Unit 7 Ionic and metallic bonds

Conductors, electrolytes and non-conductors

We can classify substances into three groups according to their behaviours on passing electricity through them.

1. **Conductors**

   These are substances which conduct electricity but are chemically unchanged during the conduction. Metals and graphite are conductors.

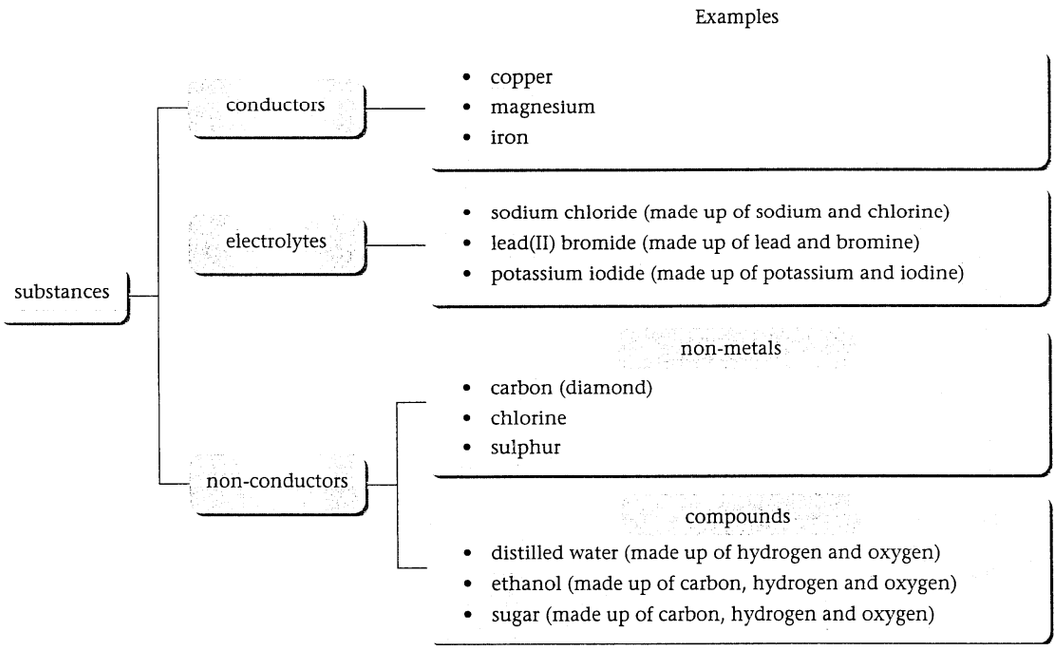
2. **Electrolytes**

   These are compounds which conduct electricity in molten states or in aqueous solutions. They are decomposed by electricity during conduction. Compounds made up of metals and non-metals are electrolytes.

   [A few compounds made of non-metals are electrolytes when conducting electricity in aqueous solutions. They will be discussed in the later units.]

3. **Non-conductors**

   These are substances which do not conduct electricity in solid states, molten states or in solutions. All non-metals (except graphite) are non-conductors. Nearly all compounds made of non-metals are non-conductors.



Chemical bonds

The differences in the behaviours towards conduction of electricity are due to the different ways that the atoms combined together in the respective substances. The ways of joining the atoms together are called chemical bonds.

Basically, there are three types of chemical bonds. They are:

1. **Ionic bonds**

   Ionic bonds are the chemical bonds between **metals and non-metals** in compounds called ionic compounds.

2. **Covalent bonds**

   Covalent bonds are the chemical bonds between **non-metal** atoms in the non-metallic elements or covalent compounds formed by different non-metals.

3. **Metallic bonds**

   Metallic bonds are the chemical bonds between **metal** atoms in metallic elements.

[There is a kind of elements called metalloids. However, metalloids have exactly the same behaviours as non-metals in chemical bonds formation.]

