4 Chemical patterns

To understand the way that chemicals react with each other, you need to take a look inside the atoms of chemical elements. When you do, there are patterns to be found that help explain the properties of the elements and the way in which elements and compounds behave when they react with each other. One of the properties of elements is their physical state. The mercury shown below is a metal, but it has such a low melting temperature that it is a liquid at room temperature.

OVERARCHING IDEAS

- Patterns, order and organisation
- Form and function
- Stability and change
- Scale and measurement
- Matter and energy

SCIENCE UNDERSTANDING

The atomic structure and properties of elements are used to organise them in the periodic table.

Elaborations

Recognising that elements in the same group of the periodic table have similar properties

Describing the structure of atoms in terms of electron shells

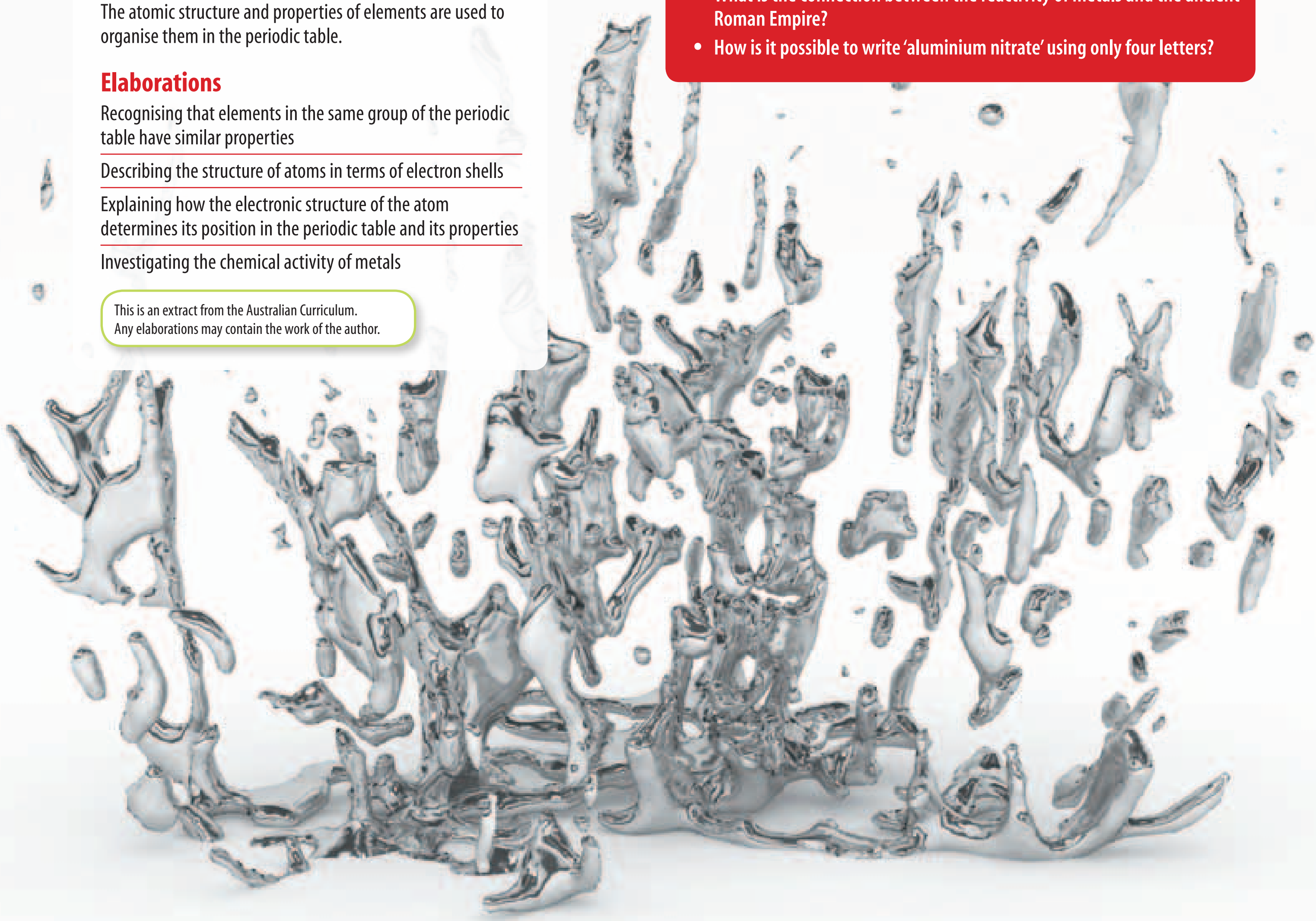
Explaining how the electronic structure of the atom determines its position in the periodic table and its properties

