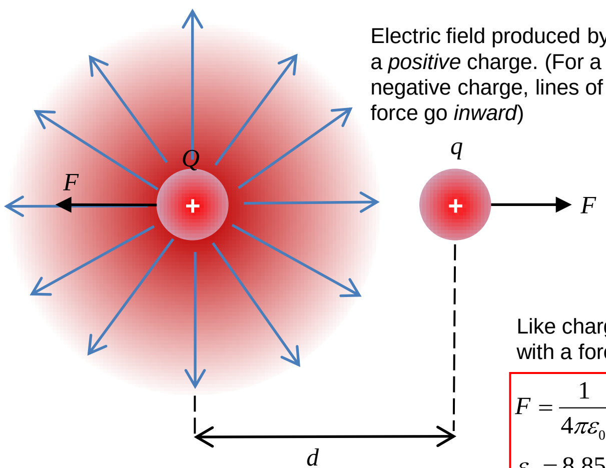
Charge and electrostatics

Charge is a fundamental property of matter. Like mass, which exerts a *force* of gravity upon other masses, *charges will exert a force on other charges*. You can model this mathematically by calculating the *electric field* produced by one or more charges. The force on a particular charge is the product of the strength of this field and the quantity of charge. Gravity works in a very similar way, with two crucial differences. Firstly, the strength of electric fields are *much stronger* than gravitational ones, as you need a planet to exert enough gravity on a human-sized mass to be significant, whereas a modest amount of current (which is the flow of charge) in a scrap yard electromagnet will lift a car. Secondly, charges come in two variants of charge, *positive and negative*. Unlike gravity, *like signed charges repel each other, whereas opposite signed charges attract.*

Matter is comprised of atoms, and atoms themselves have a structure where a positively charged nucleus lies at the centre of a cloud of negatively charged *electrons*. The nucleus comprises positively charged *protons* and uncharged *neutrons*. Electrons and protons have the same magnitude of charge as each other, but very different masses (the electron is much lighter). In electrical systems, it is therefore the electron which is doing the moving. i.e. free flowing in a 'sea' of electrons in a metal **conductor**, or bound to a collection of atoms that form the molecules of an **insulator**.

Anti-particles, such as the *positron* (the anti-electron) have the *same mass* as their particle namesake, but the *opposite sign* of charge.

The transfer of charge between atoms, in particular when atoms combine to form molecules, is the basis of *Chemistry*. When an atom loses or gains electrons it forms an *ion*.



Electric field produced by a *positive* charge. (For a negative charge, lines of force go *inward*)

Particle	Charge	Mass /kg	Mass / electron masses
Proton	$+e$	1.6726×10^{-27}	1,836
Neutron	0	1.6749×10^{-27}	1,839
Electron	$-e$	9.1094×10^{-31}	1

$e = 1.6022\times10^{-19}\,\mathrm{C}$

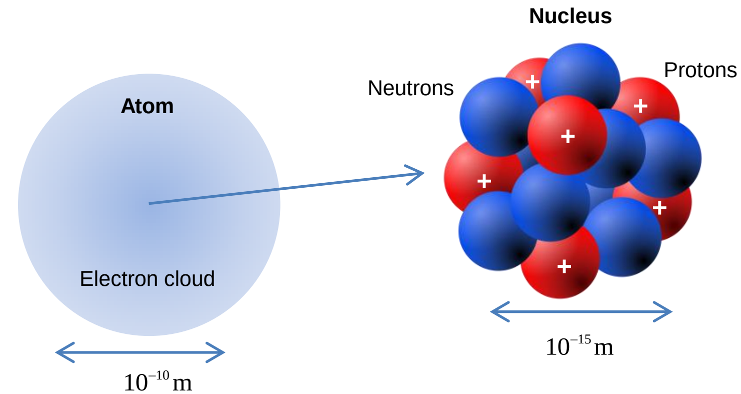
Charge is measured in *coulombs*, with the fundamental unit being the charge on the electron.

Like charges will *repel* with a force

$$\boxed{\begin{aligned} F &= \frac{1}{4\pi\varepsilon_0}\frac{qQ}{d^2} \\ \varepsilon_0 &= 8.8542\times10^{-12}\,\mathrm{Fm^{-1}} \end{aligned}}$$

This is Coulomb's Law of Electrostatics

Permittivity of free space



A positively charged nucleus is at the centre of every atom, surrounded by a cloud of electrons.