Formation of ionic bonds

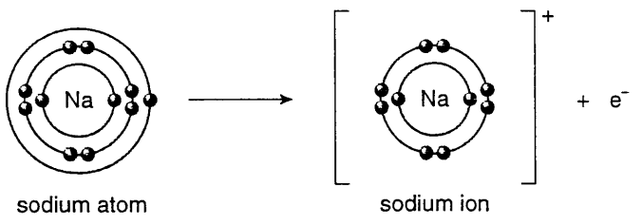
From atoms to ions

Atoms can **obtain the stable electronic arrangements of atoms of noble gases** by gaining or losing electrons. A **simple ion** forms when an atom either **loses or gains one or more electrons**. It is either **positively or negatively charged**.

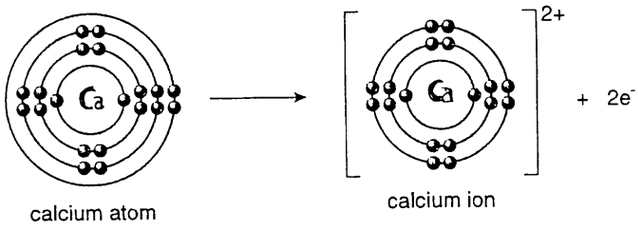
[An ion can also be formed by two or more atoms joined together by covalent bonds first. This particle then loses or gains one or more electrons to make it stable. This kind of ions is called a polyatomic ion. Polyatomic ions will be discussed later.]

Positive ions – cations

Consider a sodium atom (with electronic arrangement: 2,8,1). It is unstable as it has one electron in its outermost shell. It can obtain the electronic arrangement of the nearest noble gas neon by losing one electron. In so doing, a sodium ion is formed. The sodium ion (Na^+) has one positive charge as it has altogether 11 protons but only 10 electrons.



Similarly, a calcium atom (with electronic arrangement: 2,8,8,2) can become stable by losing its two outermost shell electrons. A calcium ion (Ca^{2+}) with two positive charges is formed since it has 20 protons but only 18 electrons.

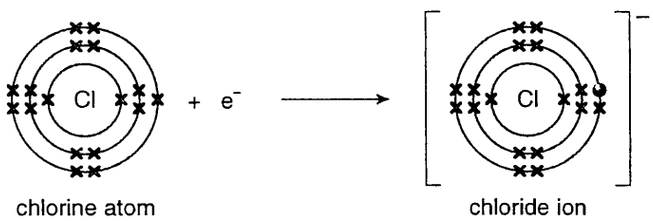


When an atom of an element loses one or more electrons, it forms a positive ion. A **positive ion** is called a **cation**.

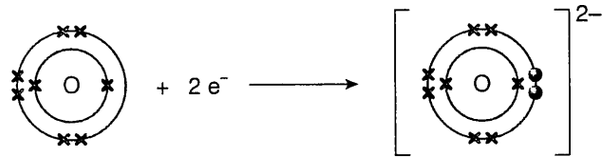
An atom of a **metal** can obtain the stable electronic arrangement of an atom of a noble gas by **losing** one or more **electrons**.

Negative ions – anions

Consider a chlorine atom (with electronic arrangement: 2,8,7). It is unstable as it has seven electrons in its outermost shell. It can obtain the electronic arrangement of the nearest noble gas argon by gaining one electron. In so doing, a chloride ion (Cl^-) is formed. The chloride ion has one negative charge as it has altogether 17 protons but 18 electrons.



Similarly, an oxygen atom (with electronic arrangement: 2,6) can become stable by gaining two electrons in its outermost shell. An oxide ion (O^{2-}) with two negative charges is formed since it has 8 protons but 10 electrons.



When an atom of an element gains one or more electrons, it forms a negative ion. A **negative ion** is called an **anion**.

An atom of a **non-metal** can obtain the stable electronic arrangement of an atom of a noble gas by **gaining** one or more **electrons**.

Predicting the charge of a simple ion

The following table shows the electronic arrangements of the atoms of and the ions formed by period 3 elements.

Element	Na	Mg	Al	Si	P	S	Cl	Ar
Electronic arrangement of the atom	2,8,1	2,8,2	2,8,3	2,8,4	2,8,5	2,8,6	2,8,7	2,8,8
Common ion formed	Na^+	Mg^{2+}	Al^{3+}	—	—	S^{2-}	Cl^-	—
Electronic arrangement of the ion	2,8	2,8	2,8	—	—	2,8,8	2,8,8	—

The following rules can be generalized.

