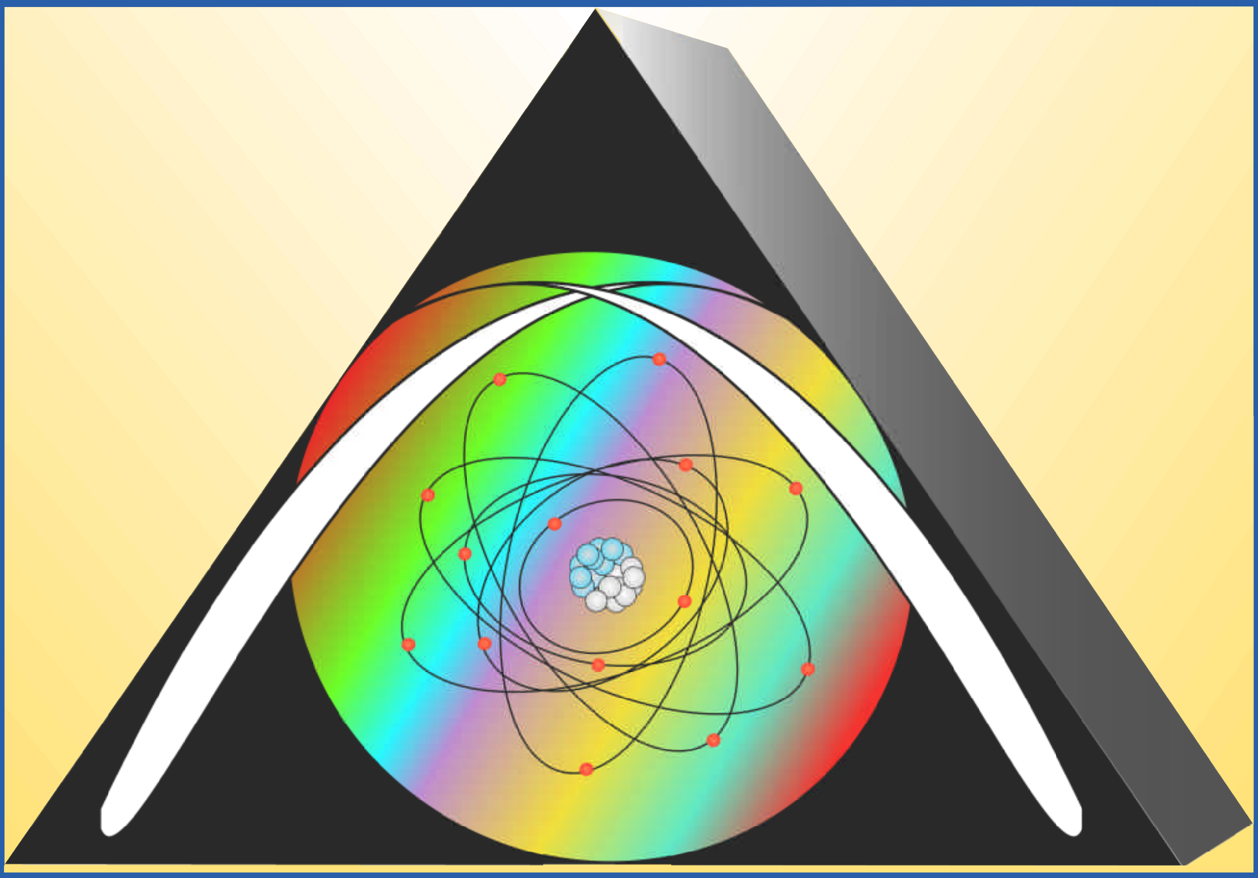
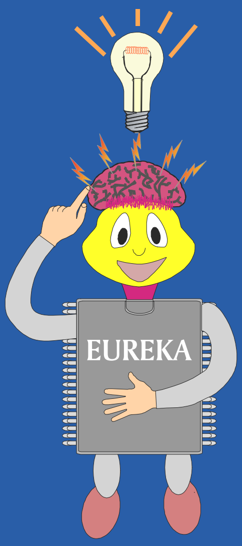
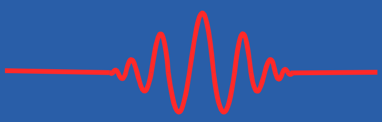
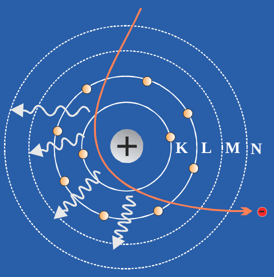
EUREKA





Greatly improves one's understanding of hundreds of science concepts related to electricity, electronics, magnetism, and many other areas in physics





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HARRY PIRKOLA

EUREKA

Harry Pirkola

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First edition

This book was set in Times New Roman

PUR Perfect Binding

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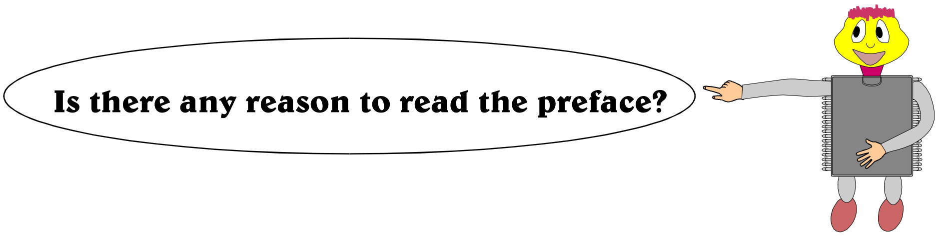
“If you cannot explain it simply, you do not understand it well enough”

Albert Einstein

PREFACE



You may want to read the preface if you are interested in learning how this book differs from other existing science educational in publication. Otherwise, you can skip it.

It is no secret that science education in general does not place much emphasis in comprehending concepts and topics. Students learn mainly by rote memorization and by following procedures causing the actual understanding of concepts to be often very limited.
Good grades or marks are not necessary an indication how well a student has understood a course material.

The process of understanding involves an abstract quality that allows a person to conceive ideas, visualize, and understand things that one cannot actually see.
Many science concepts in this book are abstract and are generally very difficult to visualize.
I have put great amount of time and effort not only to the content of the text but particularly to huge number of illustrations included in the book to make it easier a person to understand and visualize these type of concepts.

One major concern regarding science educational textbooks is that core topics and concepts in books are seldom throughly explained.
Too frequently the explanation or theory is “hidden” inside of massive amount of text, sometimes even spread out among several pages or sections. At times the explanation included is mostly in a form of mathematical derivation.

What encouraged me to write this book was the fact that there is clearly a need for this type of a book. That is, to explain various fundamental science topics and concepts more clearly and concisely than is typically done in educational textbooks.
Eureka was not designed to replace any existing textbooks but rather to complement them and to be used in conjunction with textbooks.
That is the reason why this book contains only examples but no problems.

My background as an educational consultant for over 15 years have allowed me to develop and refine various visualization and other learning techniques included in the book. My major areas of academic studies have included astronomy, computer science, electronics, mathematics, and physics.

The writing style I chose is a conversational, lecture type. Since the main purpose of this book is to explain various science concepts, the lecture type writing style is far more conducive to learning that some other a more rigid style.
The style in this book is sometimes wrongly called as “spoon-feeding”. It is true, that there are just few instances in the book that I leave the discovery to readers and not completely answer to a question. Spoon-feeding promotes rote learning, however, this book does the opposite.
The Eureka enables students to visualize and understand various concepts in such as way that rote learning is drastically reduced.

As you will see, most of the paragraphs in this book are relatively short. The purpose of this is to let a person to read a small segment of the text at a time and try to understand it before continuing to the next paragraph.
Also, the questions asked by the “IC-guy” serves the same purpose, that is, to provide additional breaks in the text.

Chapters are generally written in “reader’s digest version” or in concise and to the point manner. Afterwards, a student can refer to the actual textbook for more information. You could think that the purpose of the Eureka is to lay a solid foundation to various science topics so that a student is better able to comprehend the content of his/hers textbook(s).

Although some chapters in this book seem to loaded with mathematics, I have kept the use of math to the minimum. Because the Eureka is a science educational book, it is sometimes impossible to explain a concept without aid of mathematics. Although some concepts can be explained without mathematics, to fully explain many other concepts, can be done only with an inclusion of math.

Although I have painstakingly made sure that information in this book is accurate, I can only hope that the reviewers of this book have found all the errors including the mental ones.
While reading this book, if you notice any errors or ambiguous statements, please, let me know so that I can make the appropriate corrections.

One last thing. This is about the punctuation.
Once you begin reading this book, you may notice that the use of commas and periods does not seem to be consistent when utilizing mathematics and / or equations.
In some science educational books, the comma is included after every step of a mathematical solution to a problem or an equation derivation followed by the period.
Other science educational books do not use either commas or periods in those situations mentioned above.
I have taken sort of *middle of the road* approach where I have only used a period after an equation or calculation if it is clearly part of a more comprehensive sentence.

Being from Finland, I have to say that us Finns we really love the use of commas.
Therefore, I may have used commas in the text more liberally in this book than is traditionally done in books written in English.
The main purpose of using commas is to separate various elements from each other and thus to make sentences easier to follow and understand. In English, beyond the mandatory punctuation rules, the style of writing is *the less commas, the better* whereas in Finnish, it is the opposite.
My use of commas is somewhat a compromise of the two writing styles.

Harry Pirkola

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INTRODUCTION

At first glance, one would assume that Eureka is written solely for electrical engineering and electronics students since bulk of the topics are related to the electricity / electronics and magnetism. However, Eureka is more than that. It is a physics book with emphasis in electricity, electronics, and magnetism. Eureka also explains many topics in other areas of science such as classical mechanics, quantum mechanics, chemistry, and optics.
Many of the topics in this book are explained in terms of physics. In other words, concepts are explained from a point of view of a physicist. What this means is that, for example, many fundamental concepts in electricity and magnetism are discussed in more detail than are typically done in electrical and electronics textbooks.

Eureka begins with the topic of electric charges. Electric charges are very important because they play a central role in properties and structures of all matter.
Along with electric charges, the first chapter covers topics from structures of atoms including electron orbitals to chemical bonding and a discussion of the Coulomb’s law.
The subsequent chapters discuss topics such as electric fields, potential energy, electric current, and resistance. The concept of resistance can be correctly explained only in terms of wave mechanics or quantum mechanics. Therefore, fundamental ideas of quantum mechanics are introduced already in the chapter 6.
Although topics in quantum mechanics are often quite abstract, this book is written by using a plain and simple language that requires no background in quantum mechanics.
As a matter of fact, anyone with some high school science background should be able to understand even the most advanced topics discussed in this book.
The usage of a plain and concise language allows a layperson to comprehend topics that are usually reserved to students at senior undergraduate levels and at graduate schools.

As in any comprehensive science educational book, many of the topics and concepts in Eureka are not new to a “serious” science student.
Some newer technologies are included in antenna sections 35.4 - 35.5 that cover not only the standard antenna theory and types but also discusses of the fractal antennas including various fractal antenna designs. Additionally, this chapter has a discussion of the RFID tags that are becoming increasingly popular in many applications such as passports.

Another example is the chapter 36, *Memory Devices* that also includes discussions of the latest and future memory technologies. Some of these technologies are discussed briefly and some in more detail. For instance, the basic theory or physics of spin electronic (spintronic) type memory devices is included.
Also, memristors that are part of memristive systems are discussed in this book.
A detailed explanation is given to one of the memristors applications, a crossbar latch, in a form of a half-adder crossbar latch.

Additionally, some topics included seldom appear in science educational books such as watt balance experiment that is explained with conjunction of two better known topics: the quantum Hall effect and the Josephson effect.
Those are found in the appendix II as part of the more thorough discussion of the Planck constant.

The content in some chapters are discussed in such a detail that a non-electronics student does not need to read everything. It is of course left to each student and / or science enthusiast to decide how much of each chapter he / she wants to read.

1

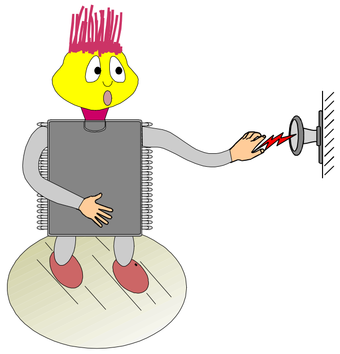
ELECTROSTATICS

1.1 Introduction

How many times have you walked on a carpet and touched a metal object such as a door knob and got “zapped”?

Tiny spark that appears is very hot and can be quite painful.

What is causing the spark?



Before we can answer to that question and to many other related questions, it is a better to first discuss of some basic properties of electrostatics.

Electrostatics is physics that deals with attraction and repulsion between electric charges.

We begin the discussion by describing couple of very simple experiments that you have probably done or seen done before and any conclusions that can be made from each experiment.

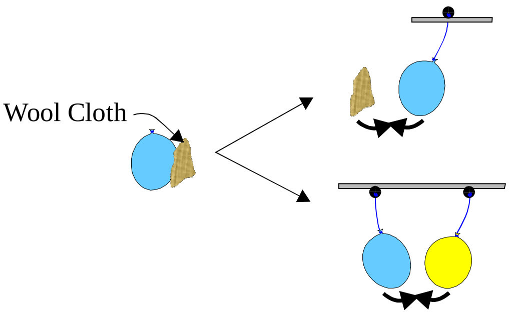
In the first experiment, two inflated balloons are hanged from separate strings as shown in the illustrations.

If only the blue balloon is rubbed with a wool cloth.

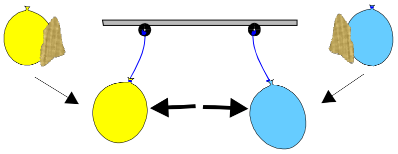
What do you observe?

The wool cloth and the blue balloon are attracted to each other.

Also, both balloons are attracted to each other.



If both balloons are rubbed with the wool cloth, you would see that the balloons are actually repelling each other. They are moving away from each other.



What does this experiment teaches us?

A rubbing action between two different materials, such as rubber balloon and wool cloth, causes them to attract each other. However, when both balloons are rubbed with a wool cloth, the balloons repel each other.

We can conclude that both balloons and the cloth have acquired a charge.

Also, since the cloth and the balloon are attracted to each other, we can conclude that one object has a negative charge and the other has a positive charge. Both balloons have the same type of charge since they repel each other.

What are we talking about when describing an object having a “charge”?

Ancient Greeks used to attract light objects by rubbing amber with fur. In today’s terms, amber is said to be **electrically charged** or possess an **electric charge**.

These terms are derived from Greek word *elektron*, meaning amber.

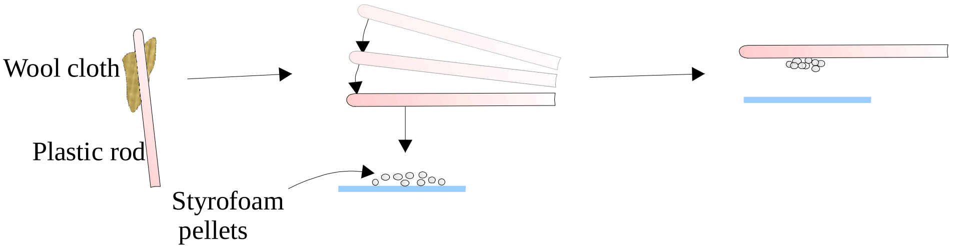
Why is a charged blue balloon and an untouched yellow balloon attracted to each other?

This suggests us that the yellow balloon has somehow acquired an opposite charge without any contact with any other object. How this is possible, will be discussed later in this chapter.

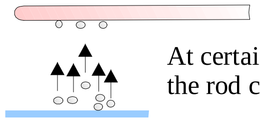
The first experiment has taught us that there are two kinds of electric charges: positive charges and negative charges. Like a magnet with two opposite poles, like charges repel and opposite charges are attracted to each other.
We also leant that by rubbing two different materials together, both materials acquire an electric charge with opposite polarities.

Let’s take a look at another similar experiment.
A plastic rod is rubbed with a wool cloth. Alternatively, a silk cloth is rubbed with a glass rod.

If the rod is slowly brought towards some small Styrofoam pellets,
we observe that a certain distance from the rod, Styrofoam pellets are captured by the rod.

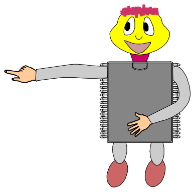


In other words, Styrofoam pellets are attracted to the plastic and they attach themselves to the rod.

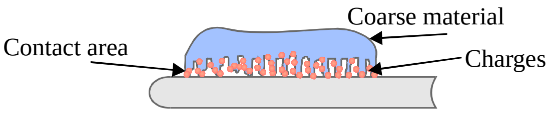


Once again, it is premature to discuss why uncharged Styrofoam pellets are captured by a charged plastic rod.
However, what we can learn from this experiment is that there must an attraction force that pulls pellets towards the rod.
By experimenting, we notice that this force gets stronger as the distance between the rod and the pellets decreases. At a certain distance from the rod, the pellets begin to straighten.
As the distance to the rod gets smaller, the attraction force becomes high enough so that the pellets leap onto the surface of the rod.

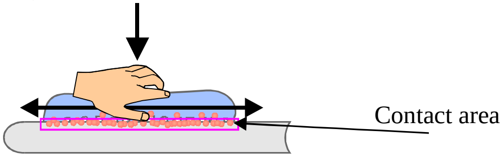
Does rubbing or scuffing cause charges to transfer from one object to another?



Yes, it does. However, rubbing one material with another (such as wool cloth and plastic rod) is not necessary to transfer charges. Simply by bringing those two materials together, will transfer certain amount of charges to the rod. This is called the *triboelectric effect*.
However, if one material is coarse (such as wool), then it is not always possible to transfer many charges to another material by simply touching two objects together.



Coarse material has relatively small contact area



By rubbing and pressing down the contact area is increased

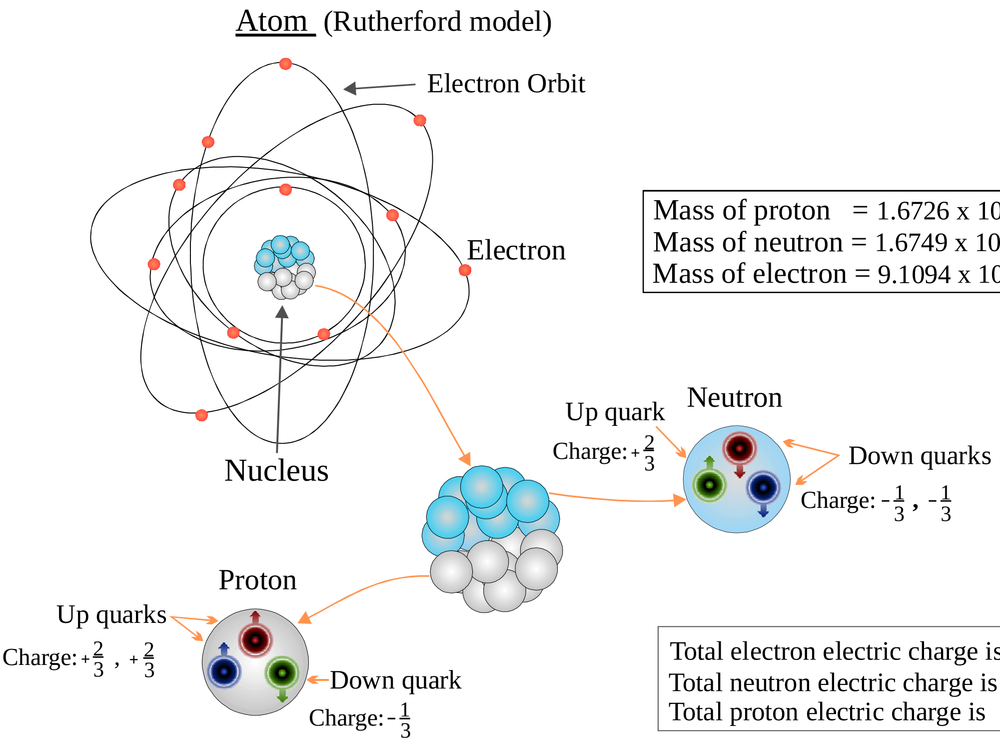
By rubbing objects together, we can increase the overall contact surface area and thus transferring more charges to the other object (plastic rod in our example).