We use the term *cloud* to correspond to the *chance* of finding an electron. The cloud density is proportional to probability of finding an electron. The shape of these charge-clouds gives rise to the particular geometries of molecules such as water, and indeed their chemical properties.

Note the dimensions of a typical atom are **about 100,000 times that of the nucleus dimensions.** This means if a nucleus was a metre wide and centred in Winchester, UK, the electron cloud would extend 100km away to Central London!

Charles-Augustin de Coulomb
1736-1806

Compare the strength of gravity for two protons at separation d with electrostatic repulsion

$$F_E = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{d^2}$$

$$F_G = \frac{Gm^2}{d^2}$$

$$\frac{F_E}{F_G} = \frac{e^2}{4\pi\varepsilon_0 Gm^2}$$

$$\boxed{\frac{F_E}{F_G} \approx 1.236\times10^{36}}$$

For two electrons:

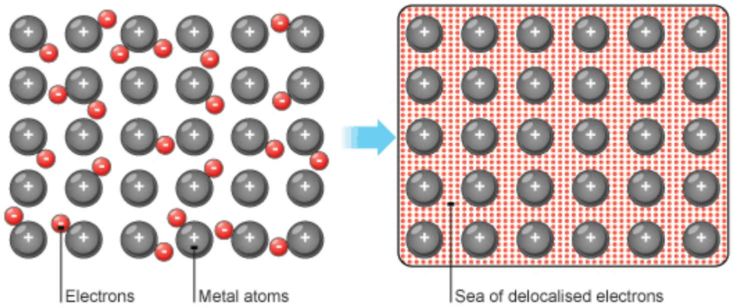
$$\frac{F_E}{F_G} \approx 1.236\times10^{36}\times1{,}836^2$$

$$\boxed{\frac{F_E}{F_G} \approx 4.165\times10^{42}}$$

So electric force is MUCH stronger at an atomic scale.

So how does a nucleus stay together?
Over scales of 10^{-15} m the *Strong* and *Weak* **nuclear forces** counteract electrostatic repulsion. Neutrons as well as protons contribute to these forces.

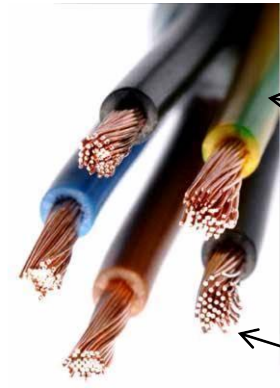
$G = 6.6741\times10^{-11}\,\mathrm{m^3kg^{-1}s^{-2}}$ Universal Gravitational constant



Metals are good **conductors** as electrons can move easily within them

For the same reason, **electrical conductors** are also **good thermal conductors.** The relatively free movement of electrons can transfer atomic vibration easily, which on a macroscopic level is the flow of *heat***.**

Good conductors are: silver, copper, aluminium, carbon
Poor conductors are: water, human body, soil



Plastic wire insulator

Copper wire.
metallic bonding of atoms so a good electrical (and heat) conductor

Semiconductors can behave like conductors when hot, and insulators when cold.

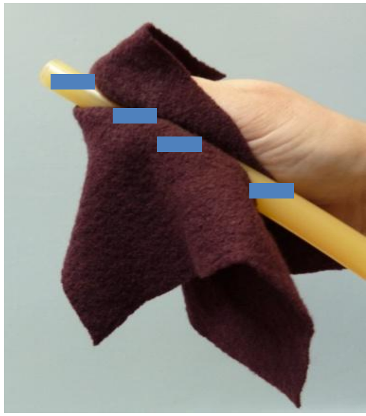
e.g. silicon, germanium

'Doping' these materials with other atoms can result in control of this transition. This is the basis of most electronic devices such as a *transistor*.

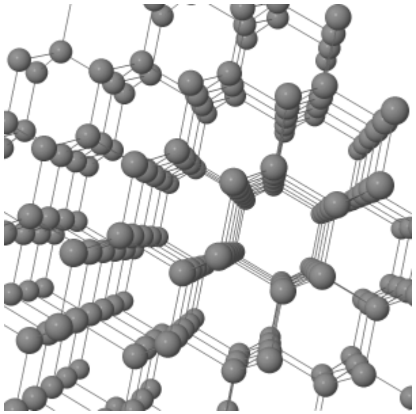
In a practical demonstration you can **transfer charge to insulators** such as **polythene** or **Perspex** via **rubbing** them with a **wool cloth**. In this process:

- Polythene will *gain* electrons from the wool, becoming *negatively* charged.
- Perspex will *lose* electrons to the wool, becoming *positively* charged.