Investigating the chemical activity of metals

This is an extract from the Australian Curriculum.
Any elaborations may contain the work of the author.

THINK ABOUT CHEMICAL PATTERNS

- Who was Dmitri Mendeleev and how was he able to predict the future?
- What are metalloids?
- Why is the petrol used for most motor vehicles unleaded?
- Why do we talk about shells when describing electrons?
- Why are you more likely to find pure gold on or near the Earth's surface than pure copper or iron?
- What is the connection between the reactivity of metals and the ancient Roman Empire?
- How is it possible to write 'aluminium nitrate' using only four letters?



YOUR QUEST

Inside the elements

Atoms are the building blocks of the chemical elements. They are, therefore, the building blocks of compounds and mixtures. For thousands of years, **alchemists** and scientists have been searching for patterns in the substances that make up the universe. Many of them succeeded to some extent. But the discovery by Lord Rutherford in 1911 that most of the atom was empty space, and subsequent discoveries about the particles inside that atom by Niels Bohr and other scientists, provided the missing links in the patterns. Answer the questions at right to find out what you already know about the atom and the chemical elements.

THINK AND REMEMBER

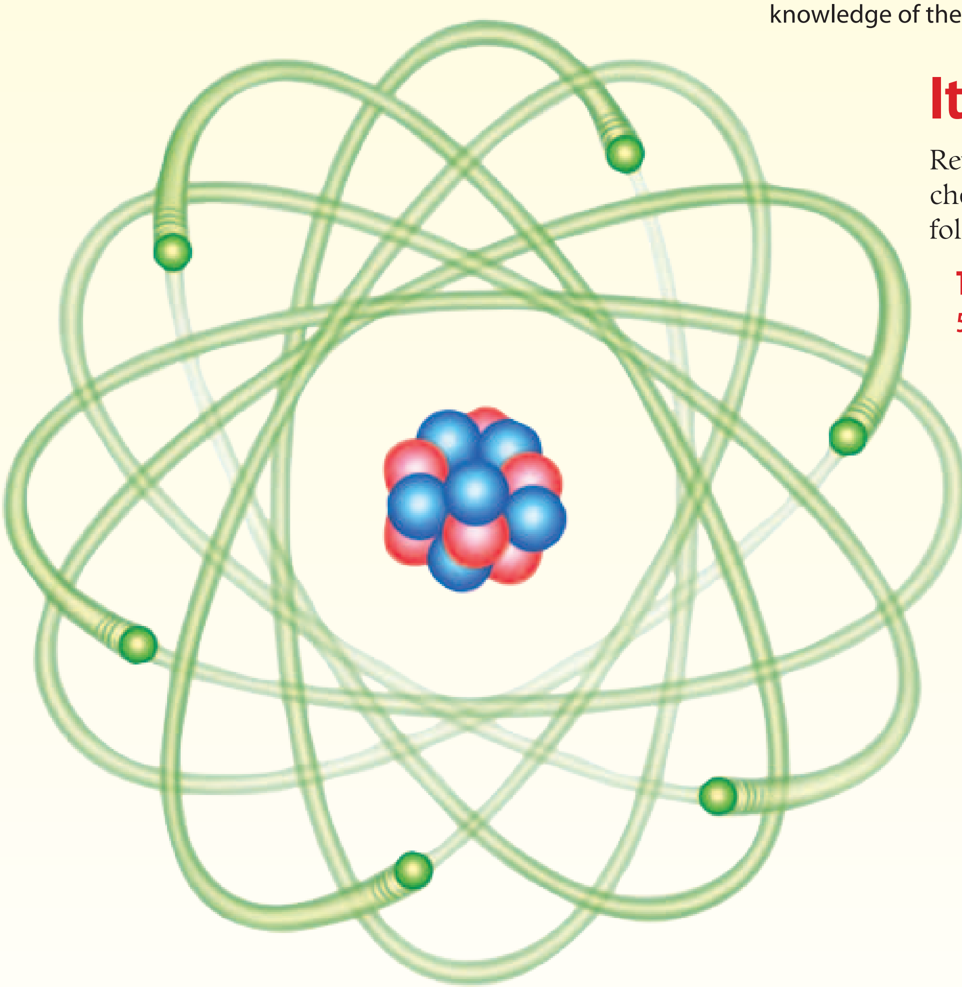
1 Identify the subatomic particle or particles that:
   (a) orbit the nucleus
   (b) can be found inside the nucleus
   (c) has/have no electric charge
   (d) has/have a positive electric charge
   (e) has/have a negative electric charge
   (f) is/are lightest.