What are electric charges and the force(s) associated with them?
Before we discuss these topics any further, this is a good place to take a look at a basic structure of an atom.

4 STRUCTURE OF ATOM

An **atom** is the smallest unit of an element that retains all the characteristics of that element.

Let’s take a look at illustration below of a composition of an atom.
Atoms are made up of **nucleus** in the center and **electrons** that are orbiting the nucleus.
Electrons have an electric charge of -1.
Nucleus is composed of **protons** and **neutrons**. Protons and neutrons are each composed of three elementary particles called **quarks**.
A proton is made up of two *up quarks* each having a charge of +2/3 and one *down quark* having a charge of -1/3. The total electric charge of a proton is +2/3 + 2/3 - 1/3 = +1.
A neutron is made up of two *down quarks* each having a charge of -1/3 and one *up quark* with a charge of +2/3. The total electric charge of a neutron is -1/3 - 1/3 + 2/3 = 0.



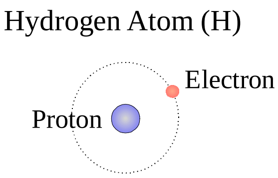
Mass of proton = 1.6726×10^{-27} kg
Mass of neutron = 1.6749×10^{-27} kg
Mass of electron = 9.1094×10^{-31} kg

Total electron electric charge is -1
Total neutron electric charge is 0
Total proton electric charge is +1

Atom	- Greek word *atomos;* uncuttable, indivisible
Nucleus	- Latin word *nux*; nucleus, kernel, nut.
Electron	- Greek word *elektron*; amber.
Proton	- Greek word *proti yli*; first constituent of matter.
Neutron	- Latin word *ne utrum*; none of both.
Quark	- Murray Gell-Mann assigned the name from the phrase “Three quarks for Muster Mark!” from the novel Finnegans Wake by James Joyce (1882 - 1941).

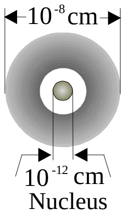
The number of protons and electrons in an atom is the same. So, if a given element (atom) has 14 protons, it also has 14 electrons orbiting around the nucleus.
Hence, the net charge of an atom is zero. An atom is electrically neutral.
Virtually all of atom’s mass is located in the nucleus.
Protons and neutrons have roughly the same mass, but the proton’s mass is about 1836 times that of an electron.

It is an interesting fact that the magnitude of an electric charge is the same for both proton and electron. This may seem odd considering the fact that a proton has almost 2000 times the mass of an electron. Think about this. If the magnitude of charges were dependent on a mass of a particle, then all atoms would be positively charged due to a huge positive charge in the nucleus.
What would happen to electrons around a nucleus? Would matter consists of only small particles?



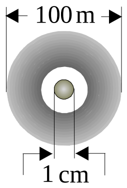
The simplest atom is the hydrogen atom. Its nucleus consist of one proton and no neutrons. Since we know that the number of protons equals to number of electrons, we can conclude that there can be just one electron about the nucleus (proton).

To draw atom structures to scale is not possible because the diameter of nucleus is so much smaller (10,000 times smaller) than the diameter of the whole atom.



The diameter of atoms ranges from less than 10^{-8} cm to more than 5×10^{-8} cm
The diameter of a typical nucleus is ~ 10^{-12} cm.

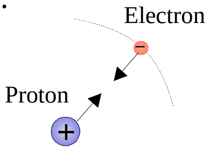
To give you a better picture of relative size of a nucleus compared to a diameter of an atom, let's pretend that the diameter of a nucleus is 1 cm. That is about the size of a shirt button.
The diameter of an atom would be 100 m which is about a length of a football field.



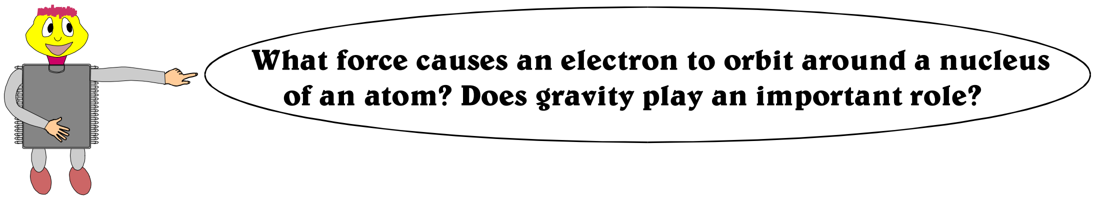
This tells us that except a very small and dense nucleus, most of the atom is just empty space.

As you have learnt by now, there are two kinds of electric charges: positives and negatives.
In atoms, protons are positively charged and electrons are negatively charged.
Neutrons have no charge. They are electrically neutral.

An electric charge is the source of the electrical force.
Charged objects exert electrical forces on other charged objects.
The attractive electrical force, in a hydrogen atom, is due to a positive charge, a proton and a negative charge, an electron.



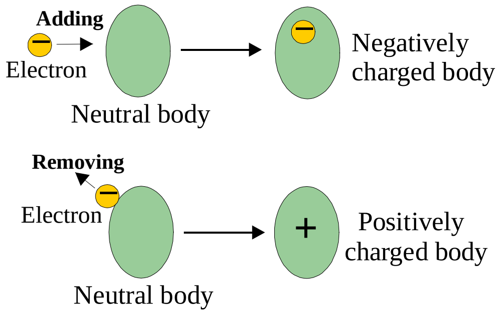
Charges exert electrical forces on each other.



Electrons and protons exert **electrical forces** on an each other.
Also, particles exert **magnetic forces** (discussed in chapter17) on each other. Magnetic forces are due to magnetic fields that are generated when charges are in motion.
Hence, the combined force is called the **electromagnetic force.**
It is the electromagnetic attraction between electrons and protons that causes electrons to orbit around a nucleus of an atom.
The electromagnetic force is much larger than the gravitational force between two electrically charged bodies. So, effects of the gravity can be ignored.

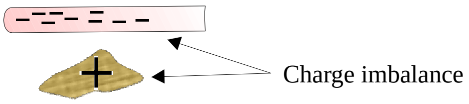
You and I are made up of atoms. Atoms are made up of electrically charged particles (with exception of neutrons). A neutral atom has the same number of positively charged and negatively charged particles. This is also true with any electrically neutral object. This means that an electrically neutral object may have billions of charged particles.

In theory, to give an neutral object a negative charge (-), we may either add negative charges or remove positive charges from that object.
In reality, we may only either add or remove electrons from objects. (In some cases adding positive charges is possible. In semiconductors by process called *doping* we can add *holes* which are missing electrons but act like positive charges.)
Typically, a positively charged object (+) is the one that has lost some of its electrons.

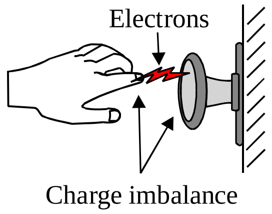


Charges can be transferred from one body to another so that one body has excess of electrons and the other one deficiency of electrons (negative charges).
The charge ”imbalance” between two bodies is called **Static Electricity**.

This charge imbalance causes objects to cling or attract to each other due to attraction of opposite charges.

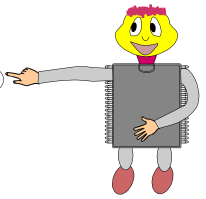


Another example of a charge imbalance can take place when you scuff your shoes on a carpet and then touch a metal object such as a door knob. The spark that develops neutralizes the large difference in the magnitude of charge between two bodies.
Electrons leap across the gap from the body with excess of electrons to a body with deficiency of electrons or to electrically neutral body.
Air is heated rapidly which a person experiences as heat pain.

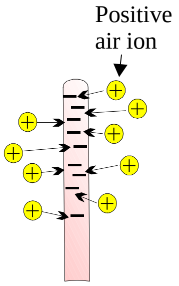


Which body has excess of electrons and which has deficiency of electrons?
It depends largely on the materials. Some materials donate more readily electrons than the others. Also, some materials more readily accept electrons than other materials. For example, wool and fur easily donate electrons whereas a rubber and plastics, silicon, and vinyl readily accept them. When your shoes pick up charges, it depends on the material of the sole of the shoes and the material your shoes make contact which polarity of charge your body acquires.

Once an object is charged, does the charge remain on that object forever? If not, where do charges go?



By experimenting, one can see that the charge do not remain on a body for an extended period.
Let’s assume that an object, such as the plastic rod, is negatively charged.
It has excess (above neutral level) electrons on the surface of the rod.
Let’s also assume that the rod is suspended in the air so nothing can touch it.
Where do the charges go from the rod? Nowhere.
Positive ions in the surrounding air “neutralize” or attach themselves next to the excess positive charges on the rod and thus nullifying the total charge on the rod.
[*ion* - an atom or a molecule that has either lost or gained electron(s)
molecule - a small number of tightly bound atoms.]
Where do these ions come from?

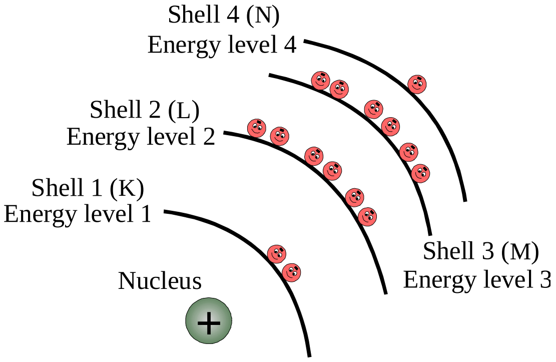


Air always contains some positively and negatively charged air ions.
Air ions are formed when a charge particle from radioactive elements in rocks, in a soil, in building materials, or from (secondary) cosmic rays from the outer atmosphere collides or is absorbed by a neutral air (oxygen or a nitrogen) molecule which loses an electron. This positively charged molecule attracts mainly water molecules. The molecule combines with around 10 -15 water molecules and the resulting cluster is called a positive air ion. A free electron can attach itself to an oxygen molecule which also attracts water molecules. This cluster of around 10 water molecules and an oxygen molecule is called a negative air ion. Weather conditions influence the number of positive and negative ions. During heavy rain and thunder, the number of ions increases greatly.

1.2 Atomic Shells, Subshells, and Orbitals

To be able to discuss various topics more in detail, we need to take a closer look at structures of atoms. This discussion involves explaining many topics by combining both classical and some basic concepts of quantum mechanics or wave mechanics.

We know that atoms are made up of nucleus and electrons around the nucleus.



Electrons are distributed to various levels called **shells**.
Shells are identified by the number or its equivalent letter designation.
The lowest level is labeled as number 1.
The next level up is number 2, and so on.
The numbers are called **principal quantum numbers**.
The equivalent letter designations of principal quantum numbers are K, L, M, N, O, P, and Q.
Hence, in terms of shells: K = 1, L = 2, M =3, ...
There are three other quantum numbers.
Those numbers will be discussed shortly.

Individual shells cannot accommodate any number of electrons.
There is a limit how many electrons can occupy each shell.
This is determined by the formula $2n^2$, where n is the principal quantum number.
For instance, the O-shell is equal to n value of five.
So, the maximum number of electron allowed in the O-shell is $2 \cdot 5^2 = 50$.
The lowest shell, the K-shell, can therefore have maximum of two electrons.

Electrons can move from one shell to another as long as there is a vacant space available.
This movement is associated with atom’s ability to absorb and emit (energy) radiation.
This absorbed or emitted energy radiation can be in a form of visible light.

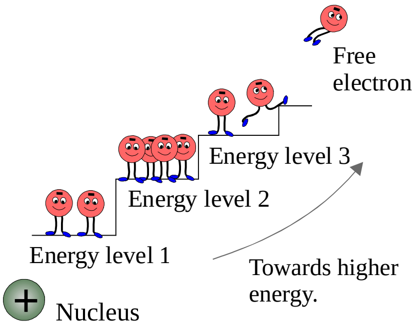
Since the electron movement between shells deals with a change in energy, it is often more convenient to call this movement in terms of a change in energy levels.
Each shell then also corresponds to a certain energy level.

At any time, an electron moves either up or down from its current shell, energy is either released or absorbed by that electron.
An electron in the K-shell requires more energy to move to the N-shell than an electron in the L-shell. If an electron moves to a higher shell, then the electron must first absorb energy to move to that higher level.
When an electron returns to a lower energy level (shell), it must release its gained energy.

Under certain conditions, an electron can gain enough energy to actually leave an atom and become a **free electron**.

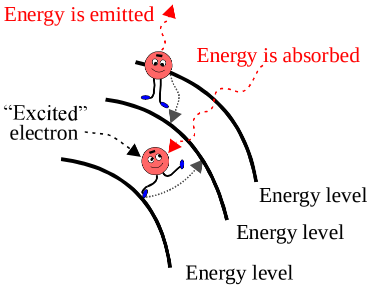
To help you to visualize a concept of energy levels, a staircase model is often used.
Each step (energy level) can occupy a certain number of electrons that can move either up or down along the staircase.
There is a smaller energy difference between two higher energy levels (2 and 3) compared to two lower energy levels (1 and 2).
In other words, the steps in the staircase become smaller the higher energy (shell) an electron occupies, and less energy is required to move to the next energy level.

A staircase model



When an electron has absorbed energy to move from its most stable energy state, called a **ground state,** to a higher energy level, the electron is said to be **excited** and an atom is in **excited state**.

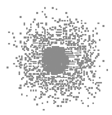
On its way back to a lower level an electron has to emit the same energy it had absorbed so it can land on a lower level it came from. Depending on the energy levels, this emitted energy can be in the form of visible light.



Orbit vs. Orbital

At this point, it is necessary to explain the difference of two terms.
An electron **orbit** is used in an outdated Bohr's model where an electron is moving around a nucleus at a certain orbit or energy level. However, to further explain the properties of atoms, we need to use the theory of *quantum mechanics* (wave mechanics). Quantum mechanics uses orbitals in place of orbits. **Orbital**s represent energy levels of electrons and their location or distribution in space.
Let's try to clarify what is meant by an electron location or distribution in space.
In wave mechanics, a location of an electron around the nucleus is often expressed in a form of **electron density distribution**.
Sometimes a term *electron cloud* is used to describe this distribution.

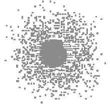
Electron cloud



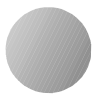
What this means is that the actual locations of electrons around nucleus are not known.
We can only calculate the probability that an electron is located at certain region around the nucleus. The darker the area (more dense), the greater the probability that an electron is located in that region. In the illustration above right, the location of an electron is not known but by looking at the electron cloud or density distribution, we can say that the probability is higher that an electron is located near the nucleus rather than further away.

When drawing geometric shapes of orbitals,
a **contour representation** is used.
This type of representation depicts a more definite, 3-dimensional, region within which an electron is found 90% of the time.
Many orbitals have quite complex geometrical shapes.

Electron density distribution



Contour representation

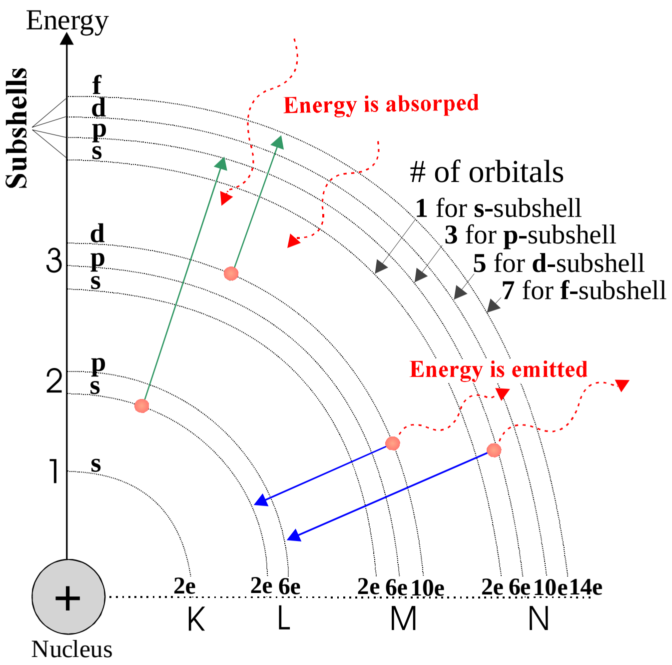


<u>Note</u>: The electron density distributions and energy levels, thus orbitals, can be described as mathematical equations. The set of equations are called **wave functions,** ψ (not covered in this book).
This means that electrons are treated not only as particles but also as waves (more about this in section 6.5).

Note: The energy diagram on the right is not that straightforward.
For many elements there is considerable overlapping of energy levels. For example, there are some elements whose 3d subshell is at higher energy level than 4s subshell.
Similarly, there are elements that have 4d at higher energy than 5s and 5p.
Even more elements have 4f subshell at higher energy than 5s, 5p, 5d, 6s, and 6p.
To correctly illustrate this would have required a different diagram.

Subshell	*l*	m_l	# of orbitals	max # of electrons
s	0	0	1	2
p	1	-1, 0 , 1	3	6
d	2	-2, -1, 0, 1, 2	5	10
f	3	-3, -2, -1, 0, 1, 2, 3	7	14

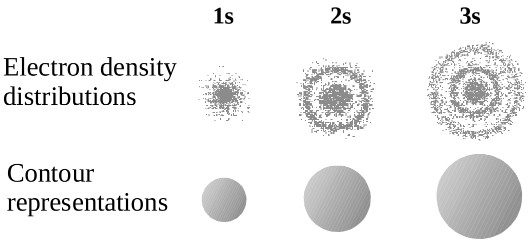
Atomic energy diagram including shells and subshells



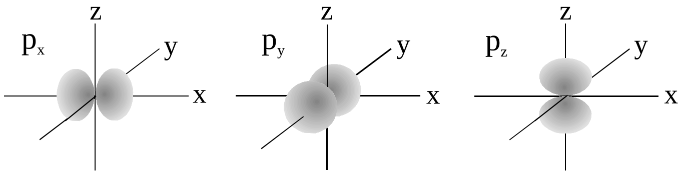
Take a look at the atomic energy diagram above right. You see that shells also have subshells. Notice that the number of subshells in each shell is the same as the principal quantum number.

The subshells are labeled with letters s, p, d, and f. These letters corresponds to the second quantum number, called **orbital angular momentum quantum number, *l*** or **azimuthal quantum number**. These numbers begin from zero so that for a subshell s, *l* = 0, for a subshell p, *l* = 1, and so on.

What are azimuthal quantum numbers? They define the shape of the orbital or geometric electron density distribution.
Below are some geometric shapes of different orbitals of a hydrogen or hydrogenlike atoms that contain only one electron.



The 2p orbitals



As you see, all s orbitals are spherically symmetric. The electron density distributions are different. Whereas in the 1s orbital, the electron density decreases with the increase in distance from the nucleus, in the 2s and 3s orbitals, the electron density varies with the distance from the nucleus.