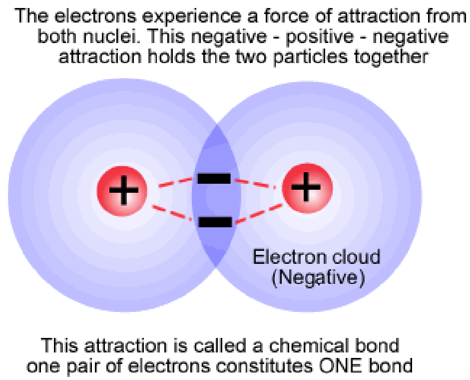
Since Perspex and Polythene are both insulators they will retain the charge on their surface until they touch a conductor, which will easily supply or extract electrons to neutralize the charge.

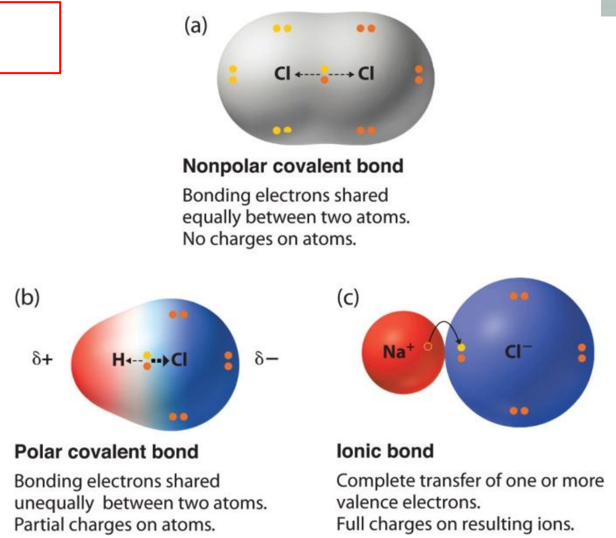


Insulators (such as **plastics**) are often polymers formed from a network of **covalent bonds.** It is much harder to extract electrons from them!



Good insulators are: plastics (PVC, polythene, Perspex...), glass, rubber, dry air

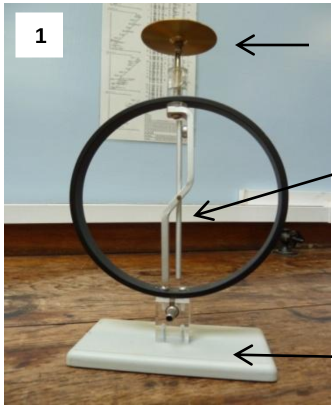




Electrons are shared between atoms in **molecules**. The separation of charge defines the type of bond, with *nonpolar covlalent* at one extreme and *ionic* another.

Ionic solids (such as table salt, or Sodium Chloride) can, unlike covalent structures, be *good conductors*, as introduced electrons will be able to flow freely. For NaCl this only happens in a molten state. Solid NaCl is a poor conductor as electrons, although unshared, are tightly bound.

Detecting charge with an Electroscope

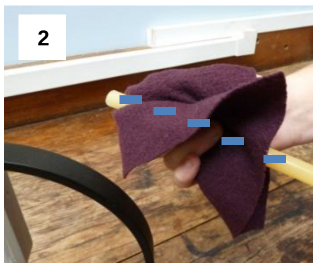


Metal cap

Easily rotatable metal arm

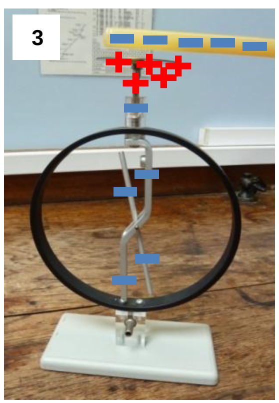
Fixed metal piece

Rub an insulating rod to transfer charge via friction. In this example the polythene rod *gains* electrons (-ve charge)



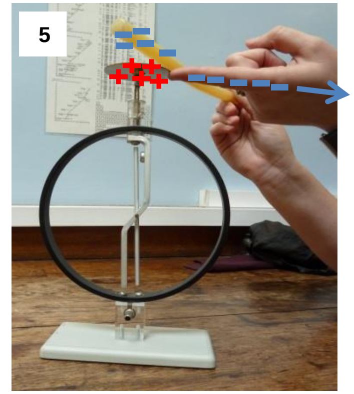
Placing the rod *near* the cap will cause electrons to be *repelled*.