Positive charge(s) on an ion formed from the atom of a metal
= group number of the metal
Negative charge(s) on an ion formed from the atom of a non-metal
= 8 – group number of the non-metal

The following table shows the charges of some common ions in the periodic table.

	Group I	Group II	Group III	Group IV	Group V	Group VI	Group VII	Group 0
Period 2	Li^+* lithium ion	Be^{2+}* beryllium ion			N^{3-} nitride ion	O^{2-} oxide ion	F^- fluoride ion	
Period 3	Na^+ sodium ion	Mg^{2+} magnesium ion	Al^{3+} aluminium ion			S^{2-} sulphide ion	Cl^- chloride ion	
Period 4	K^+ potassium ion	Ca^{2+} calcium ion					Br^- bromide ion	

Notice, the elements in Group 0 and Group IV do not form simple ions. Why?

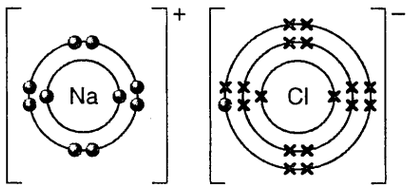
Exercises

1. Consider the element magnesium.
   (a) Draw the electron diagram of magnesium atom and magnesium ion.
   (b) Suggest the charge on a magnesium ion.
2. X is an element. It can form a cation X^+ with an electronic arrangement of 2,8,8. To which period of the periodic table does X belong? Explain your answer.

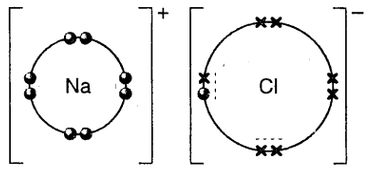
Ionic bond in sodium chloride

When an atom of sodium and an atom of chlorine come together, they can both become stable by transferring an electron form the outermost shell of sodium to the outermost shell of chlorine. A sodium ion and a chloride ion are formed. It would occur when sodium reacts with chlorine. The positively charged sodium ion is attracted to the negatively charged chloride ion by **electrostatic forces**. This attraction, which holds ions together, is a chemical bond called **ionic bond**. A compound with such a bond is called an **ionic compound**.

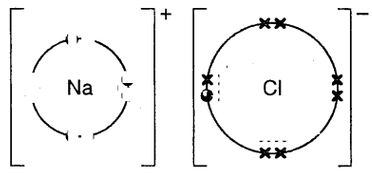
Electron diagram of the ionic compound (sodium chloride) formed by sodium and chlorine



Electron diagram of the ionic compound formed by sodium and chlorine (showing the outermost shell only)



or simply



An ionic bond is the strong electrostatic forces of attraction between oppositely charged ions.

An ionic bond is formed when one or more electrons are transferred from one atom (or group of atoms) to another.

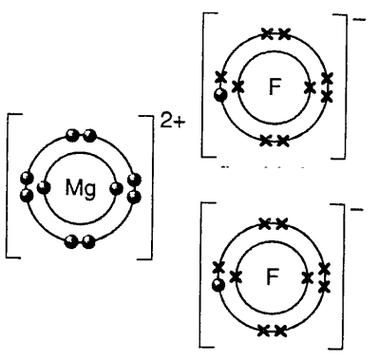
When a metal and a non-metal combine to form an ionic compound, atoms of the metal usually release electrons while atoms of the non-metal usually gain electrons.

Ionic bond in magnesium fluoride

Consider the reaction between the metal magnesium (with electronic arrangement: 2,8,2) and the non-metal fluorine (with electronic arrangement: 2,7). A magnesium atom will become stable by losing two electrons in its outermost shell to form the magnesium ion while a fluorine atom will become stable by gaining an electron in its outermost shell. Magnesium and fluorine will react similarly to that of sodium and chlorine but in a slightly different ratio. One atom of magnesium will react with two atoms of fluorine in order to complete the electron transfer.

