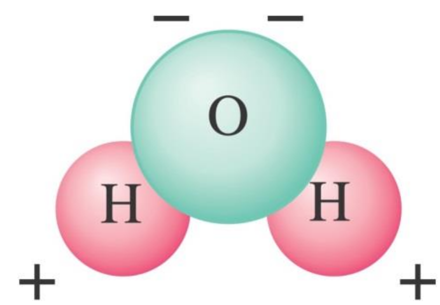
Static Electricity

- **Molecular ions** can be created when one of the bonds in a large molecule is broken.
- This is the way in which a plastic rod is charged by rubbing with wool, or a comb is charged by passing through your hair.



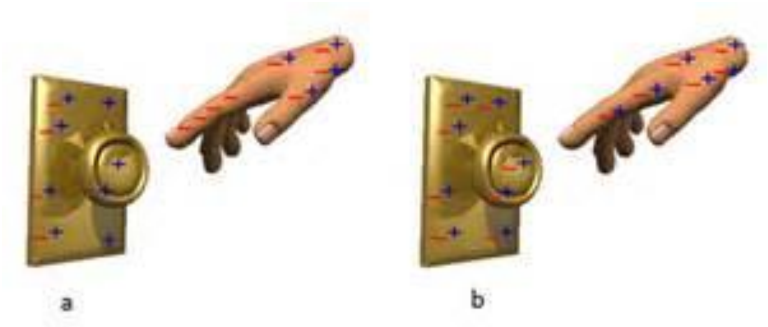
Static Electricity

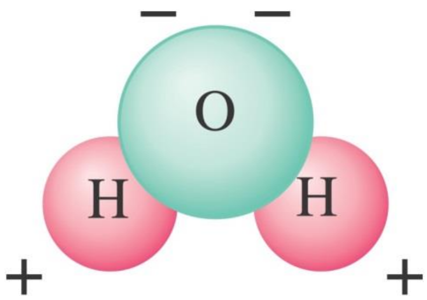




- Normally when objects are charged by rubbing, they hold their charge only for a limited time and eventually return to the neutral state. Where does the charge go?
- Usually the charge ‘leaks off’ onto water molecules in the air.
- This is because water is polar (even though water molecules are neutral, their charge is not distributed uniformly).

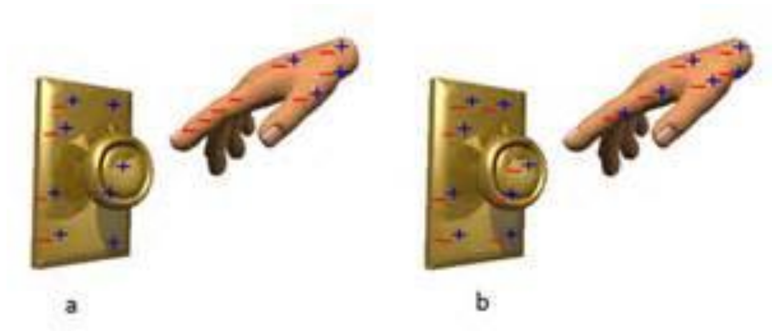
Static Electricity

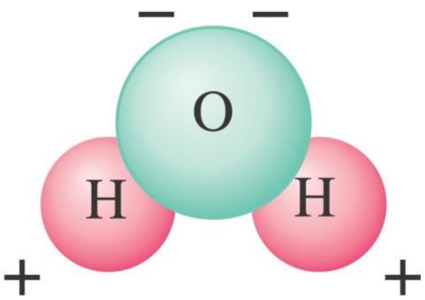




- Thus, the extra electrons on, say, a charged plastic ruler can ‘leak off’ into the air because they are attracted to the positive end of water molecules.
- A positively charged object, on the other hand, can be neutralised by the transfer of loosely held electrons from water molecules in the air.