The number of orbitals for each subshell s, p, d, and f is different. A subshell s has only 1 orbital, a subshell p has 3 orbitals, a subshell d has 5 orbitals, and a subshell f has 7 orbitals.

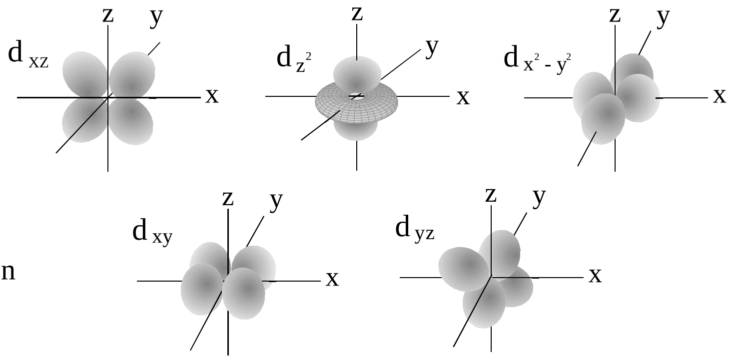
The 2p subshell has then 3 orbitals as shown above. The electron density is concentrated on two sides of nucleus or two lobes separated by a node at the nucleus.

Notice that the three orbitals have three different orientations. This brings us to the third quantum

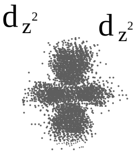
number, called the **magnetic** or **orientational quantum number, m_l.**
This number describes the orientation of the orbital in space.
This number may have integral values ranging from l to $-l$.
This means for $l = 0$, m_l is zero. However, for $l = 1$, m_l can have values of -1, 0 , or 1.
Note that there isn’t necessary any connection between m_l values and for example the orientation of the three 2p orbitals in the previous page.

For $l = 2$, m_l can have values of -2, -1, 0, 1, or 2. The values represent 5 orbitals of the d subshell. Below are contour representations of the five 3d orbitals of a hydrogen.

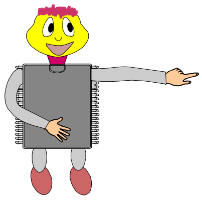
Note: The subscript designations d_{xz} , $d_{x^2 - y^2}$, and so on relate to orientation of lobes in a Cartesian coordinate system.
For example, $d_{x^2 - y^2}$ the lobes are orientated along x - and y-axes.
The orbital d_{xz} lobes are orientated in between the xz-axis.
The designation of d_{z^2} is an abbreviated version of a longer designation.


The 3d orbitals

The shapes of four of the five orbitals are the same. However, the fifth orbital, labeled d_{z^2} has a different shape. The equivalent electron density distribution for this orbital is shown on the right. The contour representation makes the orbital shape to appear vastly different from others.
All of the five 3d orbitals have the same energy. This is called **degeneracy**, that is, when there exist two or more distinct states with same energy.



Although all the orbitals shown here are for a hydrogen or hydrogenlike atoms, these shapes are also approximately correct for more complex atoms with many electrons.



How are electrons distributed among subshells?

A maximum of two electrons (e) can occupy each orbital.

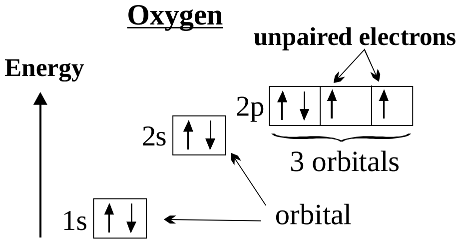
For example, we already know that shell M has three subshells: 3s, 3p, and 3d.
The 3s has one orbital, 3p has three orbitals, and 3d has five orbitals. If each orbital can have maximum of two electrons, the maximum number of electrons in M shell is $1 \cdot 2 + 3 \cdot 2 + 5 \cdot 2 = 18$.
Of course, this number can be determined from $2n^2$ where $n = 3$ or $2 \cdot 3^2 = 18$.

Anyway, the distribution of electrons is: a 3s subshell can have 2 electrons, a 3p subshell can have $3 \cdot 2 = 6$ electrons, and 3d can have $5 \cdot 2 = 10$ electrons.

This does not mean that two electrons always occupy each orbital and that subshells are full.
These are the maximum number of electrons that each subshell can possible have. We can look at a simple example of an electron distribution among various orbital of an oxygen atom.

An oxygen atom has 8 electrons. How are all the electrons distributed?
We begin at the lowest energy level which is K shell or 1s. It can have 2 electrons leaving us 6 electrons. The next energy level is 2s and this level can also have 2 electrons leaving 4 electrons. Finally, the 2p has three orbitals and can have 3·2 = 6 electrons.

How are 4 electrons filled in 2p that has room for 6 electrons?
Each orbital first gets one electron, then the last electron must occupy an already occupied orbital.
Therefore, 2p has two unpaired electrons as shown on the right.

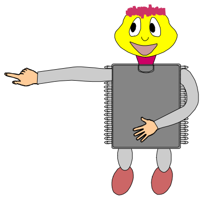


Electron distribution in various orbitals for an oxygen atom.

What are the arrow symbols inside the orbitals?
Each arrow represents an electron.
Besides orbiting a nucleus, an electron also spins about an axis which together with electron's orbital motion generate a magnetic field around it.
An electron and its direction of the spin is often represented by up-arrows ↑ and down-arrows ↓ or values of $+\frac{1}{2}$ and $-\frac{1}{2}$.
The value is our forth quantum number and is called the **electron spin quantum number**, **m_s**.
Paired electrons spin in the opposite directions and unpaired electrons spin in the same direction.

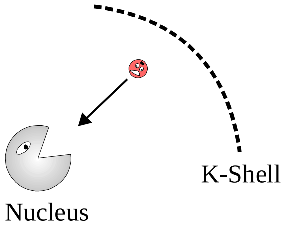
This type of representation is useful to aid in understanding magnetic properties of matter which will be covered later in this book. Also, electron spin plays a vital role in a new type of technology, called spintronics or spin electronics (section 36.12) which is utilized in today's magnetic storage devices.

Why don't electrons fall into positively charged nucleus?
Also, if like charges repel each other, then what force keeps protons together in a nucleus?



Generally, electrons cannot fall into a lower energy than its lowest allowed energy level, the K-shell.

However, there are situations where it is possible electrons to end up inside the K-shell.
For example, a high-speed electron can pass in between the nucleus and the K-shell.



An electron that collides with a nucleus is seldom absorbed by a proton.
An electron most likely just scatters off the proton.
Electron absorption by a proton can happen under a very high pressure (a star collapsing, for example).
The process is called the *inverse beta decay.*

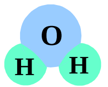
Extra: When a proton absorbs an electron, the result is a creation of a neutron and an electrically neutral elementary particle called *electron neutrino*. Neutrino has a minuscule but a non-zero mass and is very difficult to detect. This particle can pass through normal matter virtually undisturbed.

The force that keeps the positive charged protons and the neutral neutrons together in a nucleus of an atom is called the **nuclear force** or the **strong nuclear force**. Typically, a term *strong* (*nuclear*) *force* is used as the force between quarks that make up the protons and neutrons.
The discussion of this force is beyond the cope of this text.

1.3 Periodic Table of Elements

So far we have been discussing of electric charges and how to transfer these charges from one object to another. These objects have been made of nonconductive materials (insulators) such as plastic. You also know about the basic structure of an atom.
Do you understand why certain materials do not easily transmit electric charges and heat energy whereas other materials have opposite properties? What makes one material an insulator and other a conductor? Why do atoms get together to form various substances?
For instance, why do two hydrogen atoms get together with one oxygen atom to form a water molecule?
Why certain materials are brittle and break apart easily and other materials can be reshaped without breaking?
Before we can answer to those and many other questions, we need to first look at **periodic table of elements** and try to understand how elements are grouped together and what properties they have.

Water molecule

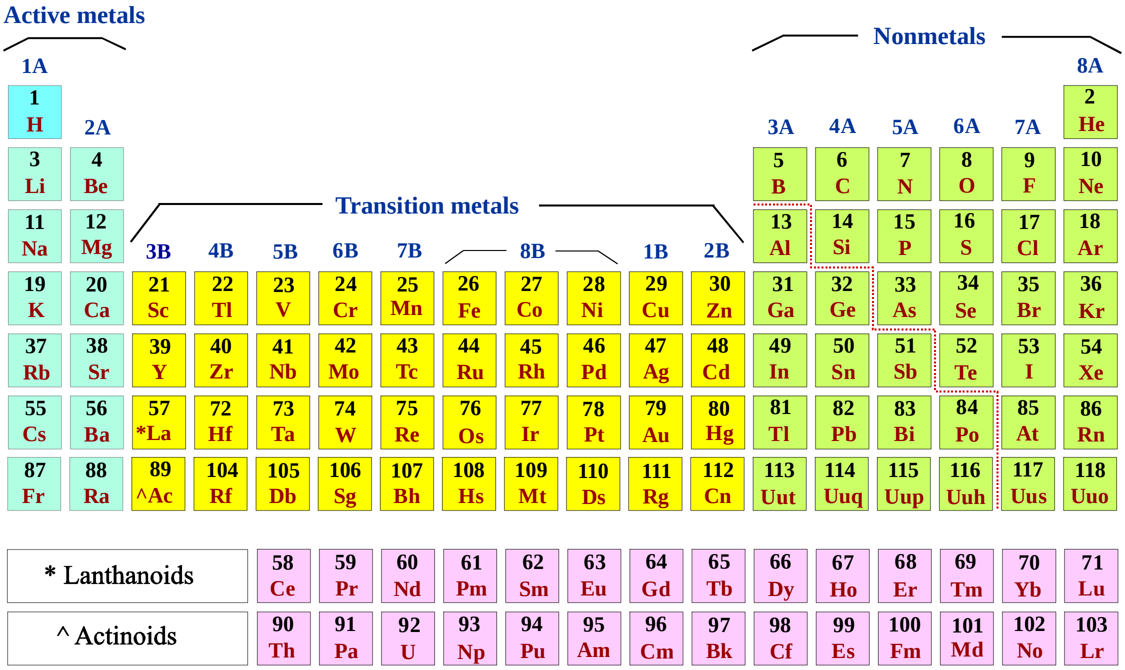


H_2O

Studying the periodic table may seem a rather boring endeavor particularly if chemistry is not one of your favorite subjects. But if you are a science student or just a science enthusiast, learning about the periodic table is important in order to form a more complete picture of your science discipline. When we talk about "a complete picture", we are referring a person having a broader understanding of one's field of study. There are very few fields in science that understanding of basic chemistry concepts is not necessary. This field you are studying is no exception.

The first periodic table was invented in 1869 by a Russian chemist Dmitri Mendeleev or Mendeleyev (1834 - 1907).
He arranged the elements (63 known at the time) in his periodic table in the order of increasing atomic mass. He observed that similar chemical and physical properties recurred "periodically" in vertical groupings. Modern periodic table is based on the periodic nature of electron configurations and elements are listed in the table by the atomic number of an **element**. (Element is a pure substance that consists of only the same type of atoms; for example pure silver, pure oxygen, and so on).

Periodic Table of Elements



Active metals

Transition metals

Nonmetals

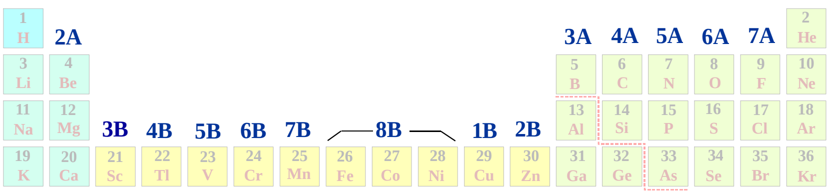
1A	2A	3B	4B	5B	6B	7B	8B			1B	2B	3A	4A	5A	6A	7A	8A
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Tl	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 *La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 ^Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo

* Lanthanoids	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
^ Actinoids	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Today's periodic table consist of 118 known elements of which 88, 92, or 94 (depending on definition) elements occur naturally. It should be noted that new elements that are discovered are not found in nature but are often result of a high-energy collisions between atoms and ions taken place in particle accelerators. The resulting new element consists of usually just one or two atoms that disintegrate (decay) very fast, often in less than 1 ms (millisecond).

The main table is divided into 18 columns. These columns are called *chemical groups*.

18 columns are called chemical groups.



The groups are labeled from 1A to 8B. Typically, the groups are labeled by using Roman numerals. For simplicity, this is not done here. The letters A and B designation is arbitrary.
There may be some common characteristics between the groups that share the same number, but in general, there is no connection.

Let's look at some of the groups:

Group 1A is called **Alkali Metals**. Lithium (Li), sodium (Na), and potassium (K) are some of the elements that belong to this group. The elements in this group are soft, shiny, and have low density. The alkali metals are very *reactive*, that is, they readily combine with other elements.
Hydrogen (H) has very little in common with elements in group 1A.
It is colorless, odorless, and highly flammable gas.

Group 2A is called **Alkaline Earth Metals**. Beryllium (Be), magnesium (Mg), and calcium (Ca) are few examples from this group. The elements are harder and more dense than alkaline metals and have higher melting points. These elements are also reactive but not as much as alkali metals.

Groups 1B to 8B are called **Transition Metals**. One of the characteristics of these groups is that their properties are much alike. Most of the transition metals conduct well electric charges and heat. They generally have a high melting point and are quite hard.

Groups 3A to 6A contain properties of both metallic and non-metallic elements. (The dash line indicates the division between metallic and non-metallic elements.) The names of the groups are based on the first element of each group such as 3A is *Boron Group* (B), 4A is *Carbon Group* (C), 5A is *Nitrogen Group* (N), and 6A is called *Oxygen Group* (O), also known as *Chalcogens*.

Group 7A is called **Halogens**. They are totally non-metallic with low melting and boiling points. Halogens readily combine with metals to form salts. For instance, chloride (Cl) and sodium (Na) from group 1A form together a compound called sodium chlorine (NaCl) which is better known as ordinary table salt. Some halogens include fluorine (F), chlorine (Cl), bromine (Br), and iodine (I).

Group 8A is called **Noble Gasses** or Inert Gasses. The term inert comes from the fact that these gasses do not readily combine with any other elements. They are unreactive or inactive whichever term you prefer to use. Noble gasses are found in small amounts in our atmosphere.
Helium (He), neon (Ne), argon (Ag), krypton (Kr), xenon (Xe), and radon (Rn) are all noble gasses.

The two separate groups from the main table are *Lanthanoids* or Lanthanides and *Actinoids* or Actinides.

3B																
21 Sc																
39 Y																
57 *La	* Lanthanoids	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
89 ^Ac	^ Actinoids	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

The name lanthanoids comes from the element lanthanum (La). This group is also known as *rare earths*. This term is somewhat misleading since most of the elements in the group are not that rare. Lanthanides (pure) are silvery metals with high melting points. The chemical and physical properties are very similar and they behave almost identically. Lanthanides are in high demand in advanced materials that are used in electronic, magnetic, and optical devices.

The name Actinoids comes from the element actinium (Ac).
Most of these elements are not found in nature. Many are produced in nuclear reactions and all actinoids are radioactive.
All actinides are also metals. The most well known actinides are silver-grey metal called plutonium (Pa) and silver lustrous metal called uranium (U).

1.4 Atomic Numbers

All elements are numbered in the periodic table. What are these numbers for?
A number 1 has been assigned for hydrogen (H), helium (He) has a number 2, and so on.
This number is called an **atomic number**.
Each atom or element has certain number of protons in its nucleus and recall, in a neutral atom, the number of protons equal the number of electrons.
Atomic numbers show the number of protons in each element.

Let’s look at an example.
Some of the group 1B elements include copper (Cu) silver (Ag), and Gold (Au).
Copper has an atomic number of 29. It has 29 protons and 29 electrons.
Since silver has an atomic number of 47, it has 47 protons and 47 electrons.
It means that silver is heavier than copper and gold with 79 protons and electrons is the heaviest of these three elements.
So, the higher the atomic number, the heavier the element.

1B	
29 Cu	**Copper (Cu)**
47 Ag	**Silver (Ag)**
79 Au	**Gold (Au)**

The weight of an atom depends on the number of protons and neutrons.
Unlike protons, the number of neutrons can vary in a given element.
The different number of neutrons in the same element are called **isotopes**.

More detailed periodic tables have additional numbers.

47 Ag 107.87	**Atomic number** **Atomic Weight**

One is called the **atomic weight**.
Atomic weight is the average value of all isotopes of that element.
For instance, silver has two isotopes 107 and 109. These numbers are called **mass numbers**.
The symbol for silver-107 isotope is $^{107}_{47}\mathrm{Ag}$ or just $^{107}\mathrm{Ag}$.
Both isotopes can be represented as $^{107}\mathrm{Ag}$ and $^{109}\mathrm{Ag}$.
Mass number shows the sum of protons and neutrons of an element.

The number of neutrons is calculated as : **# of neutrons = mass number - atomic number.**

A lighter $^{107}\mathrm{Ag}$ atom has 107 - 47 = 60 neutrons and
a heavier $^{109}\mathrm{Ag}$ atom has 109 - 47 = 62 neutrons.

Optional

What about the silver's atomic weight (AW) of 107.87? How is the weight calculated and what are its units? Atomic weight is the average value of all isotopes while taken into account their relative natural abundances. Silver-107 has abundance of 51.84% with mass of 106.905. Silver-109 has abundance of 48.16% with mass of 108.905. The average atomic weight is calculated as (51.84%)(106.905) + (48.16%)(108.905) = 55.42 + 52.45 = 107.87 atomic mass unit (amu). Note: When talking about atomic weight, we are actually referring to atomic mass. Although technically wrong, atomic weight is commonly used. Atomic mass unit comes from the assignment of an atomic mass of exactly 12 amu to carbon-12 isotope.

(Carbon has two stable isotopes: carbon-12 ^{12}C and carbon-13 ^{13}C and a radioactive cohort carbon-14 ^{14}C that is used to date or determine ages of organic material. Carbon AW is 12.011 amu)

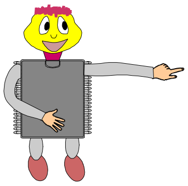
Counting and weighing one atom at a time is not possible so the counting atoms is done indirectly by weighing large quantities of atoms or molecules. The unit of mass is usually expressed in grams (g).

It is experimentally shown that in 12 g of carbon-12 there are 6.022×10^{23} (Avogadro's number) carbon-12 atoms. This quantity is called a 1 *mole* or mol. The word mole comes from Latin word *moles* meaning a mass. In other words, one mole of anything weighs the sum of its AW and has 6.02×10^{23} of that "anything". One mole of silver weighs 107.87 g and has 6.022×10^{23} Ag atoms. One mole of water H_2O weighs 2 (1.008) + 16 = 18.016 g and has 6.022×10^{23} H_2O molecules or $2 \times (6.022 \times 10^{23})$ hydrogen atoms and 6.022×10^{23} oxygen atoms.

$$\text{Hence,}\quad 1\,\text{amu} = \frac{(1/12)\,(12\,\text{g}\cdot\text{mol}^{-1})}{6.022 \times 10^{23}\,\text{mol}^{-1}} = 1.661 \times 10^{-24}\,\text{g} = 1.661 \times 10^{-27}\,\text{kg}.$$

Example 1: A pure silver coin weighs 30 g (1.06 ounces). How many silver atoms is the coin made up?
Ag atoms = ((30 g Ag) / (107.87 g Ag)) x $(6.022 \times 10^{23}) = 1.67 \times 10^{23}$ Ag atoms.

Example 2: Calculate the mass of 1 billion carbon atoms. Mass = $(1 \times 10^{9} / 6.022 \times 10^{23}) \times (12.011\,\text{g}) = 1.994 \times 10^{-14}$ g.