2 The atom shown in the diagram below left belongs to a single chemical element.
   (a) What is the atomic number of the element?
   (b) Which particles are counted to determine the atomic number of the element?
   (c) Identify the element in the diagram.

3 What is the electric charge of the nucleus of every atom?

INVESTIGATE

4 Research and report on the contributions of Lord Rutherford, Niels Bohr and Sir James Chadwick to our knowledge of the atom.



A simplified model of an atom

It's elementary

Review your knowledge of the chemical elements by answering the following questions.

THINK AND REMEMBER

5 Identify the chemical element or elements that match each of the following descriptions.
   (a) They combine chemically to produce water.
   (b) It is neither a metal nor a non-metal and is used in electric circuits inside electronic devices such as computers and mobile phones.
   (c) It has the symbol Na.
   (d) They combine chemically to produce the compound that we know as pure salt.
   (e) It is the only metal that exists as a liquid at normal room temperatures.

4.1 OVERARCHING IDEAS

Patterns, order and organisation: The periodic table

Key

	1 Hydrogen **H** **1.008**	2 Helium **He** **4.003**	
Period 1			Atomic number Name Symbol Relative atomic mass

Transition metals

	Group 1 Alkali metals	Group 2 Alkaline earth metals	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8	Group 9
Period 2	3 Lithium **Li** **6.94**	4 Beryllium **Be** **9.02**							
Period 3	11 Sodium **Na** **22.99**	12 Magnesium **Mg** **24.31**							
Period 4	19 Potassium **K** **39.10**	20 Calcium **Ca** **40.08**	21 Scandium **Sc** **44.96**	22 Titanium **Ti** **47.87**	23 Vanadium **V** **50.94**	24 Chromium **Cr** **52.00**	25 Manganese **Mn** **54.94**	26 Iron **Fe** **55.85**	27 Cobalt **Co** **58.93**
Period 5	37 Rubidium **Rb** **85.47**	38 Strontium **Sr** **87.62**	39 Yttrium **Y** **88.91**	40 Zirconium **Zr** **91.22**	41 Niobium **Nb** **92.91**	42 Molybdenum **Mo** **95.96**	43 Technetium **Tc** **98.91**	44 Ruthenium **Ru** **101.1**	45 Rhodium **Rh** **102.91**
Period 6	55 Caesium **Cs** **132.9**	56 Barium **Ba** **137.3**	57–71 Lanthanoids	72 Hafnium **Hf** **178.5**	73 Tantalum **Ta** **180.9**	74 Tungsten **W** **183.8**	75 Rhenium **Re** **186.2**	76 Osmium **Os** **190.2**	77 Iridium **Ir** **192.22**
Period 7	87 Francium **Fr**	88 Radium **Ra**	89–103 Actinoids	104 Rutherfordium **Rf**	105 Dubnium **Db**	106 Seaborgium **Sg**	107 Bohrium **Bh**	108 Hassium **Hs**	109 Meitnerium **Mt**