Static Electricity



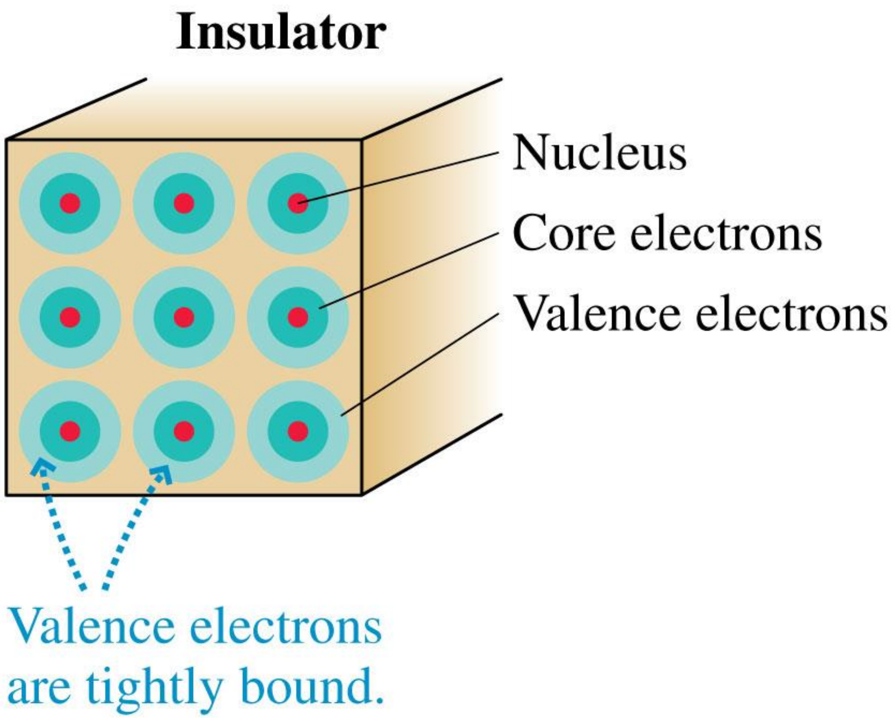


- On dry days, static electricity is much more noticeable since the air contains fewer water molecules to allow leakage.
- On humid or rainy days, it is difficult to make any object hold a net charge for long.
- Let’s now look at how well charge (usually electrons) can move within a material. The degree to which this occurs determines whether we refer to the material as either an insulator, conductor, or semiconductor.

3. Insulators, Conductors and Semiconductors

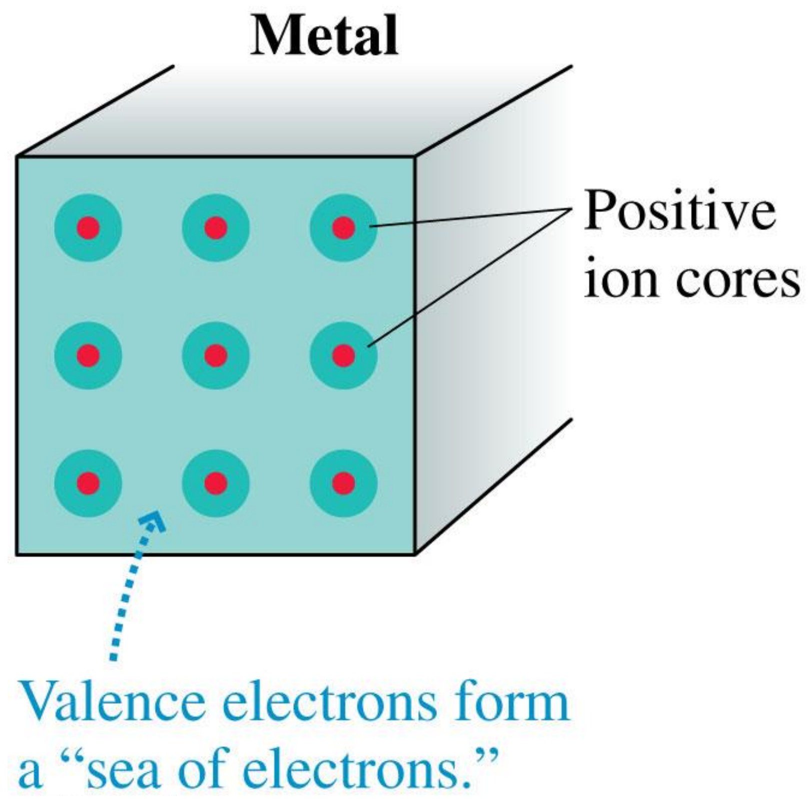
Insulators

- The electrons in an **insulator** are all tightly bound to the positive nuclei and not free to move around that much.
- Even when charging an insulator by friction, charged molecular ions on the surface tend to remain charged, not being able to accept nearby electrons to neutralize the ion.