Electron diagram of the ionic compound (magnesium fluoride) formed by magnesium and fluorine

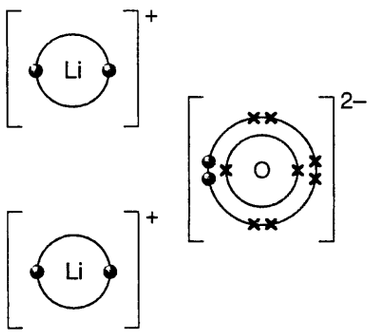
Electron diagram of the ionic compound formed by magnesium and fluorine (showing the outermost shell only)



Ionic bond in lithium oxide

Similarly, the metal lithium (with electronic arrangement: 2,1) and the non-metal oxygen (with electronic arrangement: 2,6) can also react by transferring electrons from lithium atoms to oxygen atoms. The ionic compound lithium oxide will be formed. In this situation, the ratio of lithium to oxygen will be 2 : 1.

Electron diagram of the ionic compound (lithium oxide) formed by lithium and oxygen



Electron diagram of the ionic compound formed by lithium and oxygen (showing the outermost shell only)

Exercises

1. Draw the electron diagrams, showing the outermost shell only, of the compounds formed between

   (a) sodium and sulphur

   (b) calcium and oxygen

2. The following table shows the atomic numbers of four elements.

Element	A	B	C	D
Atomic number	2	14	17	19

   (a) Which TWO elements would form an ionic compound?

   (b) Draw an electron diagram, showing the outermost shell only, of the compound formed.

Compounds containing polyatomic ions

A **polyatomic ion** is an ion formed **by a group of atoms**. For example, carbonate ion (CO_3^{2-}) is a polyatomic ion. It is formed from one carbon atom and three oxygen atoms. The whole group of four atoms carries 2 negative charges. The chemical bonds inside a polyatomic ion will be discussed in unit 8.

Polyatomic ions are usually anions but some of them can be cations. Ionic compounds are formed by a combination of cations and anions. These ions can be simple ions or polyatomic ions.

Names and formulae of ions

Names and formulae of cations

The table below shows the names and formulae of some common cations.

With 1 positive charge		With 2 positive charges		With 3 positive charges	
Chemical formula	Name	Chemical formula	Name	Chemical formula	Name
Li^+	lithium ion	Mg^{2+}	magnesium ion	Al^{3+}	aluminium ion
Na^+	sodium ion	Ca^{2+}	calcium ion	Fe^{3+}	iron(III) ion
K^+	potassium ion	Zn^{2+}	zinc ion		
Ag^+	silver ion	Fe^{2+}	iron(II) ion		
H^+*	hydrogen ion	Cu^{2+}	copper(II) ion		
NH_4^+*	ammonium ion	Pb^{2+}	lead(II) ion		

Names of cations are in general the same as the names of the corresponding atoms.

Some metals form more than one kind of ions. E.g. iron forms two different ions with charges +2 and +3, these two ions are called iron(II) ion and iron(III) ion respectively.

* Hydrogen ion can only exist in the aqueous solutions of certain compounds only.

* Ammonium ion is a polyatomic ion. It is a cation, however, it is made of non-metal atoms only.

Names and formulae of anions

The table below shows the names and formulae of some common anions.

With 1 negative charge		With 2 negative charges		With 3 negative charges	
Chemical formula	Name	Chemical formula	Name	Chemical formula	Name
F^-	fluoride ion	O^{2-}	oxide ion	N^{3-}	nitride ion
Cl^-	chloride ion	S^{2-}	sulphide ion	PO_4^{3-}	phosphate ion
Br^-	bromide ion	SO_3^{2-}	sulphite ion		
I^-	iodide ion	SO_4^{2-}	sulphate ion		
NO_2^-	nitrite ion	CO_3^{2-}	carbonate ion		
NO_3^-	nitrate ion	$Cr_2O_7^{2-}$	dichromate ion		
OH^-	hydroxide ion				
HCO_3^-	hydrogencarbonate ion				
HSO_4^-	hydrogensulphate ion				
MnO_4^-	permanganate ion				