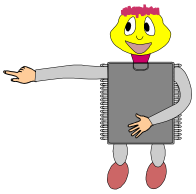


Where do the names of all the elements come from?

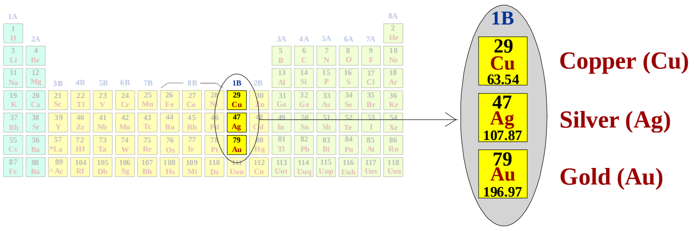
The names of atoms are derived from many sources. Some elements are known since prehistoric times. Elements such as copper comes from Latin word *cuprum*, silver from Latin word *argentum*, hence the symbol Ag. The name for gold comes from Latin word *aurum* and therefore the symbol for gold is Au. Many elements get their names from the main component of associated mineral. Others got their names based on the chemical and/or physical properties including color and odor of that element. Names are also given to elements based on the region or place where elements was discovered or mined or just named after a particular continent: americum and europium for example. Names have also given after names of celestial bodies such as uranium or names of mythological figures, and even scientists have elements named after them such as einsteinium and copernicium.

The symbols for elements are most often straightforward except those that have Latin origin. Typically, a symbol is either just first letter of the element or one additional letter to distinguish that from an element that has the same first letter. Some elements have two common names. Potassium is used in English speaking countries but in many parts of the world potassium in known as *kalium*, thus the symbol K. Sodium is another element that is also known as *natrium*, thus the symbol Na.

Why are certain elements grouped together?

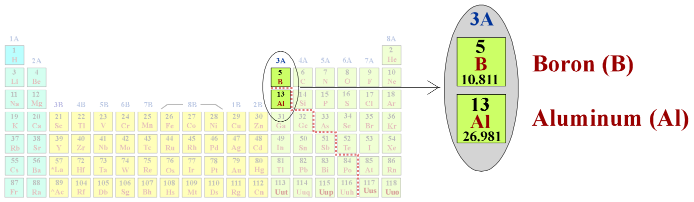


Let's first look at some group 1B elements and their grouping.



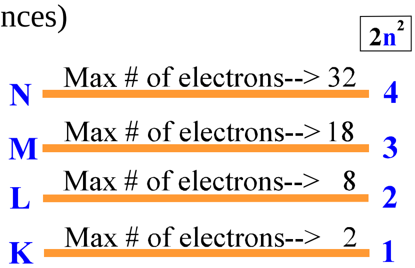
It makes sense to group copper, silver, and gold together. All of them are metals with characteristics of luster. They are malleable and ductile. Metals are also excellent conductors of electric charges and transfer of heat.

Why are for instance group's 3A first two elements boron (B) and aluminum (Al) grouped together? What properties do they have? Do they have anything in common?



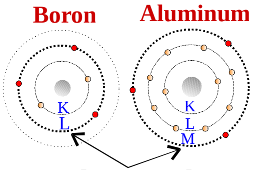
Both are never found free in nature. Boron has less metallic characteristics than aluminum. Unlike aluminum, boron is a poor conductor of electric charges in a room temperature. Impure boron is a brownish-black powder. Boron is used as an antiseptic (boric acid), used in textile industry, making insulating fiber glass, making glass, used in pyrotechnics, and possess optical characteristics. Aluminum is strong and light and can be formed, cast, and machined and is used in many industries including car and aircraft manufacturing.

Although it seems that these two elements have very little in common, the elements actually have quite similar properties. Why is that? It is because **the properties of an element are determined by the electron arrangement of its outermost electron shell** which is called the **valence shell**. The electrons in that shell are called **valence electrons**. It is those electrons that take part in chemical bonding (i.e., why atoms get together to form various substances)



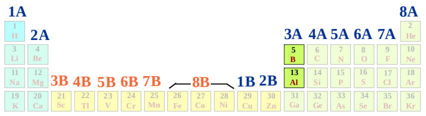
Let's first review the electron arrangements in various shells. As you may recall, the maximum number of electrons in each shell is based on formula $2n^2$ where n is the integer number corresponding to shell letters K, L, M, N, ...
For instance, the M-shell (n=3) can have maximum of 2 x (3^2) = 18 electrons.

Boron (B) has an atomic number of 5. It has therefore 5 electrons in total. The K-shell requires 2 electrons. This leaves 3 electrons in the L-shell. For boron the valence shell is L.

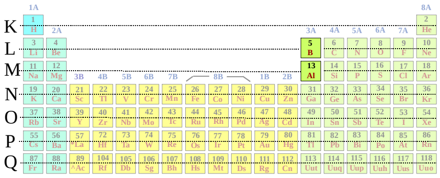


Both atoms have 3 valence shell electrons (in red)

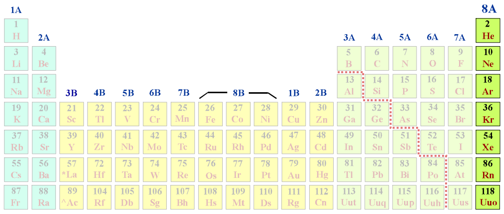
Aluminum's (Al) atomic number is 13. The shells K and L are completely filled. That leaves 3 electrons in the M-shell. For aluminum the valence shell is M.



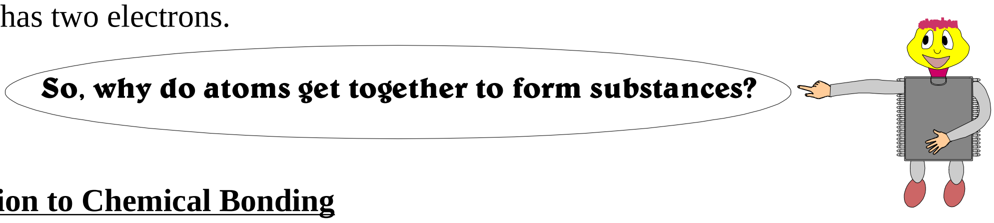
Due to an arrangement of atoms in the periodic table, it is not necessary to mathematically figure out the number of electrons in a valence shell for many of the atoms. Some of the atomic group numbers correspond to the number of electrons in a valence shell. The group number is the number of valence electrons for the following groups: alkaline metals (1A and 2A), nonmetals (3A, 4A, 5A, 6A, 7A, 8A), and transition metal groups 1B and 2B . For example, boron and aluminum belong to group 3A and both have 3 electrons in their respective valence shells.
The remaining groups numbers do not correspond to the number of valence electrons.
Transition metals are much alike and the number of valence electrons in given group is either one or two. Both lanthanides and actinoids have two valence electrons.



The horizontal rows are called **periods**, thus the name periodic table. The rows are labeled 1, 2, 3... or (K, L, M, N, ...) which are, as you probably figured out, the valence shells.
For instance, boron is located in the second (from the top) row and the corresponding shell is L. Aluminum is located in the third row and its 3 valence electrons are in the M-shell.



Look at the group numbers. What is the highest number you see? The correct answer is of course eight. What is significant about number eight? It tells us that the maximum number of electrons in an atom's valence shell can only be eight. Let's look at group 8A. Recall that elements in that group are noble gasses or inert gasses. These gasses do not easily combine with other elements and thus are quite inactive. Everyone, except helium (H), in that group have eight electrons in their outermost shell (valence shell). Helium has two electrons.

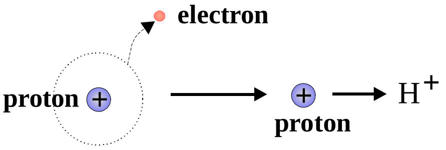


1.5 Introduction to Chemical Bonding

Group 8A elements have very stable electron arrangements and the chemical inertness of this group is quite desirable.
Elements in other groups combine (get together) so that they themselves have eight valence electrons. This is called the **octet rule** (octet meaning group of eight). Obtaining an electron arrangement of a noble gas atom is done by either sharing, losing, or gaining electrons.

If a neutral atom either loses or gains electron(s)s, the resulting charged particle is called an **ion** (Ion in Greek means "goer"). Note: A molecule with net charge is called a **polyatomic ion**. (poly- = many)

When a hydrogen atom loses its only electron, the resulting positively charged particle is called a "hydrogen ion". (Note: In this case the resulting ion consists only of a proton and the ion is actually called a proton).



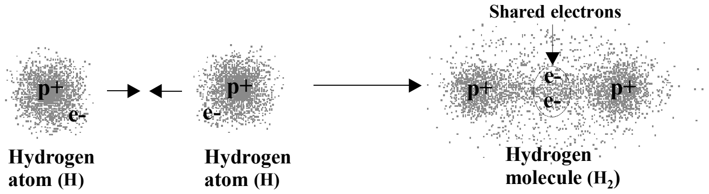
A positive ion is also called an **anion** (Anion in Greek means "upgoer").

The symbol for proton is $\mathbf{H}^+$. When an atom loses electrons, the number of electrons it loses is written in superscript integer before the + sign as: Fe^{2+}, Fe^{3+}, Sn^{4+}, ...

When an atom gains electrons, it then becomes a negatively charged particle called a negative ion. A negative ion is also called a **cation** (Cation in Greek means "downgoer").

The number of electrons, it has gained, is written as X^{n-}; for instance, F^-, O^{2-}, N^{3-}, C^{4-}, ... where n is the number of electrons gained.

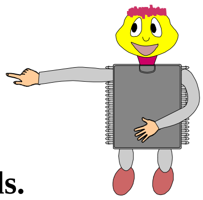
Let's look at an example of sharing electrons.
Since group 8A helium (He) has two valence electrons, a hydrogen atom needs only to gain one electron to have a stable helium electron configuration. A good way to accomplish this is to have two hydrogen atoms share one electron each.



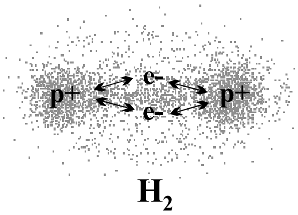
The sharing of electrons are shown by using an electron density distribution as illustrated on the left.

In this illustration, a positive nucleus (proton) is in the middle of an atom surrounded by an "electron cloud". The darker the area (more dense), the higher the probability to find an electron in that region. If you think about it, it will make sense. It is in the darker areas, the closest to the nucleus and in between the nuclei (in a H_2 molecule), where one would expect to find an electron(s).

What force keeps atoms together?



It is the electromagnetic force that causes atoms to maintain bonds.



H_2

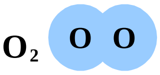
When two hydrogen atoms are near each other, the valence electrons are simultaneously attracted to both nuclei. This is called **electron-nucleus attractive force.** This attraction increases with decreasing atom separation. The ideal distance between atoms is the one that balances the electron attraction to nuclei and the repulsions between nuclei and repulsions between electrons. This is called the *equilibrium bond distance.* At the equilibrium distance, the electron orbits (energy states) overlap each other.

Sharing electrons between atoms is called the **covalent bond.**

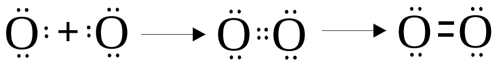
Sharing electrons in covalent bonds typically take place between **nonmetallic elements.** Bond formation is often expressed in symbolic form called electron-dot symbols or more common name is Lewis symbols or **Lewis structures**.

Valence electron

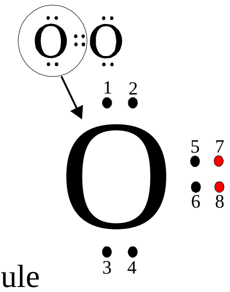
Let's look at some examples. For a hydrogen bond, the Lewis structure is H : H or H - H. Lewis structure shows two valence electrons that are shared, and as a practice, the shared electrons are shown as a line. If two pairs are shared, then two lines are used; three pairs have three lines, etc.



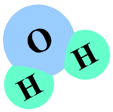
In case of two oxygen atoms combining, we have a situation where each oxygen atom has six valence electrons and each atom needs two more to have eight electrons (an octet) in its valence shell in order to achieve an electron configuration of neon of a rare gasses group 8A.



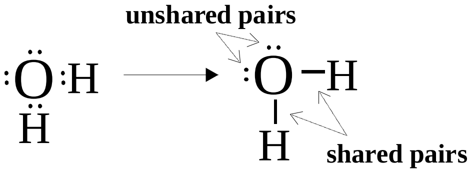
The Lewis structure shows all the valence electrons as dots and the shared electrons (electron pairs) are shown as lines between atoms. Do you see the sharing?



Let's look at the left oxygen atom (circled) and count the electrons. The left oxygen atom has six valence electrons (numbers 1 to 6) and it and the right oxygen atom both needed two additional electrons to have an octet. So, the right atom is sharing electrons 7 and 8 with the left oxygen atom. On the other hand, left oxygen atom is sharing electrons 5 and 6 with the right oxygen atom so both atoms have eight valence electrons (octet).



If we combine two hydrogen atoms with one oxygen atom, we have a water molecule that is well-known by its symbol H_2O. Its Lewis structure shows that oxygen has two pairs of electrons that are shared and two pairs that are unshared.



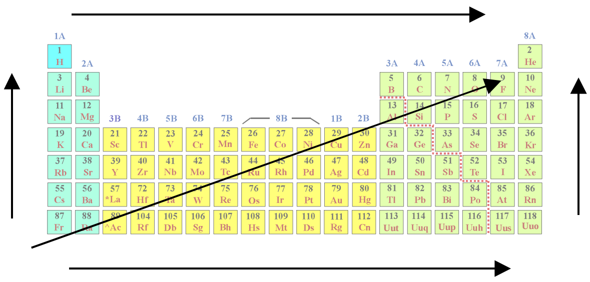
Note: Energy is released when atoms are joined during chemical bonding. A molecule must absorb energy if the bonded atoms are to be separated. The *bond energy* depends on the nature of the bond. A single bond is weaker than a double bond and a triple bond is stronger than double bond. Also, a *bond distance*, a distance between the nuclei of bonded atoms, is related to bond energy. The shorter the distance between the nuclei, the stronger the chemical bond.

Note: Not all covalent bonds attain an octet. Some molecules have odd number of electrons, such as NO, some molecules have less than eight electrons, such as BF_3, and some have more than eight valence shell electrons such as PF_5, AsF_6^-, SF_4, and PCl_3.

When two identical atoms bond, the electron pairs are equally shared. This was the case in our examples when two hydrogen atoms bonded and when two oxygen atoms bonded. However, in the formation of water molecule where two hydrogen atoms bonded with one oxygen atom, the sharing was not equal. Some atoms have stronger attraction for electrons than other elements.

To give you a better idea which elements have greater attraction for electrons, let's look at general tendencies of various properties of elements in relation to the periodical table.

The general direction is from left to right and from bottom to top (the direction of arrows)



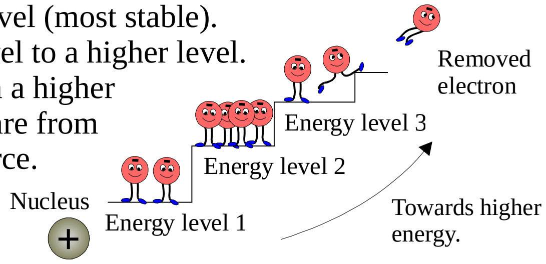
1. Decrease in atomic size

2. Increase in *ionization energy*
- energy required to remove an electron from a gaseous atom or ion.

3. Increase in *electronegativity*
- tendency of an atom to attract electrons to itself (noble gases have no attraction for electrons; group 8A is excluded.)

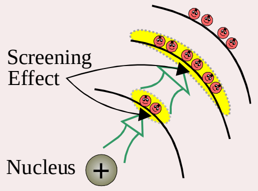
4. Increase in electron *affinity*
- energy (enthalpy)change when an electron is absorbed by a gaseous atom or ion.
- the higher negative (energy is released) value, the stronger attraction for electrons. Noble gases have no attraction for additional electrons and energy is required to add an electron.

If you think about it, these properties should not come as a surprise. Noble gases in group 8A are unreactive, meaning that they do not easily give up electrons. So, the energy to remove them (ionization energy) is the highest of any group. The group 7A halogens require just one electron to reach octet, therefore, one would expect those elements to have the highest tendencies (electronegativity) to attract electrons.



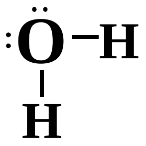
Does atomic size effect how easily an electron can be removed from the atom? You bet it does. Electrons closest to the nucleus are at the lowest energy level (most stable). Energy is needed to move electrons from lower energy level to a higher level. It takes less energy to completely remove an electron from a higher level than from a lower level. So, the closer the electrons are from the nucleus, the stronger the nuclear-electron attraction force. Outer electrons in larger atoms are further away from nucleus and thus, the attraction force is weaker. The force is inversely proportional to the square of the distance between charged particles. If the distance is doubled, then the attraction force is $2^2 = 4$ times weaker. (It is of course same for repulsive forces when like charges repel each other.)

Optional

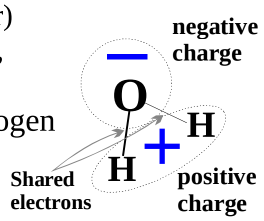


There is another factor that further weakens the attraction force between the nucleus and electrons in the outer shells. Negatively charged electrons in lower levels shield (screen) the positively charged nucleus from electrons in the higher levels. This effect is called the **screening effect.**

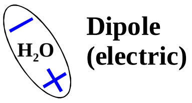
Let’s look at the water molecule and the electronegativities of hydrogen and oxygen.



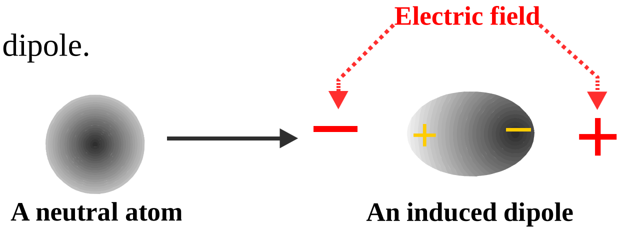
Electronegativity is the tendency of an atom to attract electrons to itself. The range for electronegativity is between 4.0 high for fluorine and 0.79 low for cesium. The value of 2.5 for carbon is used as a reference. Oxygen’s electronegativity value is 3.4 and hydrogen’s value is 2.2. When there is a difference in electronegativity, the bond is called **polar** (meaning it has two poles). A polar molecule is called a **dipole**. The bigger difference in electronegativity, the more polar the bond. (Note that the bond between two oxygen atoms is non-polar) Since the oxygen’s electronegativity value was higher than the one of hydrogen, the attraction force for the shared electrons is higher for oxygen. The shared electrons or more specifically the electron density is pulled away from the hydrogen atoms towards the oxygen atom. This creates a partial negative charge around the oxygen and a partial positive charge around the hydrogen atoms.



These kind polar molecules (dipoles) are also called **electric dipoles** and *permanent dipoles*.