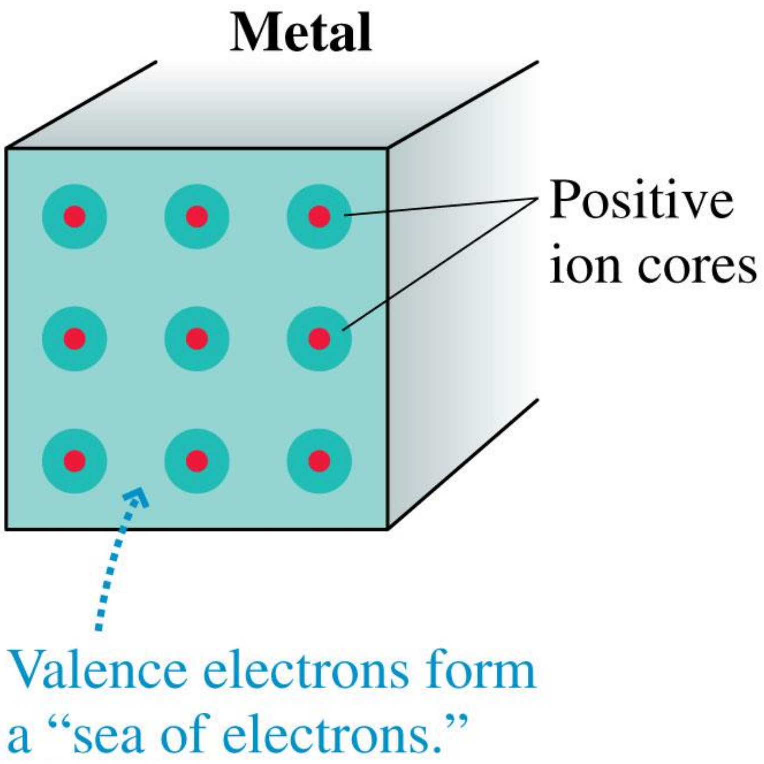


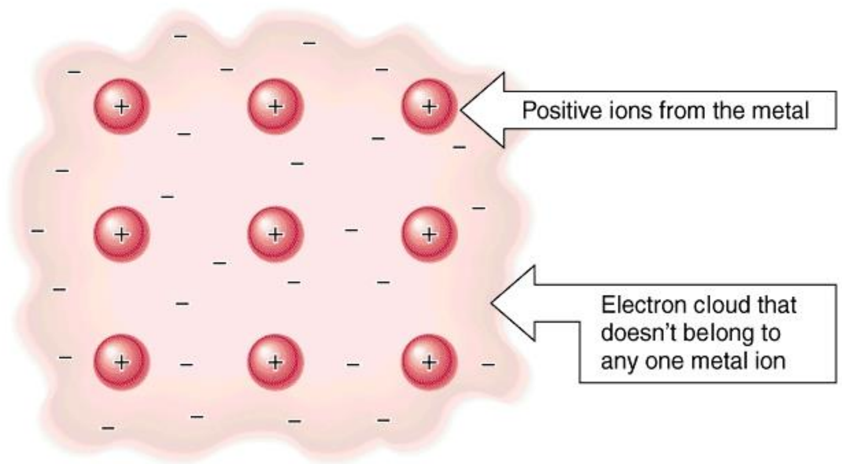
Conductors

- In metals, the outer atomic electrons are only weakly bound to the nuclei.
- These outer electrons become detached from their parent nuclei and are free to wander about through the entire solid.



Conductors





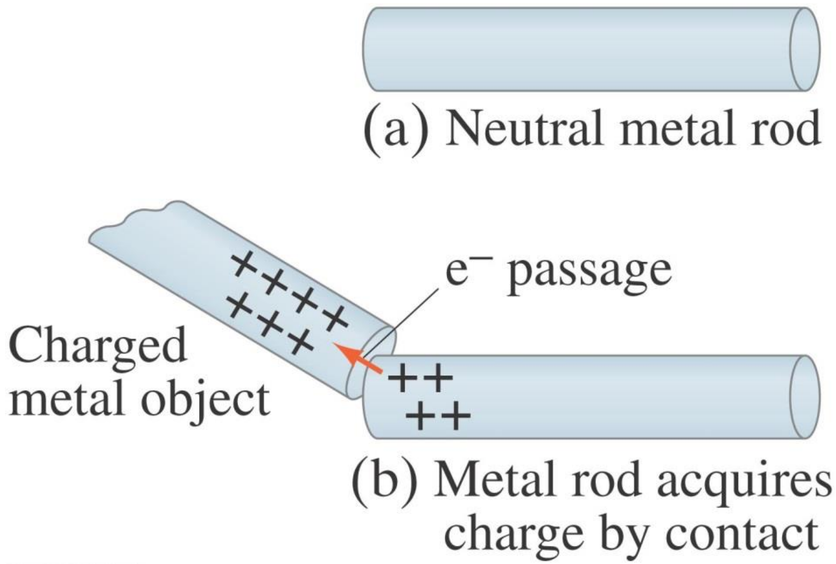
- The solid as a whole remains electrically neutral, but the electrons are now like a negatively charged liquid ('electron sea') with positively charged **ion cores** in this sea.

Semiconductors

- Metals are generally good conductors, whereas most other materials are insulators (although even insulators can conduct electricity very slightly).
- However, a few materials (such as silicon) are somewhat conductors and somewhat insulators. These materials are called **semiconductors**.
- Let’s again briefly look at how we can put charge on objects.