The electrons on the rotatable arm and fixed piece *also repel each other*, which rotates the arm



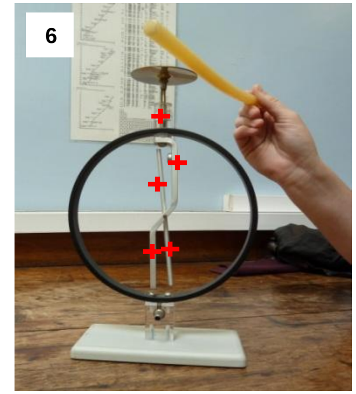
The arm rotates until the *anticlockwise turning moment* due to electron repulsion equals the *clockwise moment* due to the *weight* of the extended arms.

You might find the rotating arm *oscillates* about this equilibrium position

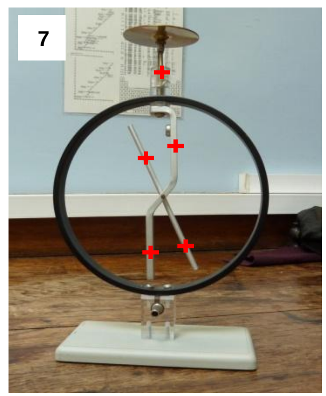


Touching the cap with you finger will *earth* it. This means any net charge can flow from the fixed piece, through the cap and to ground via the fingers.

So all of the ***induced*** –ve charge in the fixed piece and arm is now *conducted away through the fingers*. Hence the rotating arm closes.

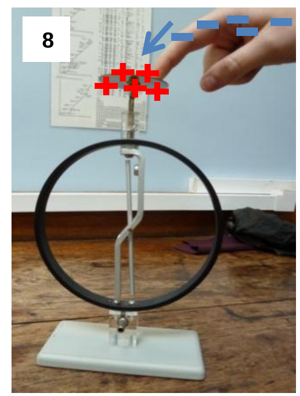


Note the charge remaining on the electroscope will be the *opposite charge* to that on the charging rod



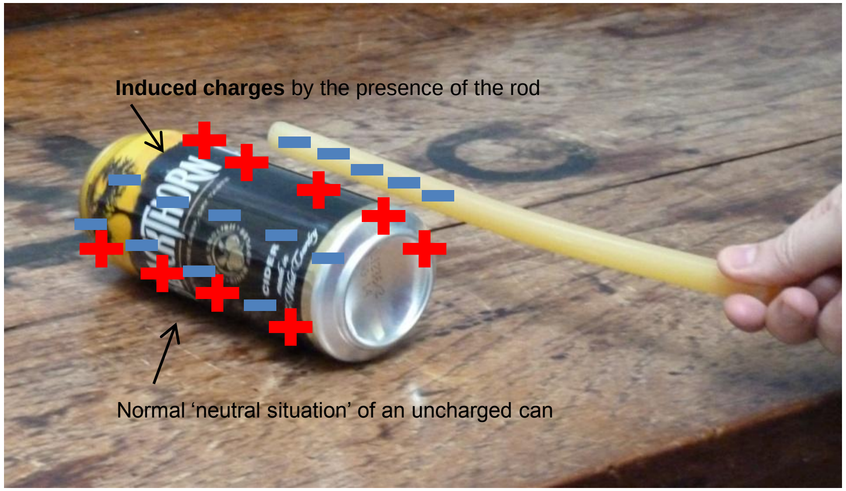
Now withdraw the –ve charged rod ....

The net +ve charge in the cap redistributes..... Causing the arm to re-open!

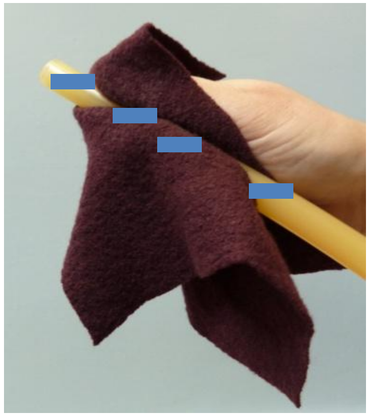


To discharge, ground the cap one last time with your fingers

‘Walking a can’ with a charged polythene rod



Rubbing a polythene rod transfers electrons to it. Polythene is an *insulator* so the charge remains on the surface (rather than flowing to ground if it were a *conductor*).



Placing the negatively charged rod near a metal can will cause the *lightly held electrons* on it to be *repelled*, leaving a *net positive charge.*

The positively charged can will therefore roll *towards* the negatively charged rod.