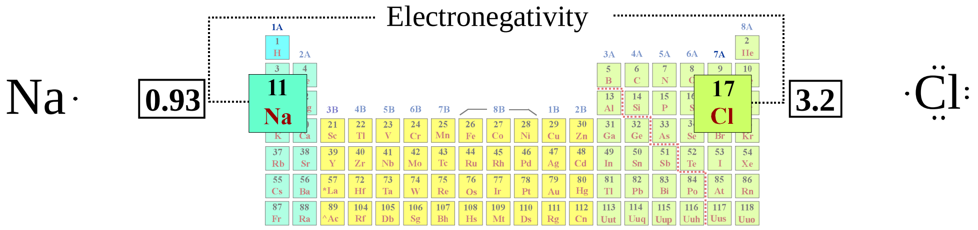


Even an individual atom can be *induced* to become a dipole. For instance, when a neutral atom is placed in between a large negative charge and a large positive charge (an *electric field*), the electrons are attracted towards the positive charge and the protons towards the negative charge. This forces an atom to “stretch” or elongate and it becomes an induced dipole. As soon as the charges (field) are removed, the atom resumes its original shape.

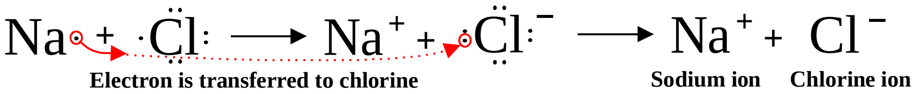


1.6 Ionic Bonds

Now, we are going to look at a situation where the difference of electronegativity is large.



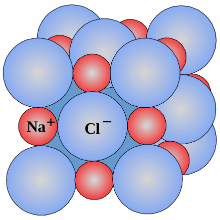
A violent reaction takes place when a sodium (Na) metal and a chlorine (Cl) gas come together to form a substance called sodium chloride (NaCl) which is better known as ordinary table salt. Due to a large difference in the electronegativity, electrons are not shared but rather the valence electron in a sodium atom is completely transferred to a chlorine atom to form a chlorine ion and a sodium ion. (Remember, when an atom either loses or gains electron(s), it is called an ion.)
Take a look at Lewis structures below. The two ions each have an octet of electrons.



The type of bond where electrons are transferred from one atom to another is called an **ionic bond.** The term “ionic bond” refers to electrostatic interactions or forces between opposite charged ions. Ionic bonds take place between nonmetallic elements and metallic elements.

A process of gaining electrons is called **reduction**. **Oxidation** is a process of losing electrons.

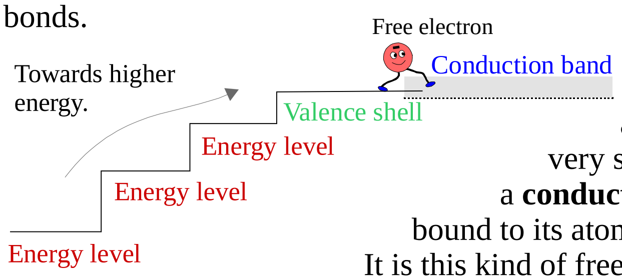
Non-metallic elements gain electrons and have excess negative charge and hence form negative ions (anions).
Metals lose electrons and have a positive overall charge and are called positive ions (cations).
An ionic compound forms because it is more stable or lower in energy than its elements.
Ions are arranged in such away as to maximize the attraction forces between ions with opposite charges and to minimize repulsion forces between ions with like charges. For instance, in NaCl crystal each positively charged sodium ion is surrounded by six negatively charged chlorine ions and each chlorine ion is surrounded by six sodium atoms. The electrostatic interactions give sodium chloride a high **lattice energy** and a high melting and boiling point. (Lattice energy is the energy required to completely break up ionic crystal of 1 mol of an ionic substance into ions or visa versa, that is, it is also the energy given out when ions come together to form ionic crystal compose of 1mol of a compound.)



Crystal structure of NaCl

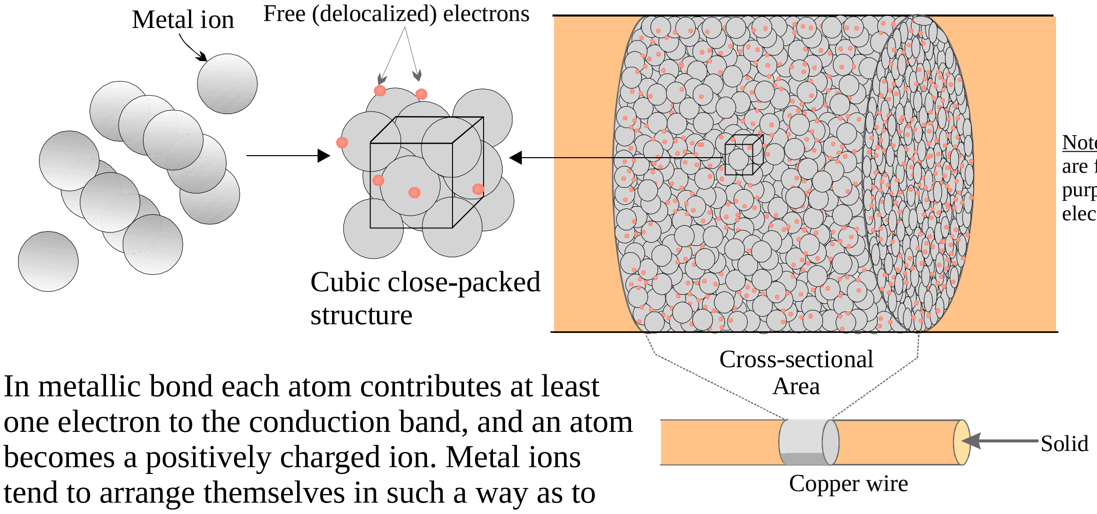
1.7 Metallic Bonds

To this point you have seen two kind of bonds: covalent bonds that deal with electron shearing and ionic bonds that are based on electrostatic forces between ions. The third kind of bond, we need to look at, is a **metallic bond.** This type of bond has some similarities with both covalent and ionic bonds.



Most of the metal atoms have either one or two valence electrons. The energy to “promote” a valence electron to a even higher energy level is very small. An electron readily moves to what is called a **conduction band** as a free electron. A free electron is not bound to its atom and can freely move along the conduction band. It is this kind of freedom that allows metals transmit electric charges.
Note: The term “band” is used to describe a large number of closely spaced (energy) levels in a material.

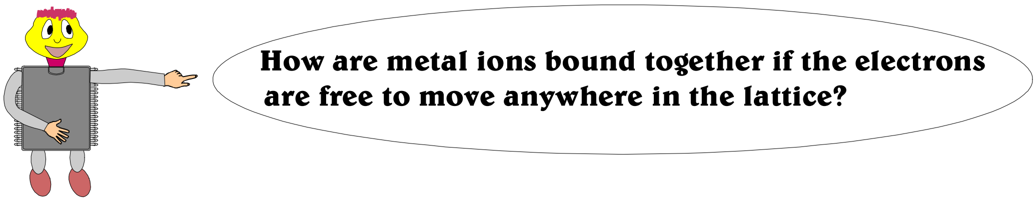
Let’s look at the bonding of metal atoms.



Note: These illustrations are for visualization purposes only. Ions and electrons are NOT to scale.

In metallic bond each atom contributes at least one electron to the conduction band, and an atom becomes a positively charged ion. Metal ions tend to arrange themselves in such a way as to minimize any empty space. This kind of lattice is called a **close-packing arrangement.** In case of copper metal, the copper ions are arranged in *cubic close-packed* structure. Each copper ion is in contact with twelve other copper ions. In this kind of arrangement, the valence shells overlap each other. This causes the conduction band to extend from one ion to all other neighboring ions and their neighbors. Electrons in the conduction band are free to move throughout the lattice.
These electrons are called **delocalized**. It means that an electron in not bound to its parent or any other atom in the structure (lattice).

The delocalized or free electron flow through metal is often called an **electron sea** or **electron gas.** An electron gas refers to a movement of a gas thorough densely packed particles such as sand. Electrons move through a metal ion lattice in a similar manner.

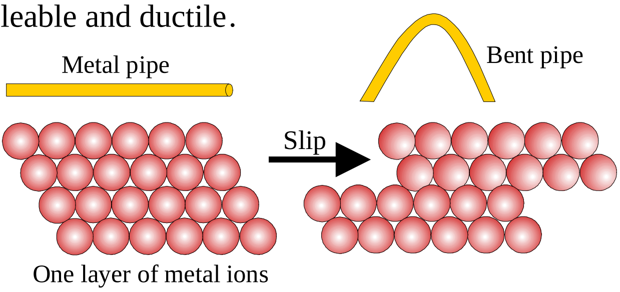


If you recall, it is the electrons in the outermost shell that take part in bonding. In this case, we are talking about the free (delocalized) electrons. How can a free electron take part in bonding if it is not bound to its parent or any other ion (atom)? That is the key to metallic bonding. Each positive ion is attracted to negatively charged electrons and each electron is attracted to ions. Electrons are then shared with all ions throughout the metal structure and it is those electrostatic attractions that hold the metal lattice together to form metallic bonds.

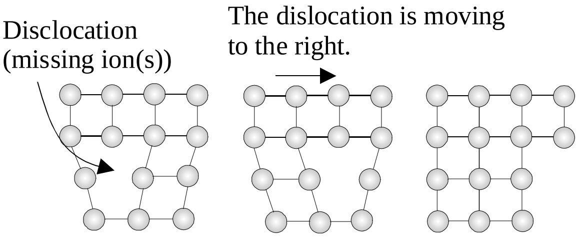
This kind of bonding give metals useful properties. Metals are **malleable**, which means that they can be shaped without breaking the bonds. Metals are also **ductile**, which means that they can be drawn out into wires.
This is possible because ions are not bound together like in covalent and ionic bonds.

We can look at two reasons why metals are both malleable and ductile.

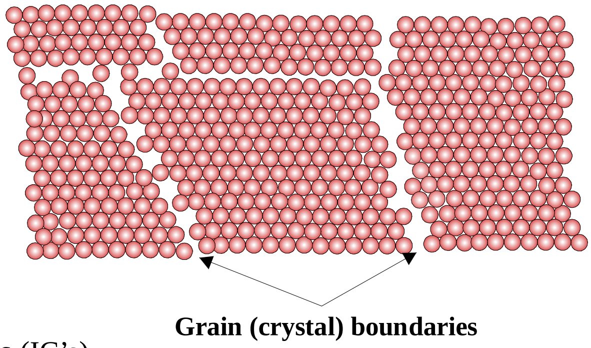
If you bend a metal pipe, it does not have to break. Instead of breaking metal bonds, some of the layers of ions *slide* with respect to other layers. This sliding of ions is called the **slip.** Metal ions have moved but they still maintain bonds with free electrons as before the slip.



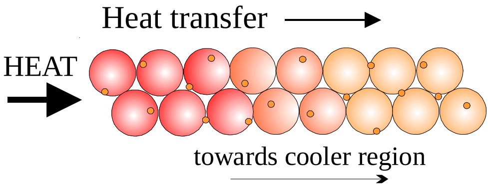
Another factor are **dislocations** which are defects or missing ions in the lattice structure. In the area of a defect, other layers try to compensate and reduce the strain by moving slightly. When a metal pipe is bent, these dislocations move easily and cause very little disruption elsewhere in the lattice.



Metals are often made from cast molten liquid. When molten liquid begin to cool and solidify, individuals crystals or grains begin to grow and eventually meet other grains (crystals).
The edges of the grains are called **grain boundaries**.
Grain boundaries can effectively hinder the movement of dislocations and can influence many properties of metal including strength and stiffness.
Grain boundaries play an important role in conduction of electric charges. (Discussed later in the text.)
Many electronic devices, particularly integrated circuits (IC’s), are fabricated from single crystal wafers and hence eliminating the “problem” of grain boundaries.



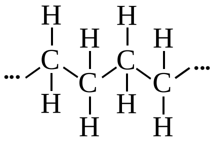
Besides being a good conductor of electric charges, metals are also good conductors of heat. When heat (energy) is applied to one end of a solid object, the atoms (ions) in that region begin to vibrate vigorously. The vibrating atoms then interact with neighboring atoms (cooler ones) and cause those atoms to vibrate more vigorously. This way the heat energy is passed along or conducted from warmer regions to cooler regions. This type of conduction is same for both metallic and non-metallic solids. So, what makes metals better conductors of heat than other solids? The key is in the abundance of free electrons in metals. In a hotter end of the metal, the vibrating ions cause electrons to gain more energy and they speed up. Some of the electrons end up in the cooler regions and undergo collisions with various particles. The energy gained from these collisions make ions vibrate more vigorously. In other words, electrons carry “kinetic” energy freely in metals and transfer this energy more efficiently to cooler regions than vibrating ions alone.



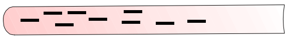
1.8 Conductor vs Insulator

We have already stated that metals are good conductors of electric charges because of the free electrons that can freely move from one region to another along the conduction band with very little energy applied.

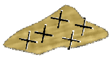
Insulator materials do not conduct electric charges well because of lack of conduction electrons or other conduction charges withing the insulator. Let's look at some examples. Plastics are considered insulators. The Lewis structure of a typical plastic (polyethylene) shows the bonds between the carbon and hydrogen atoms. Carbon has four valence electrons and it needs four more to obtain an octet (eight valence electrons). Every carbon atom is therefore bonded with two neighboring carbon atoms and with two hydrogen atoms. The resulting covalent bond leaves the valence band full. There are no higher energy levels available for valence electrons to move within the band. The energy band gap between the valence band and the conduction band is large which virtually eliminates electron movement from the valence band to the conduction band. (More about this in chapter 25, *Semiconductors*.)

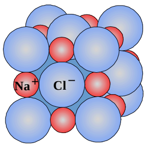

Plastic (Polyethylene)

When we give a negative charge to a plastic rod, it should be clear that the excess charges (electrons) are always located on the outside surface of the plastic and these electrons cannot move anywhere because the covalent bonds do not have any available electrons in valence shell or in the conduction band to transmit charges. Remember, the excess charges are just tiny fraction of total charges that an object such as plastic rod is made up.


Plastic rod with excess negative charge

The reason why the rod acquired those excess electrons from wool was that polyethylene molecules have a stronger attraction for electrons than the electron attraction in wool. Other materials such as glass, silk, and hair have also weak attraction to their electrons and quite readily impart electrons to materials with a stronger attraction.

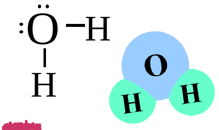

Wool has weak attraction to its electrons



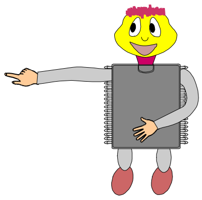
NaCl

Sodium chloride (NaCl) is an ionic bond that forms when a sodium atom loses one of its electron to a chlorine atom. This gives both ions an octet and leaves the valence band full and a large energy gap between the valence and the conduction band, thus making sodium chloride, in crystal (solid) form, an insulator.

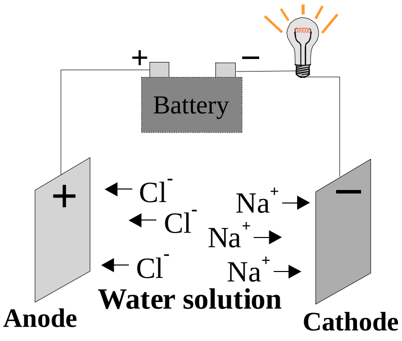
A water molecule is formed when two hydrogen atoms share their electrons with one oxygen atom.
Water is also considered to be an insulator.



Why are we warned about dangers of using live electrical equipment near water if water is an insulator?



To put it simply, only pure water is an insulator. For instance, tap water always contains some ions and additionally, when you take a bath, your body donates impurities to the water such as salts. Interesting thing happens when crystal salt ($NaCl$) is dissolved into water. The salt brakes into its components: sodium ion Na^+ and chlorine ion Cl^-.



Take a look at the illustration on the left.
Battery terminals are connected to metal plates (**electrodes**).
These plates are then submerged into a solution of water and salt ($NaCl$).
The plate that is connected to the positive terminal of the battery has a positive charge. Negatively charged chlorine ions are attracted to the plate (called *anode*) and move towards it.
Sodium ions are attracted to the negatively charged plate (called *cathode*) and move towards it.

The movement of Cl^- ions and Na^+ ions is called current or more specifically an **electric current** or a **charge current** whichever term you prefer to use.
This is a good example where electrons were not the charge carriers.
It is a big misconception that only electrons are responsible for an electric current.
As we discussed earlier, a human body is full of electrical activities but none of those activities is due to an electron current.

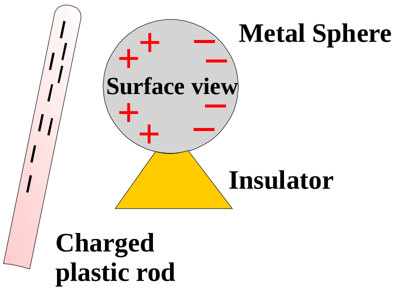
Note: Even pure water is not totally a perfect insulator. A process called *self-ionization* or *autoionization* occurs when two water molecules ($2H_2O$) collide and break into a hydroxide (OH^-) ion and a hydronium (H_3O^+) ion. The amount of ions in pure water due to self-ionization is fractionally small. However, these and other "defects" play important role in the electrical conduction of ice. Ice is called a **protonic semiconductor** because the electric current is carried by protons (H^+). The outer layer, *quasi-liquid layer*, conducts electricity 100 times better than solid ice due to its abundance of protons. This layer can be used as a heating element by moving protons (current) through the layer.

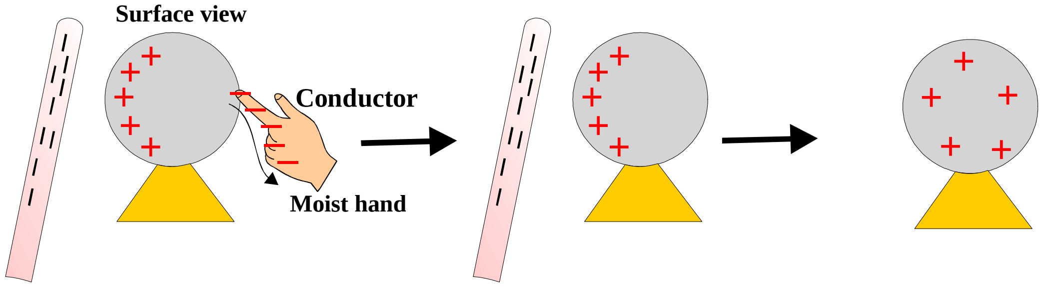
Semiconductor materials have characteristics that lie somewhere in between conductors and insulators. Semiconductors are used in electronics industry to make electronics devices and integrated circuits (IC's). The properties of ice, as a semiconductor, can be used in applications such as deicing power lines, airplane windows, and wings, or reducing friction between skies and snow. You will learn more about semiconductor materials and applications starting in the chapter 25.

Superconductors are materials the conduct electric charges with no resistance and very low losses. Initially superconductors operated only at very low temperatures but with invention of ceramic superconductors, the operating temperature has increased considerable. The ultimate goal is to have superconductors that operate at room temperature. Superconductors are used today in many applications. Medical industry is using this technology in magnetic resonance imaging (MRI), electronics industry to manufacture faster digital devices, used in transportation to design high speed trains that float or "levitate"in the air due to superconducting magnets, used in power transmission lines to carry energy without energy losses, and to design more efficient generators and energy storage systems.

1.9 Charging by induction

You have learnt how to transfer charges from one insulator to another such as the wool rubbing against the plastic rod. Let’s see what happens when a charged rod is brought near a conductor such as a metal sphere. When a negatively charged rod is brought near a neutral metal sphere, some of the free electrons in the sphere are repelled by the rod and move towards the right side of the sphere. Since the free electrons cannot escape the sphere, they accumulate onto the right surface of the sphere.
That leaves the left surface of the sphere with a deficiency of electrons or a positive charge.
These positive and negative charges are called **induced charges**.
If we took the rod far away from the sphere, the accumulated electrons distribute themselves uniformly in the sphere.
The sphere returns to its original neutral state.