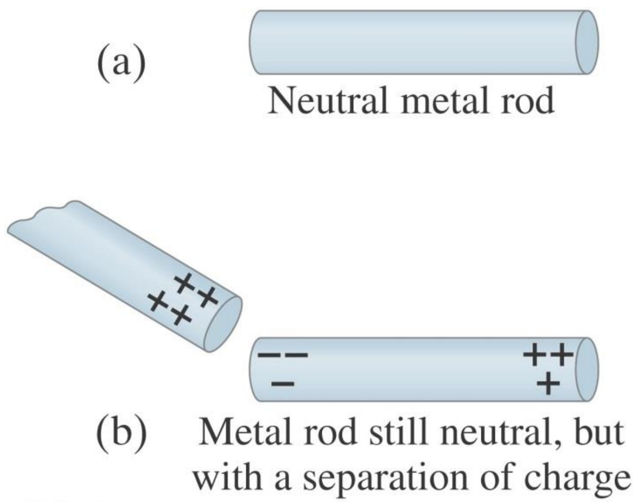
4. Charging Objects

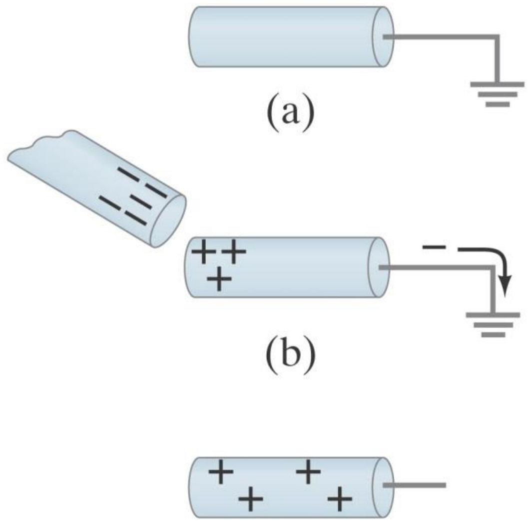
Charging by Conduction



- A neutral metal rod in (a) will acquire a positive charge if placed in contact (b) with a positively charged metal object, electrons moving as shown by the orange arrow.
- This is called charging by conduction.

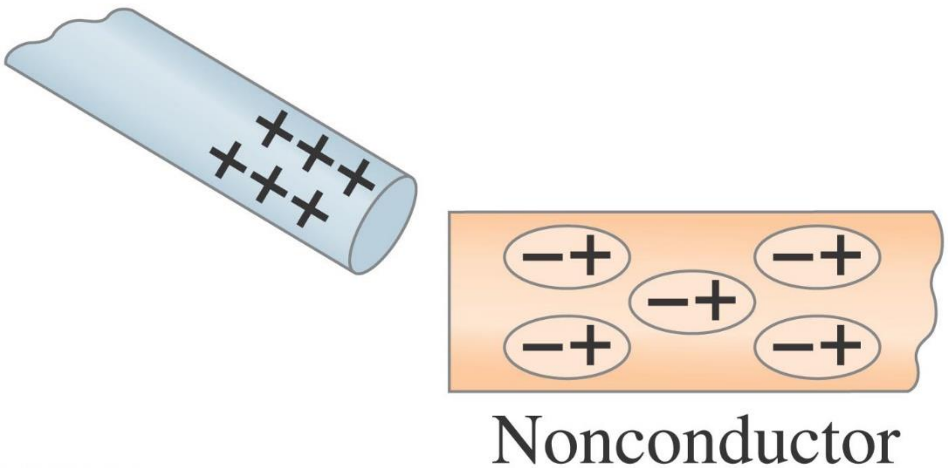
Charging by Induction





- In the figure on the right, another way to induce a net charge on a metal object is to first connect it with a conducting wire to the ground.
- The object is then said to be ‘grounded’ or ‘earthed’.
- The Earth, because it is so large and can conduct, easily accepts or gives us electrons; hence it acts like a reservoir for charge.

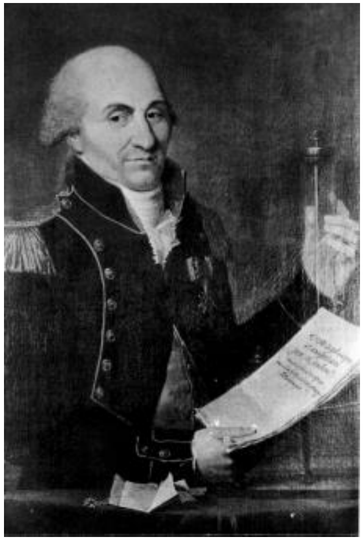
Charging by Induction

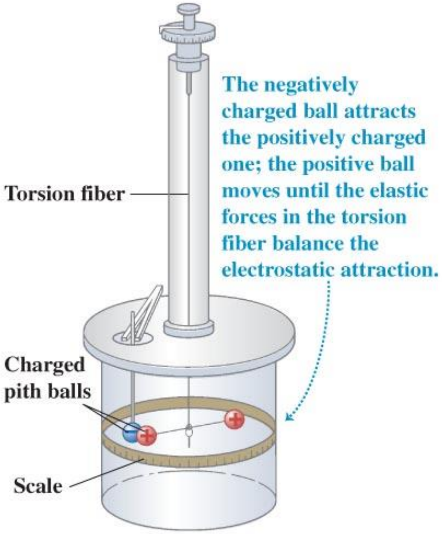


- If you a bring a positively charged object close to a neutral nonconductor, as shown above, almost no electrons can move freely within the nonconductor, but they can move slightly within their own atoms and molecules.
- Let’s now look at how we can try and quantify the force of attraction or repulsion between charges: **coulomb’s law.**