The names of anions are more complicated than those of cations. However, the following rules can still be generalized in naming anions:

1. Simple anions are ending with the suffix '-ide'. (Hydroxide ion is an exception, it ends with '-ide' but it is a polyatomic ion.)
2. Polyatomic ions with oxygen atoms would end with either '-ate' or '-ite'. For example,

   NO_2^- nitrite and NO_3^- nitrate

   SO_3^{2-} sulphite and SO_4^{2-} sulphate

   A polyatomic ion formed by an element with more oxygen atoms will end up with '-ate' while the other one in the same class with fewer oxygen atoms will end up with –ite'.
3. The prefix of '-per' or others will be added if there are more than two types of polyatomic ions formed by an element with oxygen atoms.

Naming ionic compounds

When naming an ionic compound, name the positive ion (cation) first followed by the negative ion (anion). For example, a compound consists of sodium ions and chloride ions are called sodium chloride. More examples are listed in the table below.

Positive ion in the compound	Negative ion in the compound	Name of the compound
lithium ion	oxide ion	lithium oxide
magnesium ion	fluoride ion	magnesium fluoride
ammonium ion	chloride ion	ammonium chloride
calcium ion	nitrate ion	calcium nitrate
copper(II) ion	carbonate ion	copper(II) carbonate
iron(III)	hydroxide ion	iron(III) hydroxide
iron(II) ion	sulphate ion	iron(II) sulphate
potassium ion	permanganate ion	potassium permanganate

Chemical formulae of ionic compounds

A chemical formula is a way of representing a chemical substance using symbols and figures. The chemical formula of an ionic compound shows:

1. the types of ions present; and
2. the ratio of one type of ion to the other.

For example, when sodium reacts with chlorine to form sodium chloride, the ratio of the sodium ion to chloride ion in the compound is 1 : 1. The formula of the compound is then formed by putting the formulae of respective ions together, omitting the charges. The formula of sodium chloride is NaCl.

The formula of an ionic compound must be in the correct ratio since the overall compound is neutral and does not have any electrical charges.