A conductor is touching the sphere and electrons are repelled from the sphere to the conductor.

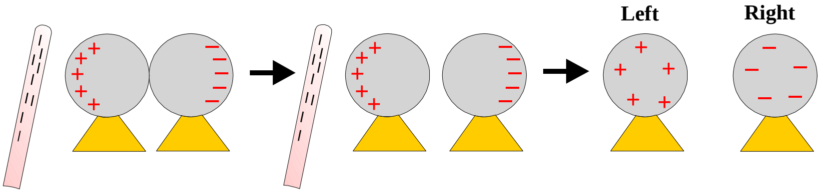
Left side of sphere has a positive charge

Negative charged rod is removed. That leaves a uniform positive charge on the surface of the sphere.

If the charged rod is brought near the sphere and we touch the sphere with a conductor, such as a moist hand, some free electrons are repelled to the conductor. Once the conductor is removed, the left surface of the sphere has a positive charge. After the negatively charged rod is removed, the positive charges distributes themselves uniformly on the surface of the sphere.

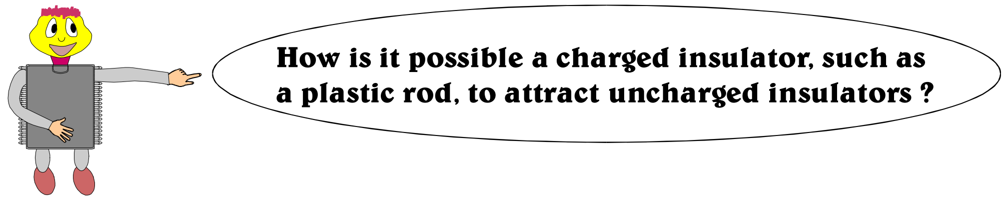
Note: When a charged rod is placed near a sphere, only some of the free electrons move onto the surface. This is because the induced surface charges (negative and positive) exert forces on the free electrons inside the sphere. The direction of these forces is towards left (towards the rod). That is, electrons on the surface exert repulsion force and the positive surface charges exert attraction force on free electrons inside the sphere. The movement of the free electrons onto the right surface stops when the repelling force (due to rod) to the right equals the force (due to induced charges) to the left. Think about this. What would happen to metal bonds if you could easily “drain” a metal object, such as a sphere, most of its free electrons just by driving free electrons onto surface and repel them to a another conductor? There would not be enough free electrons to exert attraction forces on metal ions to hold metal bonds together.

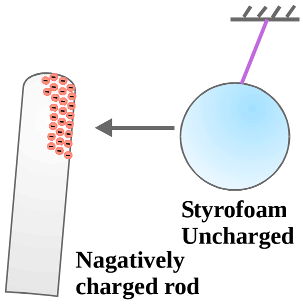
Another way to demonstrate induction is to use two spheres. When the spheres are touching each other, you could think that they are just one large sphere that has a positive charge on the left surface and a negative charge on the right surface. Once the spheres are separated and the rod removed, the left sphere has an uniform positive charge on the surface and the right sphere has an uniform negative charge on the surface.



It should be clear that since the rod did not touch the sphere, the rod did not lose any of its negative charges (electrons).

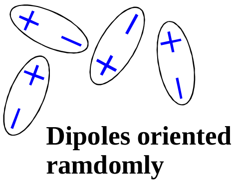
1.10 Induced Charges on Insulators (Dielectrics)

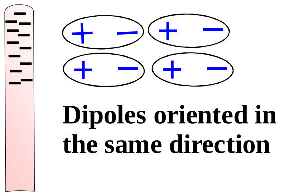




In other words, if we have a Styrofoam ball suspended from the ceiling and a negatively charged plastic rod is brought near the Styrofoam ball, then why is the uncharged Styrofoam attracted to the rod?
If the Styrofoam had a positive charge, then the attraction force would be easy to understand. Unlike in conductors where charges can move, the charges in insulators cannot move or can they?

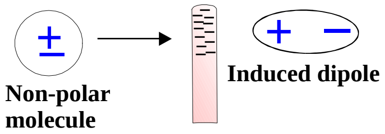
Few pages back we talked about permanent dipoles and induced dipoles.
Water molecule was a good example of a permanent dipole.

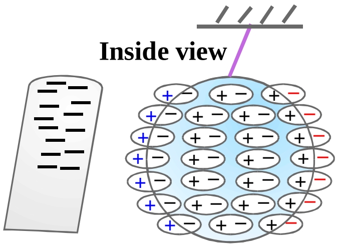




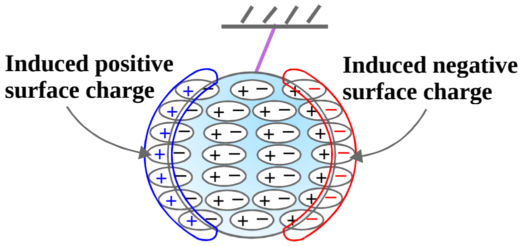
If the insulator material (also called **dielectric**) consists of polar molecules, the dipoles are oriented randomly. If a charged object is brought near these dipoles, the dipoles orient themselves so that positive end of the dipoles are pointing towards the negatively charged object (opposite charges attract).

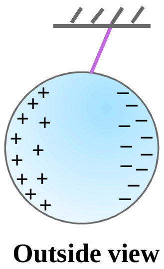
Induced dipoles align the same way as permanent dipoles when near a charged object.
An induced dipole can be created when a charged object, such as a plastic rod, is brought near a non-polar atom or molecule of an insulator. The electron density in the molecule moves away from the negatively charged rod and this stretches the molecule and it becomes an induced dipole.





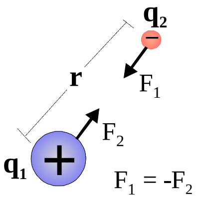
If we were to look at the inside or cross-sectional view of the Styrofoam, we could see all dipoles aligned in the same direction. This is called **polarization**.
There is an induced excess charge in the two thin surface layers indicated by the blue and red colors. These charges are bound to the molecules near the surface.





From the outside view, the Styrofoam has an excess negative charge on one surface and an excess positive charge on the opposite side. The positive excess charges are then attracted to the negatively charged rod and the negative excess charges on the Styrofoam surface are repelled away from the rod.
Since the positive charges are physically closer to the charged rod than the negative charges, the Styrofoam ball experiences a net force (attraction) towards the rod.
Once the charged rod is removed, the electron density of the molecules moves towards left and the Styrofoam ball returns to its uncharged state.

1.11 Coulomb's Law



Recall the basic model of a hydrogen atom. The nucleus consists of a positively charged proton which is attracted to the negatively charged electron.
The two charged particles exert electrical forces on each other.
The forces obey *Newton's third law*. In other words, the force that the proton exerts on the electron has the same magnitude as the force the electron exerts on the proton but has the opposite direction. This also true if the magnitudes of charges are not equal.
The force is a vector quantity, it requires both the magnitude and direction.

These forces are inversely proportional to the square of the distance between particles. If distance is doubled, then the force (attraction or repulsion) is 4 times weaker.

The force between two charged particles is also directly proportional to the product of the charges.

The force between two charged particles can be written as a mathematical expression. This is know as **Coulomb's law.** $\boxed{F = k\,\frac{|q_1 q_2|}{r^2}}$ units *newtons* (N)

Coulomb's law is considered as the fundamental equation of electrostatics.

k is called a proportionality constant $\cong 8.99 \times 10^{9}\ \mathrm{N\,m^2C^{-2}}$

The direction of the force is along the line joining the two particles.
The absolute value bars are needed because the magnitude of a vector quantity is always positive.
Should the product $q_1 q_2$ be negative, this indicates that charges exert attraction forces on each other since they have opposite signs (one negative and one positive).

The unit of electrical charge is one *coulomb* (1C)**.**
The magnitude of charge (electron or proton) is $e = 1.602\,176\,487 \times 10^{-19}$ C or $e \cong 1.602 \times 10^{-19}$ C.

1 coulomb is therefore 6.24×10^{18} electrons. For comparison, there are about 1.4×10^{24} free electrons in one cubic inch of copper at room temperature and about 8.5×10^{22} free electrons in one cubic centimeter of copper.

Note: Although two different classes of phenomena, the equation of Coulomb's law has the same form as the Newton's law of gravitation $F = G\,\frac{m_1 m_2}{r^2}$ where G is the gravitational constant. $G \cong 6.674 \times 10^{-11}\ \mathrm{N\cdot m^2\cdot kg^{-2}}$.

You have now enough information to make the relative comparison of the magnitudes of both electrostatic and gravitational forces of a hydrogen atom.
The radius of the hydrogen atom ($r \cong 5.29 \times 10^{-11}$ m) is not needed for comparison.
Mass of proton $\cong 1.673 \times 10^{-27}$ kg and mass of electron $\cong 9.109 \times 10^{-31}$ kg.

$$8.99 \times 10^{9}\ \mathrm{Nm^2C^{-2}}(1.602 \times 10^{-19}\ \mathrm{C})^2 \gg 6.674 \times 10^{-11}\ \mathrm{N\cdot m^2\cdot kg^{-2}}(1.673 \times 10^{-27}\ \mathrm{kg})(9.110 \times 10^{-31}\ \mathrm{kg})$$

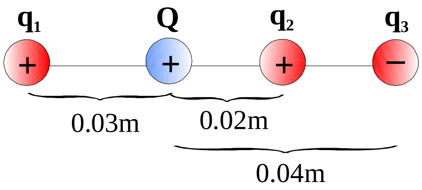
$$\text{(electrostatic) } 2.31 \times 10^{-28} \gg 1.02 \times 10^{-67} \text{ (gravitational)} \quad \text{or} \quad \frac{F_{ELECT}}{F_{GRAV}} = 2.26 \times 10^{39}$$

Electrostatic force is much larger than gravitational force. $F_{ELECT} \gg F_{GRAV}$

Should there be more than one particle exerting force on another particle,
the total force exerting on that particle is the vector sum of individual forces.

Let's look at an example.

There are four charges: q_1 is located 3 cm from charge Q, q_2 is 2 cm from Q, and q_3 is 4 cm from Q.



$\mathbf{Q} = +2 \text{ x } 10^{-9}\,\text{C}$
$\mathbf{q_1} = +3 \text{ x } 10^{-9}\,\text{C}$
$\mathbf{q_2} = +4 \text{ x } 10^{-9}\,\text{C}$
$\mathbf{q_3} = -5 \text{ x } 10^{-9}\,\text{C}$

$$\boxed{F = k\frac{|qQ|}{r^2}}$$

What is the total force exerted on Q by charges q_1, q_2, and q_3?

First, we calculate the individual forces exerting on Q.

$$F_1 = \frac{(8.99 \text{ x } 10^{9}\,\text{Nm}^2\text{C}^{-2})(3 \text{ x } 10^{-9}\,\text{C})(2 \text{ x } 10^{-9}\,\text{C})}{(0.03\,\text{m})^2} = 5.9933 \text{ x } 10^{-5}\,\text{N} \longrightarrow \text{Right}$$

Since like charges repel, the force F_1 is trying to push charge Q to the right (away from q_1).

$$F_2 = \frac{(8.99 \text{ x } 10^{9}\,\text{Nm}^2\text{C}^{-2})(4 \text{ x } 10^{-9}\,\text{C})(2 \text{ x } 10^{-9}\,\text{C})}{(0.02\,\text{m})^2} = 1.798 \text{ x } 10^{-4}\,\text{N} \longleftarrow \text{Left}$$

Force F_2 is also a repelling force and thus charge q_2 is pushing Q to the left.

$$F_3 = \frac{(8.99 \text{ x } 10^{9}\,\text{Nm}^2\text{C}^{-2})(5 \text{ x } 10^{-9}\,\text{C})(2 \text{ x } 10^{-9}\,\text{C})}{(0.04\,\text{m})^2} = 5.619 \text{ x } 10^{-5}\,\text{N} \longrightarrow \text{Right}$$

Force F_3 is an attractive force and is trying to pull Q to the right (towards q_3).

To calculate the total force, we must add all the forces exerting to the right and subtracting the forces exerting to the left (or visa versa, you choose the direction).

Total force $F_{Tot} = F_1 - F_2 + F_3 = 5.99\text{x}10^{-5}\,\text{N} - 1.79\text{x}10^{-4}\,\text{N} + 5.61\text{x}10^{-5}\,\text{N} = -6.37\text{x}10^{-5}\,\text{N}$

We chose the right direction as a positive direction.
The minus sign indicates that the total force on Q is $6.37\text{x}10^{-5}$ N to the left.

The Coulomb's law is often written as $\boxed{F = \dfrac{1}{4\pi\varepsilon_0}\dfrac{|q_1 q_2|}{r^2}}$

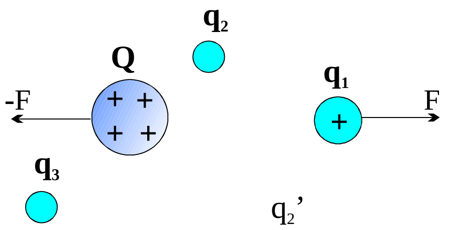
where $\dfrac{1}{4\pi\varepsilon_0} = 8.987552 \text{ x } 10^{9}\,\text{N}\cdot\text{m}^2\cdot\text{C}^{-2}$

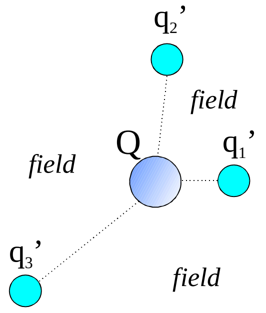
and the constant $\varepsilon_0 = 8.854188 \text{ x } 10^{-12}\text{C}^{-2}\cdot\text{N}^{-1}\cdot\text{m}^{-2}$. (Discussed in chapter 16 "*Capacitance and Capacitors*")

Note that $8.987552 \text{ x } 10^{9} = c^2 \cdot 10^{-7}$ where c = speed of light $\approx 3 \text{ x } 10^{8}\,\text{m/s}$.

2

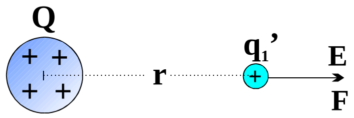
ELECTRIC FIELD





We have discussed that two charged particles exert electrical forces on each other. The force exerting on Q by q_1 has the same magnitude as the force exerting on q_1 by Q but has an opposite (negative) direction.
The charge Q is also exerting electrical forces on q_2 and q_3.
In fact, Q is exerting forces on every charged particle around it.
This is easier to visualize if we made charges q_1, q_2, and q_3 so small that the forces they exert are negligible.
We call these kind of charges **test charges** (q_1', q_2', and q_3').
So, charge Q is the only one exerting electrical force in the region.
Imagine that Q produces an **electric field** around it and the forces are exerted on q_1', q_2', and q_3' by the **field** rather than Q directly.
We say that it is the electric field, produced by Q, that exerts forces on test charges q_1', q_2', and q_3'.

The strength of the field at a certain point depends only on the charge Q and its distance (r) from a test charge.



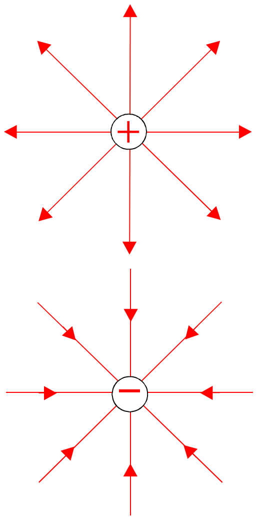
Mathematical expression for the electric field (E) strength is $\boxed{E = k\frac{Q}{r^2}}$

The relationship between the field and force is $\boxed{E = \frac{F}{q_1'}}$ $\boxed{F = q_1'E}$ where q_1' is a positive test charge.

For a positive charge, the direction of the force is the same as the direction of the field.
For a negative charge, the direction of the force is opposite to the direction of the field.

The electric field unit is $1\frac{N}{C}$ or $1\frac{V}{m}$ $\left(\frac{volt}{meter}\right)$ Note the familiar term *volts*. The connection between volts and E - field is explained in the next chapter.

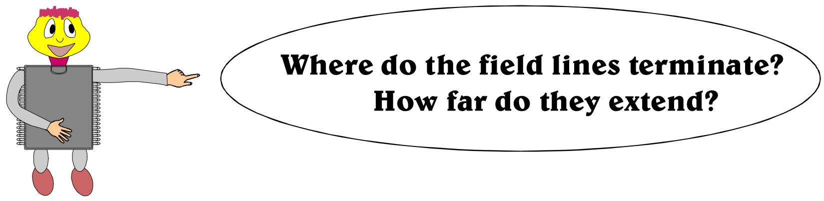
Let's look at a concept called **field lines**.
Field lines are imaginary lines whose direction at any point is the same as the direction of the field at that point.
Remember, field exists everywhere around the charge and not only where the lines are drawn.
Field lines help you better to visualize the direction of the field.



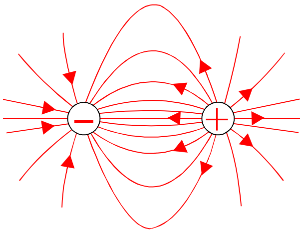
A term **flux** can be used to describe the number of field lines crossing a surface. For simplicity, in this book, flux is the same as field lines.

When lines are straight and parallel and equal distance apart, the field is called *homogeneous* or *uniform***.** Electric field in that region does not vary.

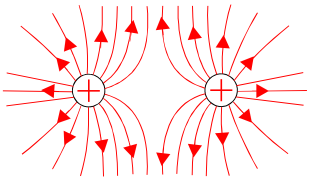
The direction of the field lines is outwards for the positive charge and inwards for the negative charge.



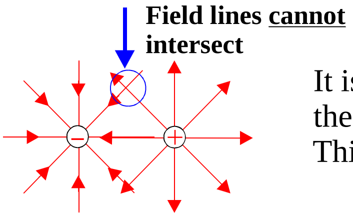
Field lines terminate so that in one end there is a negative charge and in the other end a positive charge. The field lines extend until this has happened.
Inside a room field lines are then terminated by the floor, ceiling, walls, or objects in the room.
The spacing of field lines is directly proportional to the field strength. The field lines are closely spaced in between the positive and negative charge because the field is large in that region.



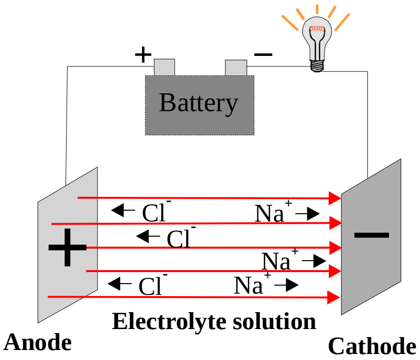
The illustration on the right shows field lines (flux) for two equal charges, one a positive and one a negative charge.
The field lines for this "electric dipole" are similar to the magnetic field lines created by two bar magnets.
Besides being closely spaced, the field lines are also more uniform in between the two charges.



What happens when a positive charge encounters another positive charge?
Since like charges repel each other, the field lines will also repel.

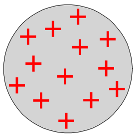


It is important to understand that at any point, the resulting field can have only one direction. This means that the field lines cannot intersect.