5. Coulomb’s Law

Coulomb's Law

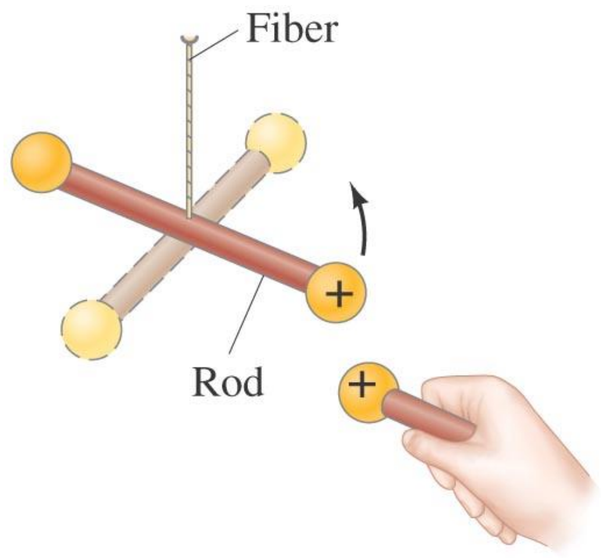


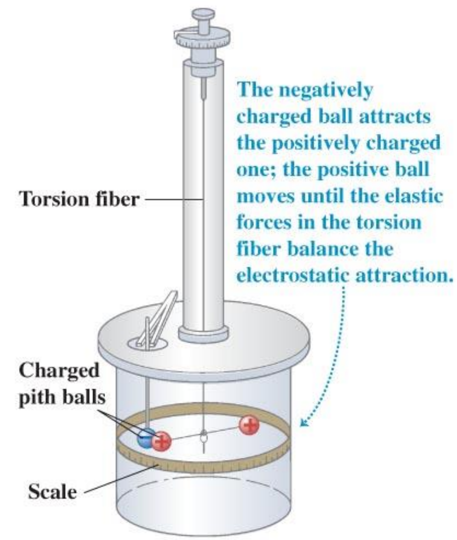


(a) A torsion balance of the type used by Coulomb to measure the electric force

- We have seen that an electric charge exerts a force of attraction or repulsion on other electric charges, but what factors affect the magnitude of this force?
- To find an answer to this, the French physicist Charles Coulomb (1736-1806) investigated electric forces in the 1780s using a torsion balance.

Coulomb's Law

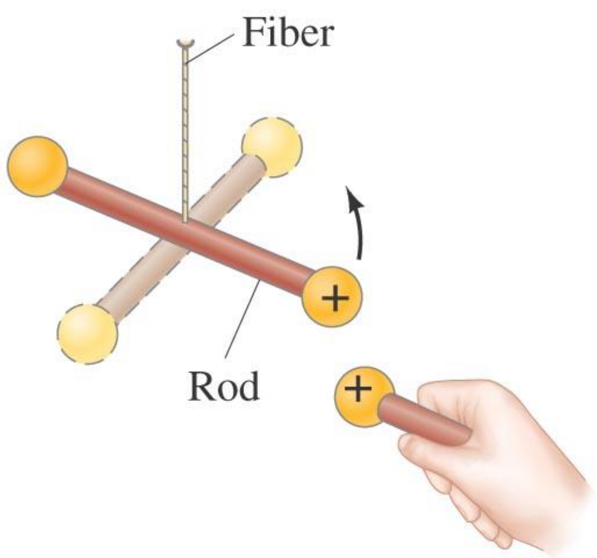


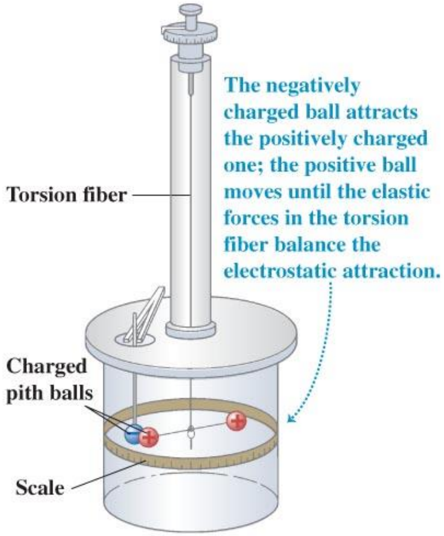


(a) A torsion balance of the type used by Coulomb to measure the electric force

- Precise instruments for the measurements of electric charge were not available in Coulomb's time. Nonetheless, Coulomb was able to prepare small spheres with different magnitudes of charge in which the ratio of the charges was known.