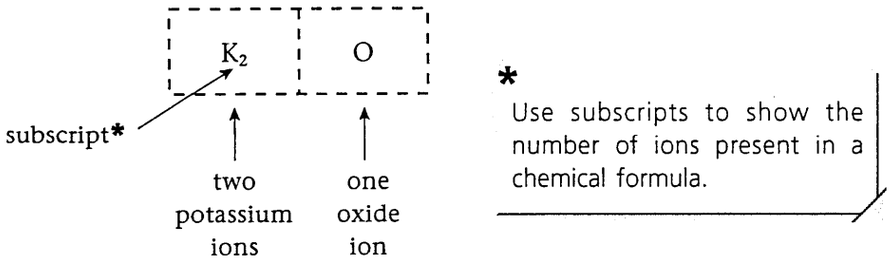
Writing formula of an ionic compound

1. Potassium oxide

   Formula of potassium ion: K^+ Formula of oxide ion: O^{2-}

   Ratio of potassium to oxide should be 2 : 1

   The chemical formula of potassium oxide is K_2O

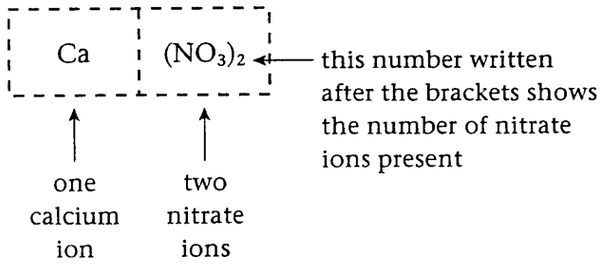


2. Calcium nitrate

   Formula of calcium ion: Ca^{2+} Formula of nitrate ion: NO_3^-

   Ratio of calcium to nitrate should be 1 : 2

   The chemical formula of calcium nitrate is $Ca(NO_3)_2$

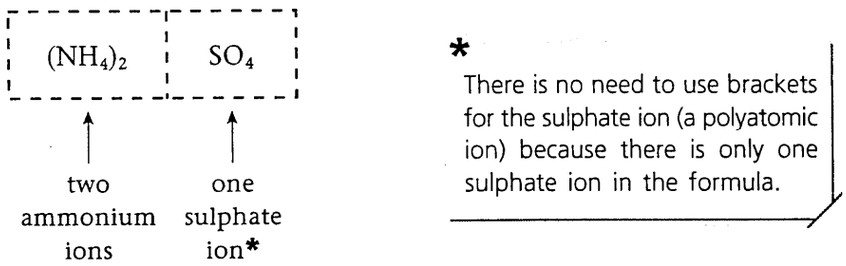


3. Ammonium sulphate

   Formula of ammonium ion: NH_4^+ Formula of sulphate ion: SO_4^{2-}

   Ratio of ammonium to sulphate should be 2 : 1

   The chemical formula of ammonium sulphate is $(NH_4)_2SO_4$



More examples on writing chemical formulae are shown in the table below.

Step	Calcium oxide		Copper(II) hydroxide		Iron(III) carbonate	
1 Write down the symbols of ions in the compound.	Ca	O	Cu	OH	Fe	CO_3
2 Write down the number of charges of each ion on the top of each symbol.	2 Ca	2 O	2 Cu	1 OH	3 Fe	2 CO_3
3 Cross multiply the numbers and the symbols.	2 Ca, 2 O		2 Cu, 1 OH		3 Fe, 2 CO_3	
	$= Ca_2$	$= O_2$	$= Cu_1$	$= (OH)_2$	$= Fe_2$	$= (CO_3)_3$
4 Combine the symbols and simplify the ratio if necessary.	CaO (Simplify the ratio of 2 : 2 to 1 : 1.)		$Cu(OH)_2$ (Omit the number of 1 for Cu.)		$Fe_2(CO_3)_3$	

Exercises

1 Write down the names of the following compounds:

a) $MgCl_2$ b) Fe_2O_3 c) $Ca(OH)_2$

2 Work out the chemical formulae of the following compounds:

a) sodium sulphate b) copper(II) chloride c) ammonium carbonate

d) lead(II) hydroxide e) potassium nitrate f) potassium dichromate

3 M is an element in the third period of the periodic table. It forms a hydroxide which has the chemical formula $M(OH)_3$. What is the chemical formula for the sulphate of M?

Colours of ionic compounds

Potassium dichromate solution is an orange solution. However, potassium chloride solution is colourless. It clearly shows that dichromate ion is the one with the orange colour in the potassium dichromate solution.

The table below shows the colours of some ions.

Ion	Chemical formula	Colour
Iron(II)	Fe^{2+}	pale green
Iron(III)	Fe^{3+}	yellow
Copper(II)	Cu^{2+}	blue or green
Permanganate	MnO_4^-	purple
Dichromate	$Cr_2O_7^{2-}$	orange
Chromium(III)	Cr^{3+}	green
Nickel(II)	Ni^{2+}	green
Manganese(II)	Mn^{2+}	very pale pink (or colourless)

From the table, it can be suggested that all coloured ions are formed by the so called transition elements. Actually, ions formed from main group elements (Group I to Group VII) are colourless.

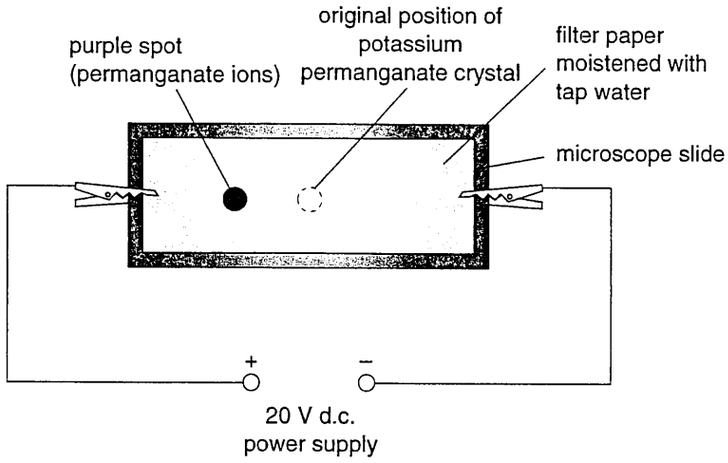
Colours of gemstones

The colours of gemstones are due to the presence of traces of coloured ions. Some examples are listed below.