The period number refers to the number of the outermost shell containing electrons.

Lanthanoids

57 Lanthanum **La** **138.91** 2,8,18,18,9,2	58 Cerium **Ce** **140.122** 2,8,18,20,8,2	59 Praseo-dymium **Pr** **140.91** 2,8,18,21,8,2	60 Neodymium **Nd** **144.24** 2,8,18,22,8,2	61 Promethium **Pm** **(145)** 2,8,18,23,8,2	62 Samarium **Sm** **150.4** 2,8,18,24,8,2	63 Europium **Eu** **151.96** 2,8,18,25,8,2

Actinoids

89 Actinium **Ac** **(227)**	90 Thorium **Th** **232.04**	91 Protactinium **Pa** **231.04**	92 Uranium **U** **238.03**	93 Neptunium **Np** **237.05**	94 Plutonium **Pu** **(244)**	95 Americium **Am** **(243)**

Russian chemist Dmitri Mendeleev confidently predicted the properties of the chemical element germanium 15 years before it was discovered. He was able to do this because all known elements had been arranged into a set of rows and columns called the **periodic table**.

The periodic table below shows 112 elements. At the time of publication, scientists have reported the discovery of elements with atomic numbers up to 118. However, some of the discoveries have not been confirmed by the International Union of Pure and Applied Chemistry (IUPAC). Until they are, their existence is 'unofficial'. Those yet to be confirmed are elements 113, 115, 117 and 118. The discoveries of elements 114 and 116 were confirmed in June 2011. The properties of new elements are predicted before their discovery, just as they were in Mendeleev's time.

Group 10	Group 11	Group 12	Group 13	Group 14	Group 15	Group 16	Halogens Group 17	Noble gases Group 18
			5 Boron **B** **10.81**	6 Carbon **C** **12.01**	7 Nitrogen **N** **14.01**	8 Oxygen **O** **16.00**	9 Fluorine **F** **19.00**	10 Neon **Ne** **20.18**
			13 Aluminium **Al** **26.98**	14 Silicon **Si** **28.09**	15 Phosphorus **P** **30.97**	16 Sulfur **S** **32.06**	17 Chlorine **Cl** **35.45**	18 Argon **Ar** **39.95**
28 Nickel **Ni** **58.69**	29 Copper **Cu** **63.55**	30 Zinc **Zn** **65.38**	31 Gallium **Ga** **69.72**	32 Germanium **Ge** **72.63**	33 Arsenic **As** **74.92**	34 Selenium **Se** **78.96**	35 Bromine **Br** **79.90**	36 Krypton **Kr** **83.80**
46 Palladium **Pd** **106.4**	47 Silver **Ag** **107.9**	48 Cadmium **Cd** **112.4**	49 Indium **In** **114.8**	50 Tin **Sn** **118.7**	51 Antimony **Sb** **121.8**	52 Tellurium **Te** **127.8**	53 Iodine **I** **126.9**	54 Xenon **Xe** **131.3**
78 Platinum **Pt** **195.1**	79 Gold **Au** **197.0**	80 Mercury **Hg** **200.6**	81 Thallium **Tl** **204.4**	82 Lead **Pb** **207.2**	83 Bismuth **Bi** **209.0**	84 Polonium **Po** **(209)**	85 Astatine **At** **(210)**	86 Radon **Rn** **(222)**
110 Darmstadtium **Ds**	111 Roentgenium **Rg**	112 Copernicium **Cn**						