Coulomb's Law





(a) A torsion balance of the type used by Coulomb to measure the electric force

- Coulomb reasoned that if a charged conducting sphere is placed in contact with an identical uncharged sphere, the charge on the first would be shared equally by the two of them because of symmetry. He thus had a way to produce charges equal to ½, ¼, and so on, of the original charge, allowing him to measure the relationship between force and charge.

Coulomb's Law

Coulomb's law:

1. If two charged particles having charges q_1 and q_2 are a distance r apart, the particles exert forces on each other of magnitude

$$F_{1\text{ on }2} = F_{2\text{ on }1} = \frac{K|q_1||q_2|}{r^2}$$

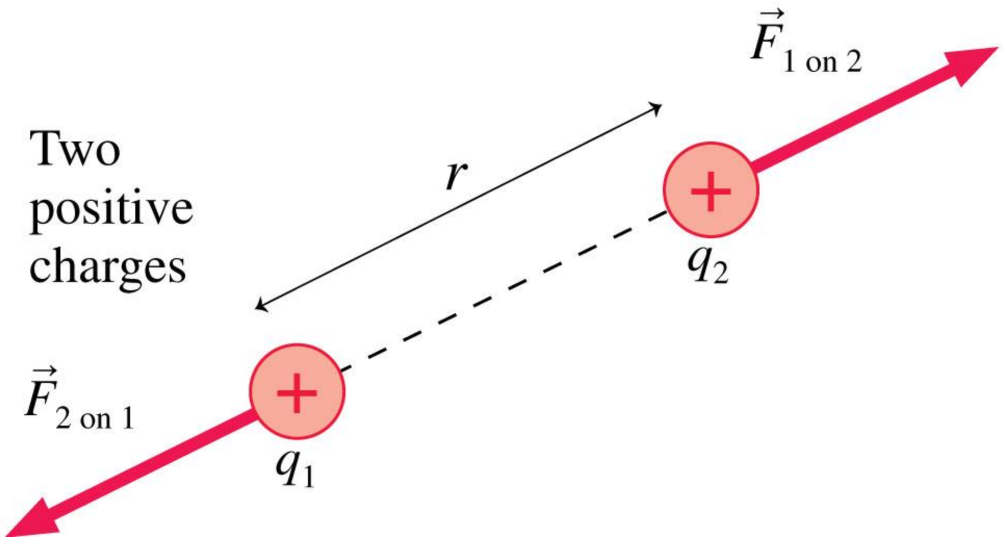
where K is called the **electrostatic constant.** These forces are an action/reaction pair, equal in magnitude and opposite in direction.

2. The forces are directed along the line joining the two particles. The forces are *repulsive* for two like charges and *attractive* for two opposite charges.

In SI units, $K = 8.99 \times 10^9\ \mathrm{N\,m^2/C^2}$.

Coulomb's Law

- When two positively charged particles are a distance, r, apart, they each experience a repulsive force.

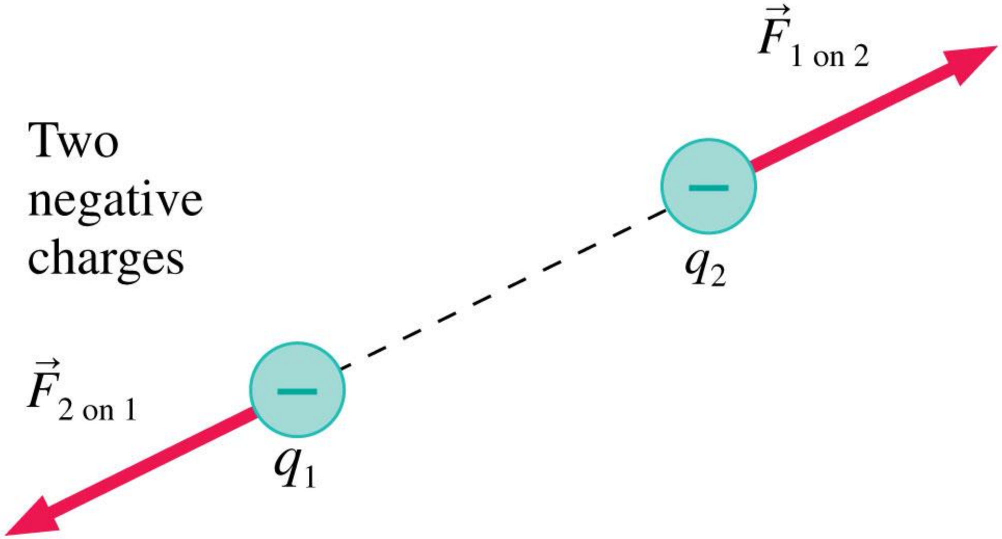


$$F_{1\text{ on }2} = F_{2\text{ on }1} = \frac{K|q_1||q_2|}{r^2}$$

In SI units, $K = 8.99 \times 10^9\ \mathrm{N\ m^2/C^2}$.