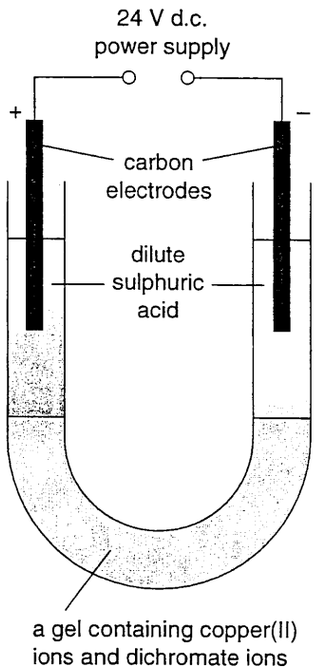
Gemstone	Colour	Ion present	Chemical formula of the ion
Jade	Green	Chromium(III)	Cr^{3+}
Emerald	Green	Chromium(III)	Cr^{3+}
Amethyst	Purple	Manganese(III)	Mn^{3+}
Peridot	Light green	Iron(II)	Fe^{2+}
Topaz	Yellow	Iron(III)	Fe^{3+}
Turquoise	Greenish blue	Copper(II)	Cu^{2+}

Movement of coloured ions

We can observe the movement of ions using the set-up as shown in the diagram followed. When a small crystal of potassium permanganate is placed at the center of a strip of filter paper moistened with tap water, the purple dot will move slowly to the positive electrode showing that there is a negatively charged particle (the permanganate ion) which is purple in potassium permanganate. No colour movement can be seen towards the negative electrode shows that the cation is colourless.

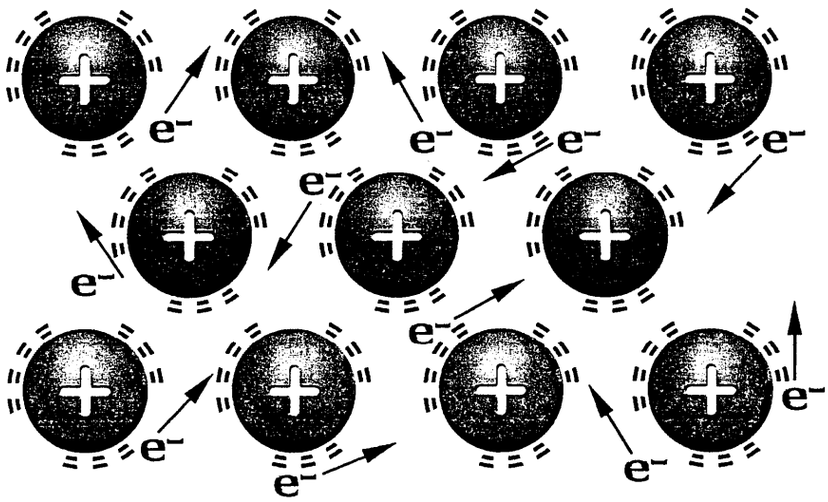


The movement of coloured ions in copper(II) dichromate can also be observed in another set up shown below. The limb towards the positive electrode will gradually turn orange while the limb towards the negative electrode will gradually turns blue.



Metallic bonds in metals

In a piece of metal, the outermost shell electrons of each atom are not held tightly to the nucleus. Instead, they are **free to move randomly** in the piece of metal. We can regard the **mobile electrons** as a **'sea' of electrons**. Thus, a piece of metal consists of positively charged ions surrounded by a 'sea' of electrons. The outermost shell electrons are said to be **delocalized** as they are not associated with a particular ion and can move around.



The attractive forces between the negatively charged electrons and the positively charged ions hold the particles of a metal together. This type of bonding is found only in metals and is called a metallic bond.

A metallic bond is a type of bond in which positive metal ions are held together by a 'sea' of mobile electrons.