Metals ← → **Non-metals**

64 Gadolinium **Gd** **157.25** 2,8,18,25,9,2	65 Terbium **Tb** **158.93** 2,8,18,27,8,2	66 Dysprosium **Dy** **162.50** 2,8,18,28,8,2	67 Holmium **Ho** **164.93** 2,8,18,29,8,2	68 Erbium **Er** **167.26** 2,8,18,30,8,2	69 Thulium **Tm** **168.93** 2,8,18,31,8,2	70 Ytterbium **Yb** **173.04** 2,8,18,32,8,2	71 Lutetium **Lu** **174.97** 2,8,18,32,9,2

96 Curium **Cm** **(247)**	97 Berkelium **Bk** **(247)**	98 Californium **Cf** **(251)**	99 Einsteinium **Es** **(254)**	100 Fermium **Fm** **(257)**	101 Mendelevium **Md** **(258)**	102 Nobelium **No** **(255)**	103 Lawrencium **Lr** **(256)**

The patterns emerge

Two thousand years ago, only 10 elements had been identified. They were carbon, sulfur, iron, copper, zinc, silver, tin, gold, mercury and lead. By the early nineteenth century, over 50 elements had been identified. Chemists had already begun to search for patterns among the elements in the hope of finding a way to classify them. It was difficult at that time to find patterns because there were still many undiscovered elements.

In 1864, British chemist John Newlands arranged the elements in order of increasing atomic weight and found that every eighth element shared similar properties. In 1869, Mendeleev, building on the work of Newlands and other scientists, discovered a way of organising the elements into rows and columns. This arrangement formed the basis of what we now know as the periodic table. The elements were arranged in rows in order of increasing mass or atomic weight. Mendeleev called the rows of elements **periods** and the columns, which each contained a family of elements, **groups**. It is called the periodic table because elements with similar properties occur at regular intervals or periods. In a strange twist of fate, German chemist Lothar Meyer, who worked independently of Mendeleev, also came up with a similar arrangement of the elements at about the same time.

The observation that the physical and chemical properties of the elements recur at regular intervals when elements are listed in order of atomic weight is known as the **Periodic Law**.

An educated guess

Mendeleev was so confident about the periodic law that he deliberately left gaps in his periodic table. He was able to predict the properties of the unknown elements that would fill the gaps. Mendeleev predicted the existence of germanium, which he called eka-silicon. This element was discovered in 1886, 15 years later. The table below shows the accuracy of Mendeleev's predictions.

Mendeleev's work led many scientists to search for new elements. By 1925, scientists had identified all of the naturally existing elements.

The periodic table shown at the beginning of this section includes the names, **symbols** and **atomic numbers** of the first 112 elements. The symbols are a form of shorthand for writing the names of the elements and are recognised worldwide. Some periodic tables describe the properties of each element, including its physical state at room temperature, melting point, boiling point and **relative atomic mass** (see the table below). Most elements exist as solids under normal conditions and a few exist as gases. Only two elements exist as liquids at normal room temperature — bromine and mercury.

Counting sub-atomic particles

The periodic table is organised on the basis of atomic numbers. The atomic number of an element is the number of protons present in each atom. Atoms with the same atomic number have identical chemical properties. Because atoms are electrically neutral, the number of protons in an atom is the same as the number of electrons. The **mass number** of an atom is the sum of the number of protons and neutrons in the atom. The number of neutrons in an atom can therefore be calculated by subtracting the atomic number from the mass number. This information is usually shown in the following way:

$$^{A}_{Z}\mathrm{E}$$

where A = the mass number (number of protons and neutrons), Z = the atomic number (number of protons) and E = the symbol of the element.