Coulomb's Law

- When two negatively charged particles are a distance, r, apart, they each experience a repulsive force.

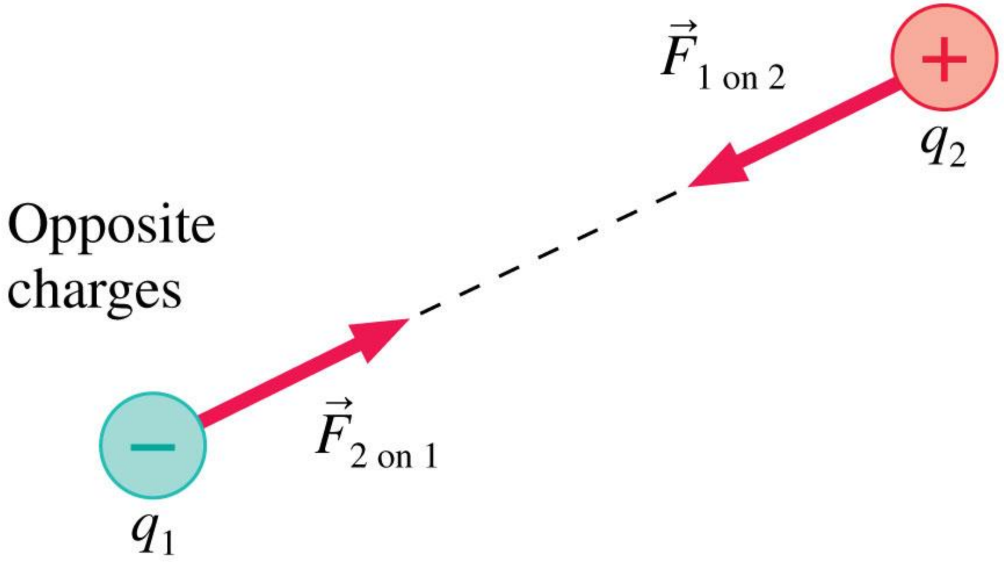


$$F_{1 \text{ on } 2} = F_{2 \text{ on } 1} = \frac{K|q_1||q_2|}{r^2}$$

In SI units, $K = 8.99 \times 10^9 \text{ N m}^2/\text{C}^2$.

Coulomb's Law

- When two oppositely charged particles are a distance, r, apart, they each experience an attractive force.



$$F_{1 \text{ on } 2} = F_{2 \text{ on } 1} = \frac{K|q_1||q_2|}{r^2}$$

In SI units, $K = 8.99 \times 10^9 \text{ N m}^2/\text{C}^2$.

Coulomb's Law

$$F_{1 \text{ on } 2} = F_{2 \text{ on } 1} = \frac{K|q_1||q_2|}{r^2}$$

- The unit for charge (Q) in Coulomb's law is the Coulomb (C).

- 1 C is defined as the amount of charge, which if placed on each of two point objects that are 1.0 m apart, will result in each object exerting a force on each other of
  $$(9.0 \times 10^9 \mathrm{N} \cdot \frac{\mathrm{m}^2}{\mathrm{C}^2})(1.0\mathrm{C})(1.0\mathrm{C})/(1.0\mathrm{m})^2 = 9.0 \times 10^9 \mathrm{N}.$$

- This would be an enormous force. In the real world, we rarely encounter a 1 C charge.

Coulomb's Law

$$F_{1\text{ on }2} = F_{2\text{ on }1} = \frac{K|q_1||q_2|}{r^2}$$

- We now know that **1 Coulomb** is be equal to an excess or deficiency of about 6,250,000,000,000,000,000 electrons.
- Or stated in reverse terms, one electron ($\boldsymbol{e}$) has a charge of about 0.00000000000000000016 Coulombs , or

$$(\mathbf{1\ e} = 1.602176 \times 10^{-19}\mathrm{C})$$

Coulomb's Law

$$F_{1 \text{ on } 2} = F_{2 \text{ on } 1} = \frac{K|q_1||q_2|}{r^2}$$

$$(\mathbf{1\ e} = 1.602176 \times 10^{-19}\mathrm{C})$$

- Since an object cannot gain or lose a fraction of an electron, the net charge on any object must be an integral multiple of this charge.
- We say electric charge is quantised, existing only in discrete amounts: $1e$, $2e$, $3e$, etc.
- Because e is so small, however, we normally do not notice this discreteness in macroscopic charges. $1\mu C$ requires about 10^{13} electrons, which thus seems continuous.