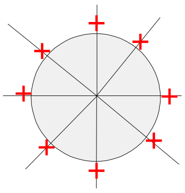


Example 1.
Some table salt (NaCl) is dissolved into water to form an **electrolyte** solution. Electrolyte is an ionic solution that can transmit or conduct electric charges.
A battery is connected to two metal plates so that one metal plate has a positive charge and the other one has a negative charge.
Chlorine ions Cl^- are attracted to a positively charged plate (anode) and sodium ions Na^+ are attracted to a cathode.
The movement of ions is called an electric current.
Field lines (red lines) have been added to show the electric field between the metal plates.
This example clearly demonstrates the correlation between an electric field and the movement of charges. Here, the charges do not move without the presence of an electric field.

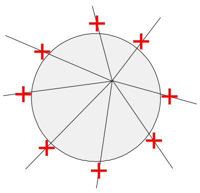
Solid Metal Sphere



Inside View - A



Inside View - B



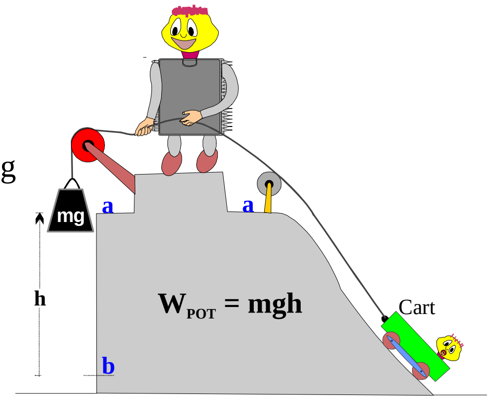
Example 2.
A solid metal sphere has a positive charge. The charges are distributed uniformly on the surface of the sphere.
The question is, what is the electric field inside the sphere?
Let's first look at the point in the center of the sphere (view A). Due to symmetry, the E-field is zero. Think about it. Each charge on the surface is a source of an electric field. Therefore, the total E-field from all surface charges in the center must be zero. How about a point off-center (view B)? The E-field is still zero. Although the off-center point is closer to one part of the charged surface, the amount of surface charge area on that side is smaller compared to the surface charge area on the opposite side, greater distance away from the point. A larger charge area with greater distance balances the smaller charge area with smaller distance. Hence, the electric field everywhere inside the sphere is zero.

3

POTENTIAL ENERGY and VOLTAGE

3.1 Potential and Potential Energy

Let’s first review few concepts. Energy is often defined as capacity to do work or to transfer heat. Energy is found in many different forms: gravitational, mechanical, chemical, electrical, heat energy, light energy, and nuclear energy.
Kinetic energy (*KE*) is associated with moving objects, that is, it is the energy of motion ($E = \frac{1}{2} mv^2$).
Potential energy (***PE***) is the energy stored in an object by virtue of its position or displacement



The illustration on the right is an example of a gravitational potential energy. When an object with weight *mg* (mass of an object times acceleration due to gravity) is pulled up from a height *b* to a height *a*, an object is said to have potential to do work. This object has gained energy by virtue of increasing the height of an object. In other words, the energy that was used to bring an object to the height of *h* is now stored as a potential energy.
Potential energy (PE) can be expressed as $\mathbf{W_{POT} = mgh}$
where m is mass of an object, h is height and
g is acceleration due to gravity constant ~ $9.8\,ms^{-2}$.

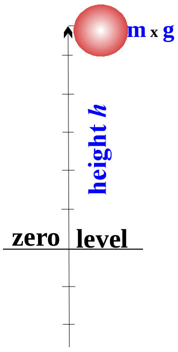
The unit of energy is 1 *joule* (J). (1J = 0.239 cal)

An example.
A mass of 60 kg weight is lifted from the ground (height b) to the height of 3 meters (height a).
Calculate the potential energy of the weight. $W_{POT} = 60\,kg \times 9.8\,m\,s^{-2} \times 3\,m = 1764\,J$

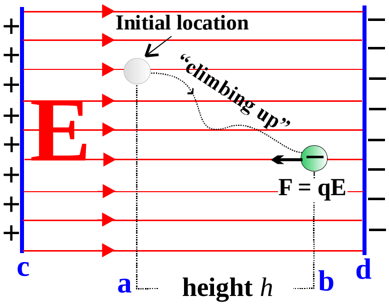
One should realize that potential energy does not automatically have a zero level. This level has to be chosen. It is often convenient to choose ground as a zero level or a reference level.
If the reference level is not zero, then the displacement value is derived by subtracting the end height from the initial height (the height difference).

Potential energy does not depend on path but only on the different height between two points.

If the (green) cart was pulled up to the 3 m level (height *a*) and the mass of the cart was 60 kg, the potential energy of that cart would be the same as the object’s PE in our example. PE = 1764 J.
The cart took longer path to reach the height of 3 meters, but the potential energy is the same because the gravitational potential energy does not depend on the path.



When we deal with electric fields, we can talk about *potential* and potential energy separately.
Although term “potential” is not really used in mechanics, we can try to visualize the concept anyway. On the right is an object with mass m and it is located at height *h*.
Since potential energy is the energy stored in an object by virtue of its displacement, then what is just “potential”? If we removed the object, what do we have left?
Gravity (g) and the displacement (height *h*) are still there.
Gravity and the displacement without an object cannot gain energy nor do work.
We can only conclude that there is “potential” for it.
You could think that if potential is gravity with height ($g \cdot h$), then potential energy is an object with potential $W_{POT} = m \cdot (g \cdot h)$ or $W_{POT} = mgh$. Do you see the difference?

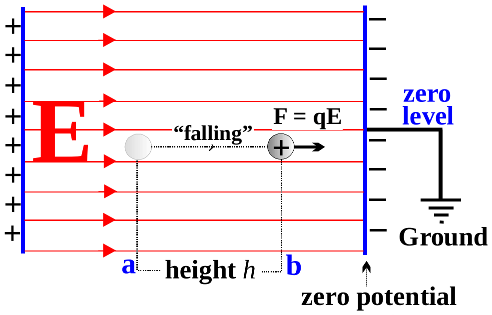


Take a look at the illustration on the right.
Here, we have a negative test charge that is moved towards a more negative end of an uniform electric field (E).
This means that the potential energy of the test charge is increasing.
For instance, if a particle (an electron) is moved from "height *a*" to "height *b*", the work done or the energy used to move the particle from *a* to *b* is stored as a potential energy.

We can express the potential energy (W_{POT}) as the product of the force on an electron and the displacement or height. $\mathbf{W_{POT} = F \cdot \mathit{h} = qE \cdot \mathit{h}}$

Note: A symbol **q** can be used for a test charge as long as it is understood that the magnitude of **q** is very small; for example, **q** is an electron or a proton.

From the illustration (top right) you can see that the maximum displacement (height) for the particle is the distance between points *c* and *d*.
Potential energy is the highest when the displacement the highest.
Potential energy does not depend on path. It is only the displacement (*h*) that matters.

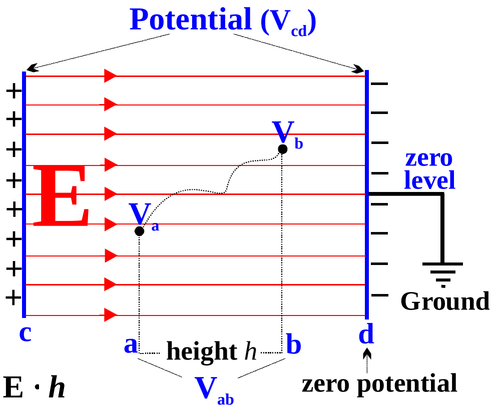


A zero level is almost always chosen to be ground or a conductor connected to ground. At that level, potential energy is zero. If a positively charged particle is moved towards the positive end of the field (E), the energy is used to increase potential energy of the charge. This is like moving an object to a higher level against the force of gravity.

Should the particle "fall" towards a zero level (the same direction as the field), the "loss" of potential energy is then converted to a kinetic energy of the particle. $\mathbf{W_{POT} = W_{KIN} = qE \cdot \mathit{h} = \tfrac{1}{2}\,mv^2}$

(Note: Negatively charged particles "fall" to the opposite direction, against the field.)

In mechanics, we pictured potential being gravity with height (*h*). How would we describe potential when we talk about a charge in an electric field?



The electric potential energy depends on the magnitude of the field, the magnitude of charge, and the displacement value (height). If we were to remove the charge, what is left? Are there any work done on anything? No.
The electric field (E) and the displacement (*h*) are still present, which are independent from the charge (q).
You can think that if potential (V) is the electric field (E) with the displacement (*h*), then potential energy is a charge (q) with potential (E · *h*) and thus $W_{POT} = qE \cdot h$ or $\mathbf{W_{POT} = qV}$.

The potential between points *a* and *b* can be expressed as $\mathbf{V_{ab} = E \cdot \mathit{h}}$

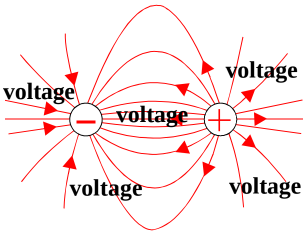
Since the unit for an electric field is $1\frac{V}{m}\left(\frac{\text{volt}}{\text{meter}}\right)$, the unit for the potential is expressed in *volts* (V).

Since potential energy and charge are both scalars, it follows that the potential is also scalar.

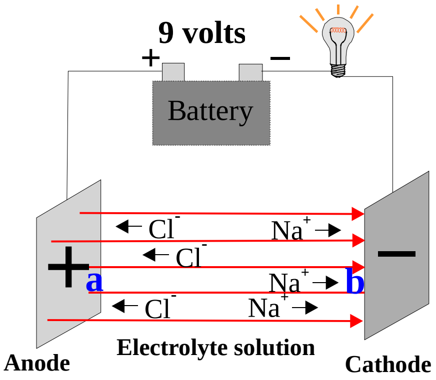
Potential is always measured between two points. If we ask, what is the potential at point *a* (V_a), we need to know with respect to what other point. If that information is not given, then we assume that potential is with respect to ground (zero potential).
Potential difference is often used in place of potential to avoid confusion.

3.2 Voltage

The term potential may have been new to you but volts and voltage should be familiar to everyone. When you buy batteries, you need to know not only the size of the battery but also how many volts is required, 1.5 volts or 9 volts, for example. Most of your household appliances run on either 120 volts or 240 volts.

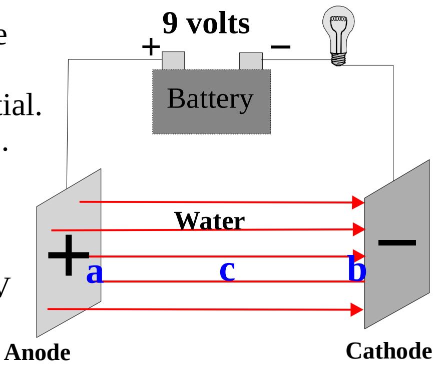


You know now that potential is same as voltage. Electric fields exist around charge particles. We know that field lines terminate so that in one end there is a negative charge and in the other end a positive charge.
Potential or voltage exists everywhere in the electric field.
Voltage can be measured by using a voltmeter.



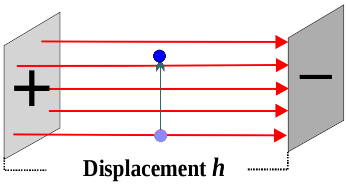
Here is an illustration you have seen few times. A battery is connected to two metal plates that have acquired an opposite charge, a one positive and the other one a negative charge. Between plates there is an electrolyte solution (water and salt). We know that when a battery is connected to the plates, ions move and we call this movement as electric current.

Suppose the battery voltage is 9 volts. What is the potential between points *a* and *b*? We do not have to know the electric field nor the displacement since we know the potentials at each end of the field (points *a* and *b*). $V_{ab} = V_a - V_b = 9$ volts - 0 volts = 9 volts.
Recall that zero potential is chosen to be at the negative end or ground (point *b*).
So, potential at that end is zero.

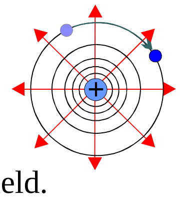


What about the situation where an electrolyte is replaced with pure water? What happened to the electric field or potential between points *a* and *b*? Nothing. The field is still there and so is the potential. There is no current because of lack of ions, but there is "potential".
If the potential V_{ab} is 9 volts, then what is the potential between points *a* and *c* (c is a half way point).
Since the potential decreases linearly from anode to cathode, we do not need to know the displacement. The potential $V_{ac} = 4.5$ V (half the battery voltage). How about potential between *b* and *c*?
$V_{bc} = V_b - V_c = 0 \text{ V} - 4.5 \text{ V} = -4.5$ V. As you see, potential can be negative. It all depends on a chosen direction. This is equivalent of measuring battery voltage using a voltmeter and putting a negative lead to the positive terminal and a positive lead to the negative terminal and reading negative volts.

3.3 Equipotential Surfaces



If a charge (q) moves in an electric field so that there is no displacement (*h*), it means that there is no change in potential, and thus no work is done to move the charge.

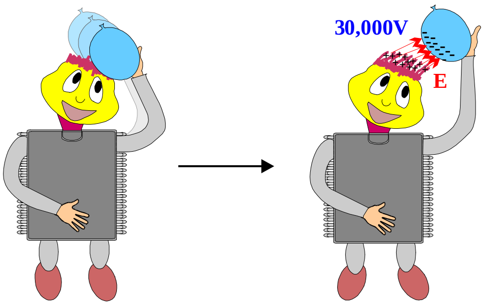


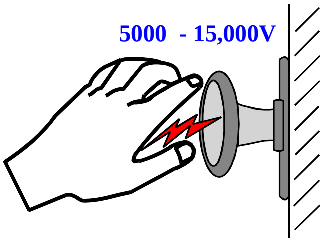
Potential distribution can be represented by **equipotential surfaces** (shown in black circles). The potential has same value on every point on any one circle. No work is required to move a charge over an equipotential surface. As you can see from both illustrations, an equipotential surface is always at right angles to the direction of the field.

3.4 Examples of Potential Differences

Although the term voltage is familiar in our everyday life, how many of us really know the immense voltages associated, for instance, with static electricity?

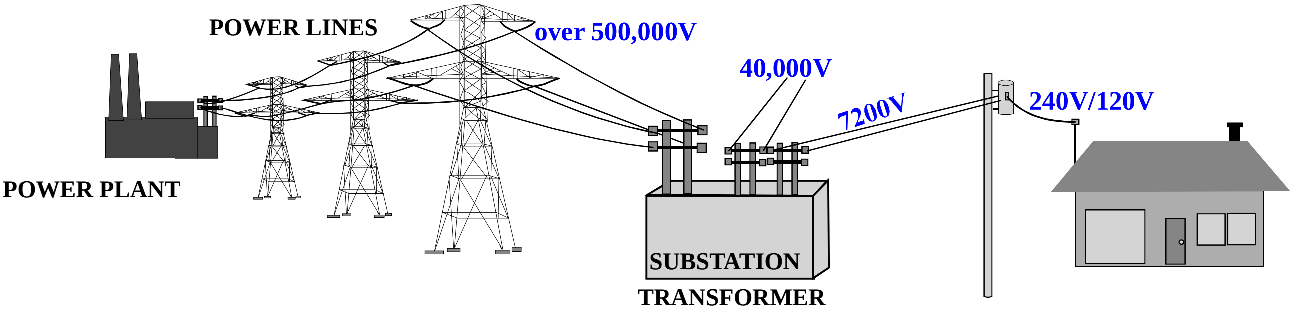
If you were to rub your hair with a rubber balloon, your hair would impart electrons to the balloon. Because air is considered a poor conductor of charges, there is a huge charge imbalance between the hair and the balloon. The electric field is very strong and the potential difference between the hair and the balloon can be tens of thousands of volts.



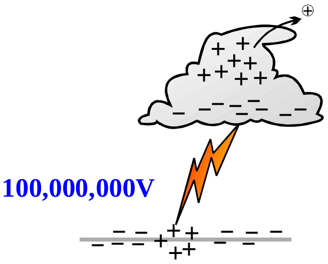


When you get "zapped" by a door knob, did you know that right before the spark develops, the voltage between your finger and the knob can be as high as 15,000V? As a matter of fact, it takes several thousand volts of potential difference before you can actually feel any sparks.

Besides static electricity, there are other sources of very high potentials. Your household voltages of 120 volts and 240 volts did not start that low when electricity was generated by a power plant.

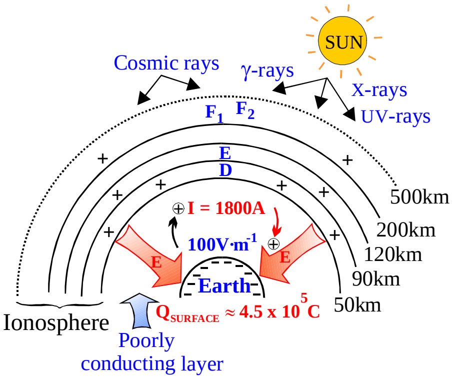


In order to minimize losses in transmission, potential in the transmission lines can be over half a million volts. That voltage is then reduced by substations that redirect lines to various industries and residential areas. Typically, the voltage that your local street transformer receives is 7200 volts.



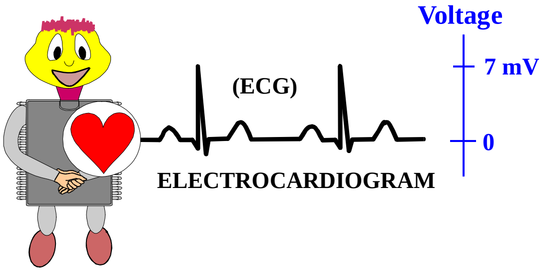
During thunderstorms the potential difference between a thunder cloud and ground can be as high as a hundred million volts.

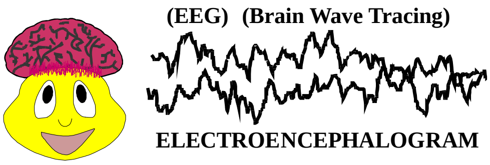
Earth is a good conductor of electric charges. Above the surface of the earth, there is a poorly conducting layer that extends to about height of 50 km. Above that begins the **ionosphere** which is a quite good conductor. Earth is negatively charged and the outer conductor has a positive charge. The direction of the electric field is downwards. The potential difference between these conducting layers is about **400,000** volts.



As stated before, a human body is full of electrical activities.
Voltages, that can be measured, are usually quite small.

Electrocardiogram (ECG) measures potentials in person's heart and levels are given in millivolts.
(1 millivolt = 1 mV = 1 thousandth of volt)



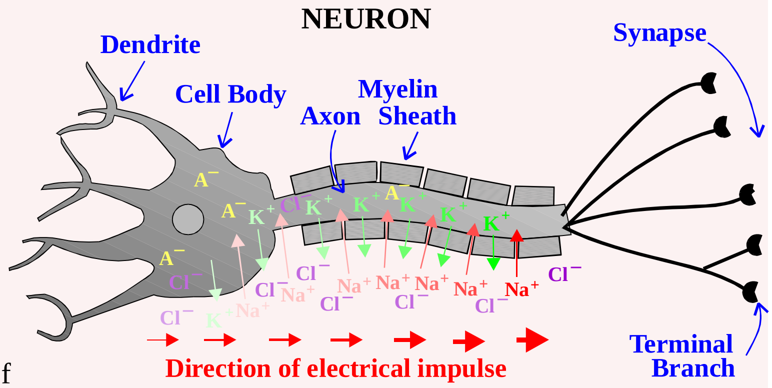


Brain wave activities can be observed by use of EEG. There are many different waves: alpha, beta, delta, and theta waves. These voltages are quite small. Potentials are usually less than 40 microvolts
(1 microvolt = 1μV = 1 millionth of volt).
The exceptions are some sleep cycles where potentials are somewhat higher.