Coulomb's Law

$$F_{1\text{ on }2} = F_{2\text{ on }1} = \frac{K|q_1||q_2|}{r^2}$$

- The constant, k, is often written in terms of another constant, ϵ_0, called the **permittivity of free space**. It is related to k by $k = \frac{1}{4\pi\epsilon_0}$.
- Coulomb's law can then be written as

$$F = \frac{1}{4\pi\epsilon_0}\frac{Q_1 Q_2}{r^2}$$

where

$$\epsilon_0 = \frac{1}{4\pi k} = 8.85 \times \frac{10^{-12}\mathrm{C}^2}{\mathrm{N}} \cdot \mathrm{m}^2.$$

Coulomb's Law

$$F_{1\text{ on }2} = F_{2\text{ on }1} = \frac{K|q_1||q_2|}{r^2}$$

- Coulomb's law is, ideally, precise for point charges (spatial size of the charges is negligible compared to the distance between the charges).

- For finite-sized objects, it is not always clear what value to use for r. However, we can make the assumption that the charge on the objects is distributed uniformly on these objects, and that r is the distance between the centres of these objects.

- Coulomb's law also only describes the force between two charges when they are at rest (**electrostatics**).

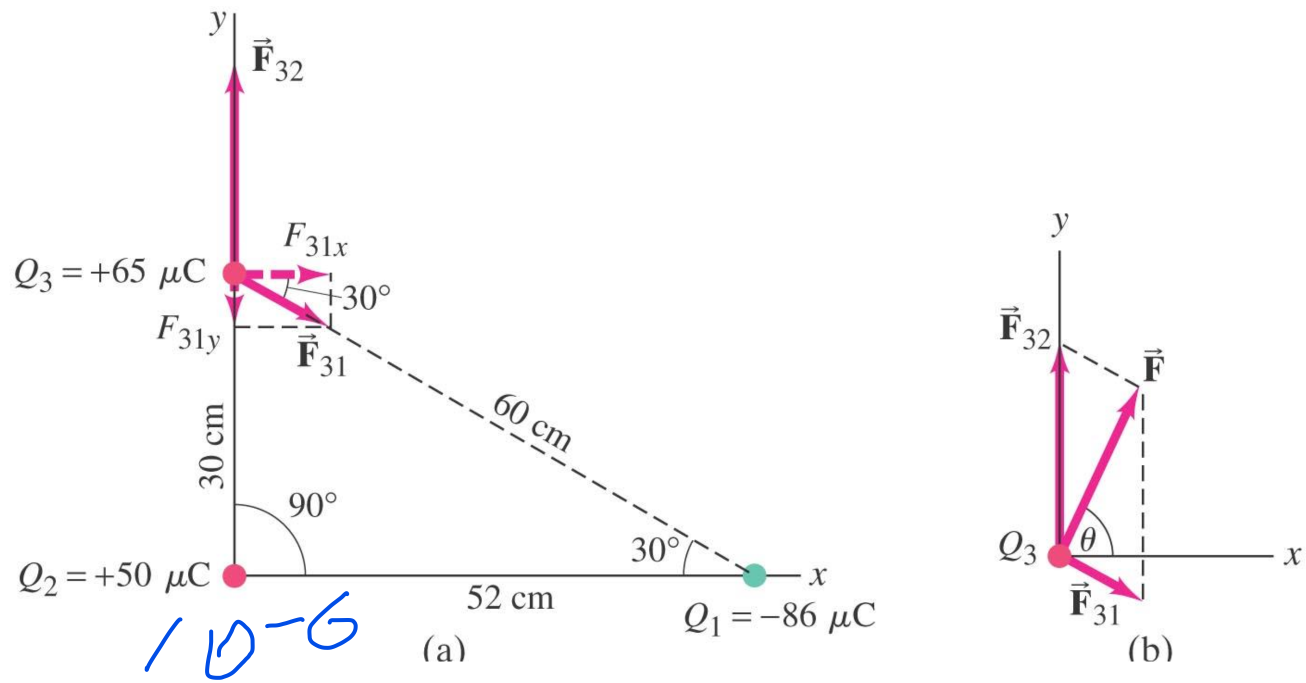
Coulomb's Law

$$F_{1\text{ on }2} = F_{2\text{ on }1} = \frac{K|q_1||q_2|}{r^2}$$

- Coulomb's law also only gives the force on a charge due to only one other charge. If several (or many) charges are present, the net force on any one of them will be the vector sum of the forces due to each of the others. This is called the **principle of superposition**, and is based on experiment.

- For continuous distributions of charge, the sum becomes an integral.

Possible Exam Question: Have a Read (p.654)



Q. Calculate the net electrostatic force on charge Q_3 shown in the above figure (a) due to charges Q_1 and Q_2.

Summary of today's Lecture

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1. What is the Electrical Force?
2. Static Electricity
3. Insulators, Conductors and Semiconductors
4. Charging Objects
5. Coulomb's Law

Lecture 9: Optional Reading

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- **Ch. 21.5**, Coulomb's law; p.651-655
- **Ch. 21.6**, The Electric Field; p.656
- **Ch. 21.8**, Field Lines; p.663-664

Home Work

Do not forget to attempt the **Additional Problems** for this lecture before logging in to **Mastering Physics** to complete your assignments.