Optional

Nerve cells transmit electrical signals by changing a cell's polarity from a negative to a positive and back to a negative and propagating this change along the cell. (*neurons*)

Nerve cells (*neurons*) transmit electrical signals by changing a cell's polarity from a negative to a positive and back to a negative and propagating this change along the cell.
When a neuron is at rest, the potential difference between inside and outside the cell is -70 mV.
It means that due to negatively charged organic (A$^-$) ions, the cell inside is more negative than outside.
If a (sensory) nerve cell receives a stimulus, such as a touch, some positive sodium ions (Na$^+$) leak through channels into the cell moving its potential towards a more positive direction.
If enough Na$^+$ ions flow in so that potential reaches the threshold potential, large influx of Na$^+$ enters the cell and this starts an *action potential*.

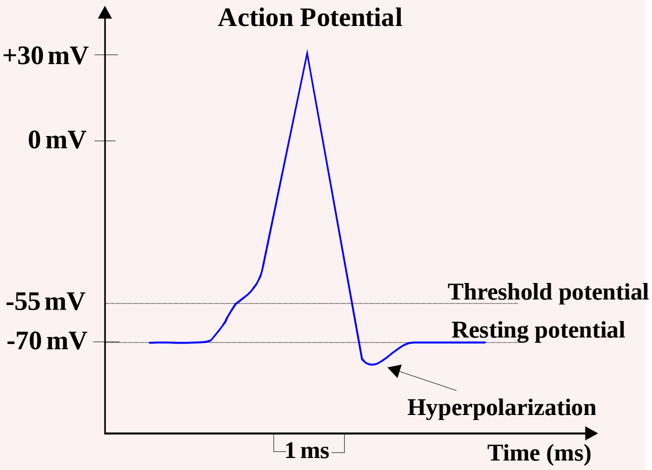


Surge of Na$^+$ drives the potential difference to +30 mV. This takes place in about 1 ms.

Na$^+$ channels close and potassium ion (K$^+$) channels open.
This allows K$^+$ ions leave neuron and the cell begins to reverse its polarity.

The potential actually goes below the rest potential for a brief period.
This is called *hyperpolarization*.
Chlorine (Cl$^-$) ions inhibit the transmission of nerve impulses by opening Cl$^-$ channels and letting Cl$^-$ ions into the cell.
The original potential levels are restored by so called Na$^+$/K$^+$ pump.

Although it is not clear from the illustration, the action potential begins at the dendrite and travels down along the axon to the terminal branches. The impulse transmission between two neurons at the synapse is chemical.



Note: Many painkillers work by blocking various channels in order to impede the transmission of pain signals. For instance, local anesthetic, used by dentists, works by blocking sodium (Na$^+$) channels.

4

ELECTRIC CURRENT

4.1 Introduction

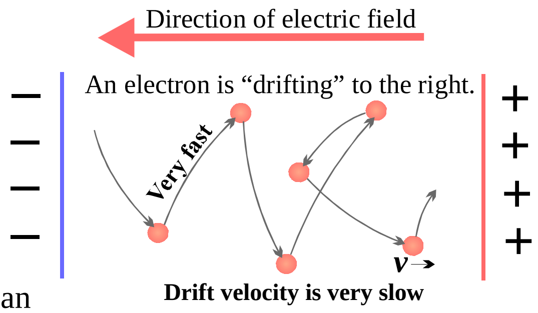
Most of the previous sections have dealt with electrostatic forces between charges.
Now, we introduce a new term called **electrokinetics**.
Electrokinetics is study of charges in motion.

Note: It is important to understand that electrostatics does not only involve charges at rest.
When charges are in motion, the electrostatic forces do not suddenly disappear somewhere.
Electrostatic forces effect charges whether they are moving or stationary.

In previous sections we called moving charges as electric current. We have also discussed that moving charges can consists of electrons, positively charged ions, and negatively charged ions. Later, when discussing of semiconductors, another kind of "charge", called a *hole* is introduced.

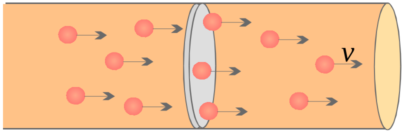
The moving charges in metals are electrons. Recall, electrons "fall" or accelerate due to influence of an electric field. In the "real world" this may not be true. Electrons in conductors, at room temperature, gain thermal (heat) energy and accelerate and move very fast without the presence of an electric field. This movement is random so that electrons do not have any net gain to any direction. Electrons accelerate in the straight line and soon collide with various particles and get scattered to other directions. Some of these scatterings are collisions that result electrons losing their kinetic energy. Electrons have to gain thermal energy to be able to accelerate again.

In the presence of external force, such as an electric field, an electron path is curved.
Although the direction of an electron acceleration is random, the electron will have a net gain to one direction. This is due to a curved path an electron travels between collisions. This path is curved towards the direction of a higher potential.
The electron movement is called "drifting" at a certain average velocity (*v*). This **drift velocity** is much smaller than the random velocity.



What is (electric) current?
Current is a scalar quantity, that is, it has no direction.
Current tells you the rate at which charges flow across an area per unit time (gray circular area in this example).
This is same as you filling a bucket with a water hose, and the rate at which water is coming out of the hose is, for instance, 1 gallon per minute (1 gal / min).

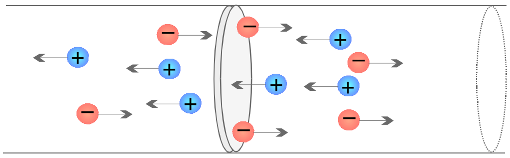
Current (I) is the rate of charge flow across an area per unit time.



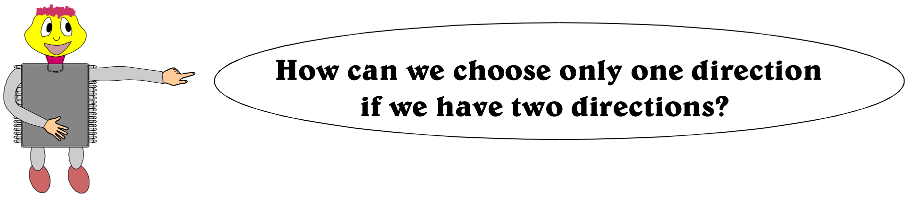
Current (I) is then $\boxed{I = \frac{Q}{t}}$ where Q = *coulombs* (C), t = *seconds* (s), and I = *amperes* (A)

Current is therefore *one coulomb per second*. The unit of current is 1 *ampere* (1A).
If you recall, one coulomb equals to 6.24×10^{18} electrons. That is a huge number.
In electronics, currents are typically much smaller than 1A and are often expressed in either milliamperes ($1\ mA = 10^{-3} A$) or in microamperes ($1 \mu A = 10^{-6} A$).

Although current itself has no direction, we still need to determine the direction of charge current that will be used throughout this text.

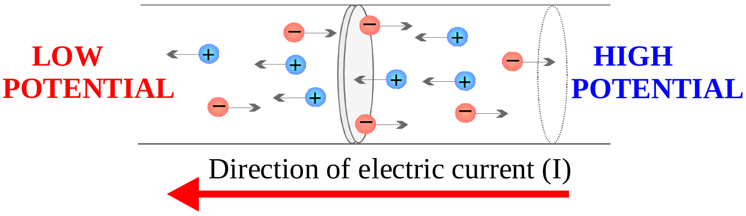


It is clear that, in this illustration, the negative charges flow to the right and positive charges flow to the left. However, when analyzing electric circuits, there can be only one electric current direction.



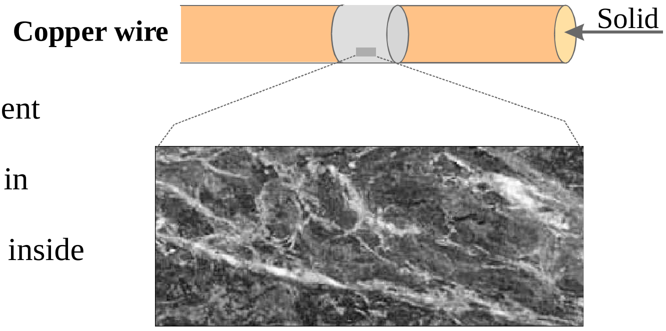
Let's look at the illustration above and see what effect the charge flow has on each end of the cylinder. If positive charges move towards left, what does that do to the right side? It becomes more negative and the left side becomes more positive. Since electrons are flowing to the right, it makes the left side even more positive and the right side more negative. Do you see the point? It does not matter whether the negative charges or positive charges or both are responsible for the charge flow. The net effect is the same: right side acquires more negative and left side more positive charge. This means that we can choose just one direction. Let's say that the right direction is towards a higher potential and left side is towards a lower or zero potential, then we can choose the direction to either from a high potential to a lower potential or visa versa. Or can we?

Since the moving charges in metallic conductors consist of only electrons, it would make sense that we choose the electric current direction in the same direction as the flow of electrons. Unfortunately, that is not possible. During the time of discovery of electricity, it was wrongly assumed that positive charges were responsible for the charge flow in conductors, and the direction of electric current was chosen to be in the direction of positive charges.
As stated earlier, it does not matter which direction is chosen as long as everyone is using the same convention for the direction.
So, today as a convention, electric current direction in conductors is from high potential to lower potential.



4.2 Electron Sea

The flow of electrons is often described as *electron gas* or *electron sea.*
Imagine if you could take a picture of the turbulent flow of electrons in a conductor.
This "sea" would probably look like white caps in a stormy ocean.
Silvery or whitish streams are electrons flowing inside a conductor.

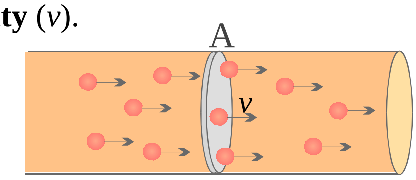


Note: **This is NOT an actual photograph of an electron flow in a conductor but rather a good "guesstimate" how it probably looks like.**

Question: Why is it impossible that the image on the right is an actual photo of an electron flow?

4.3 Current Density

We have discussed that in the presence of electric field, electrons move or drift against the direction of the field at certain average velocity. This is called the **drift velocity** (v).
We have already established that current is a rate at which charges flow across an area per unit time.
However, there is another way we can express current (I).



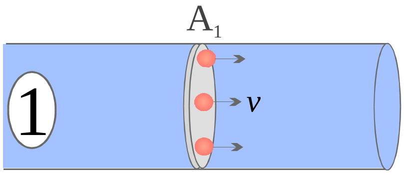
The magnitude of current depends on the density of free electrons (n), often expressed in *electrons per cubic meter*, on the charge of an electron (q), on the drift velocity (v) of electrons, and on the cross-sectional area (A).

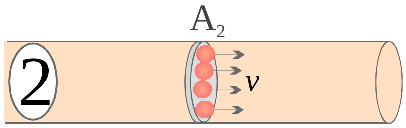
$$\boxed{I = \frac{Q}{t} = nqvA}$$

Current (I) divided by the cross-section area (A) is called the **current density** (J)

$$\boxed{J = \frac{I}{A}}$$

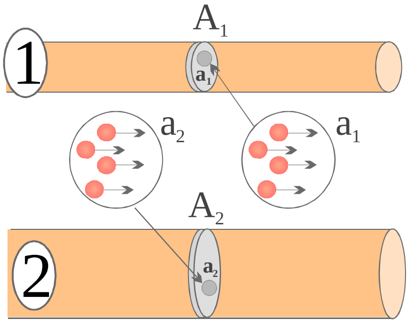
Current density (J) can also be written as $\boxed{J = nqv}$. The unit of J is *amperes per square meter* (Am^{-2})





Example 1.
A cylinder 1 has a cross sectional area of A_1 and a cylinder 2 has a cross sectional area of A_2. Three charges cross an area A_1 per second and four charges cross an area A_2 per second.
If the drift velocities are the same in both wires, which cylinder has higher current density? (area $A_1 >$ area A_2)

You don't need to do any calculations to conclude that the cylinder 2 has higher current density. Area A_2 has a higher concentration of charges per area (higher density). Remember, current density depends on the density of free electrons (n), on the charge (q), and on the drift velocity of charges (v) [$J = nqv$] .



Example 2.
There are two copper wires with cross sectional areas of A_1 and A_2. The area A_2 equals twice the area A_1.
The drift velocities and the density of free electrons (n) are the same for both wires.

If the field (voltage) was the same for each wire, how much electric current would flow in one wire relative to the other? Although the current densities are the same, a wire 2 is twice as big and thus contains twice as many free electrons.
We can conclude that the charge flow is also twice as large in a wire 2 than in a wire 1.

If the electric field strength (voltage) in a wire1 is doubled, the drift velocity of free electrons is also doubled. Electrons would move (drift) twice of their original velocity and twice as much electrons would flow across the area A_1 per unit time than before making the electric current in the wire 1 equal to the current in the wire 2.

By doubling the voltage in the wire 1, how does that effect the magnitude of the current density (J)?

The electric current is doubled, and since $J = \frac{I}{A}$, the current density is also doubled.

5

RESISTANCE

5.1 Resistivity

We have discussed of the relationship between the electric field and the current density.
By increasing the field strength (voltage), we can increase the current density (J).
In a perfect conductor there would not be any *resistance* for the charges to flow.
However, even very good conductor substances such as silver, copper, and gold will resist the charge flow. This is called in a substance a **resistivity** (ρ).
If the resistivity is increased, the greater the electric field (E) is needed to maintain the current density (J).
The proportionality between E and J can be expressed as $\rho = \frac{E}{J}$, where ρ is resistivity.

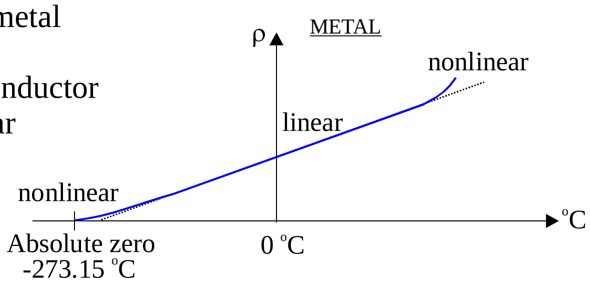
Resistivity is the *electric field per unit current density*. The unit is Ω m (*ohm meter*)
As you might expect, the resistivity is the smallest among metals and the largest among insulators.

The ρ value for semiconductors such as carbon and silicon can vary from 3.5×10^{-5} Ω m for carbon to about 1000 Ω m for silicon.

SUBSTANCE	ρ_0 , Ω m	α , $^0C^{-1}$
Silver Copper	1.64×10^{-8} 1.72×10^{-8}	0.0038 0.00393
Carbon	3.50×10^{-5}	-0.0005
Glass	$10^{10} - 10^{14}$	-

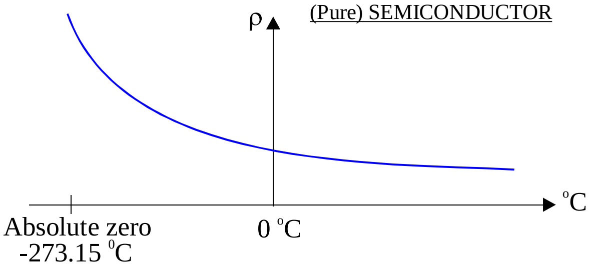
Resistivity values are usually given at room temperature.
Resistivity varies with temperature. If we need to know ρ value for other than at room temperature, this can be accomplish by using the equation $\rho_T = \rho_0[\,1 + \alpha\,(\,t - t_0\,)\,]$ where ρ_0 is resistivity at 20 °C (room temperature) and α is called the *temperature coefficient of resistivity* at reference temperature t_0 at 20 °C.

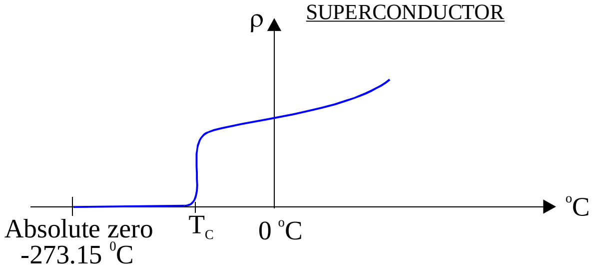
If you look at the right column for α values, you will notice that for semiconductor carbon, the α is negative whereas metals, such as silver and copper, the temperature coefficient of resistivity are both positive.
What this means is that **the resistivity in metals increases with the increase in temperature.**
The straight line portion on the graph indicates that a metal within that temperature range is a *linear conductor*.
In the curved (not straight) portions of the graph, the conductor is said to be *nonlinear*. In this illustration, the nonlinear regions are located at each end of the graph.



Semiconductors (Chapter 25) have negative temperature coefficients.
This means that **the resistivity in semiconductors decreases with the increase in temperature.**
One application is a semiconductor called *thermistor* which can be used as a temperature sensor.

Superconductors at higher temperatures behave like conductors. At temperatures below -100 °C (called the critical temperature T_C) the resistivity suddenly drops to zero.

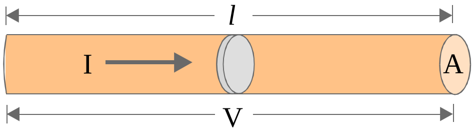




5.2 Resistance and Ohm’s Law

Resistivity (ρ) depends on the substance (material) and on the temperature.
Is resistance same as resistivity? Not exactly but they are related.

Let's say that we have a conductor with length *l* and a cross-section area A. The current density (J) is constant and the potential difference between the ends of the conductor is V. The electric field is uniform along the length of the conductor.



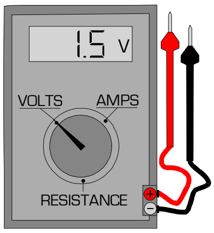
Review: If the resistivity is increased, for instance, by increasing the temperature, the electric field (E) has to be increased in order to maintain the same current density (J). $\longrightarrow E = \rho J$

Electric current (I) depends on current density (J) and cross-section area (A). $\longrightarrow I = J A$

If the length (*l*) is constant, then electric field (E) varies with voltage (V). $\longrightarrow V = E l$

Measuring current densities and electric fields can be quite difficult.
It will be much easier to define resistance in terms of voltage and electric current.
Most of the people have a multimeter at home that allows measuring at least volts, electric currents, and resistance.

Multimeter



We can re-arrange the above equations so that $\rho = \dfrac{E}{J}$

$$E = \frac{V}{l} \qquad J = \frac{I}{A}$$

Substituting the equations, we obtain the following relationships: $\dfrac{\rho l}{A} = \dfrac{V}{I}$

The left side of the equation $\dfrac{\rho l}{A}$ is called the **resistance** (R). $\boxed{R = \dfrac{\rho l}{A}}$ or $R = \dfrac{V}{I}$

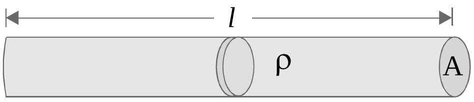
The equation is often written as $\boxed{V = R I}$ This equation is known as the **Ohm’s law**.

Instead of memorizing the Ohm’s law, it is better to understand the relationships in the equation.

What is it we are trying to establish? Flow of charges (electric current).
How do we do that? By applying voltage. We already know that current is directly proportional to the voltage. What factor is trying to prevent the flow of charges? Resistance.
We can then write a relationships between electric current, voltage, and resistance.

$$\textbf{Trying to establish}\quad I = \frac{V \quad \textbf{Causing the electric current}}{R \quad \textbf{Opposing the electric current}}$$

From the equation $R = \dfrac{\rho l}{A}$ we can determine four factors that effect resistance.



1) Material > ρ
2) Temperature
3) Cross-sectional area (A)
4) Length (*l*)

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