Properties of eka-silicon and germanium

Properties of eka-silicon as predicted by Mendeleev	Properties of germanium, discovered in 1886
A grey metal	A grey-white metal
Melting point of about 800 °C	Melting point of 958 °C
Relative atomic mass of 73.4	Relative atomic mass of 72.6
Density of 5.5 g/cm^3	Density of 5.47 g/cm^3
Reacts with chlorine to form compounds with four chlorine atoms bonded to each eka-silicon atom	Reacts with chlorine and forms compounds in a ratio of four chlorine atoms to every germanium atom

For example, the element iron has a mass number of 56 and an atomic number of 26. It can be represented as follows:

$$^{56}_{26}\mathrm{Fe}$$

Once you know the atomic number and the mass number of an element, you can work out how many electrons and neutrons are in that element.

The atomic number of iron is 26 because all iron atoms have 26 protons. Iron's mass number of 56 indicates that most iron atoms have a total of 56 protons and neutrons.

To calculate the number of neutrons, the atomic number is subtracted from the mass number to give 30 neutrons. Since atoms are electrically neutral and protons have a positive charge, each iron atom has 26 electrons.

How heavy are atoms?

Measuring and comparing the masses of atoms is difficult because of their extremely small size. Chemists solve this problem by comparing equal numbers of atoms, rather than trying to measure the mass of a single atom.

A further problem arises because not all atoms of an element are identical. Although all atoms of a particular element have the same atomic number, they can have different numbers of neutrons. Hence, some elements contain atoms with slightly different masses.

These different masses are used to calculate an average or **weighted mean**, which is based on the relative amounts of each type of atom. This number is referred to as the relative atomic mass and is usually not a whole number. The mass number (A) of an element can usually be found by rounding off the relative atomic mass.

Families of elements

The periodic table contains eight groups (or families) of elements, some of which have been given special names. (Remember that these groups form columns in the periodic table.)

- Group 1 elements are known as the **alkali metals**. The alkali metals all react strongly with water to form basic solutions.
- Group 2 elements are referred to as the **alkaline earth metals**.
- Group 17 elements are known as the **halogens**. The halogens are brightly coloured elements.

Illuminated signs use tubes filled with the noble gas neon.

Chlorine is green, bromine is red-brown and iodine is silvery-purple.
- Group 18 elements are known as the **noble gases**. The noble gases are inert and do not readily react with other substances.
- The block of elements in the middle of the table is known as the **transition metal block**.

Is it a metal?

The line that zigzags through the periodic table separates the **metals** from the **non-metals**. About three-quarters of all elements are classified as metals. The metals are found on the left-hand side of the table. The non-metals are found on the upper right-hand side of the table. Eight elements that fall along this line have properties belonging to both metals and non-metals. They are called **metalloids**.

METALS

The metals have several features in common.
- They are solid at room temperature, except for mercury which is a liquid.
- They can be polished to produce a high shine or **lustre**.
- They are good **conductors** of electricity and heat.
- They can all be beaten or bent into a variety of shapes. We say they are **malleable**.
- They can be made into a wire. We say they are **ductile**.
- They usually melt at high temperatures. Mercury, which melts at −40 °C, is one exception.

WHAT DOES IT MEAN?

The word *malleable* comes from the Latin word ***malleus***, meaning 'hammer'.

NON-METALS

Only twenty-two of the elements are non-metals. At room temperature eleven of them are gases, ten are solid and one is liquid. The solid non-metals have most of the following features in common.

- They cannot be polished to give a shine like metals; they are usually dull or glassy.
- They are **brittle**, which means they shatter when they are hit.
- They cannot be bent into shape.
- They are usually poor conductors of electricity and heat.
- They usually melt at low temperatures.
- Many of the non-metals are gases at room temperature.

Common examples of non-metals are sulfur, carbon and oxygen.

INQUIRY: INVESTIGATION 4.1

Chemical properties of metals and non-metals

KEY INQUIRY SKILLS:

- planning and conducting
- processing and analysing data and information

Equipment:

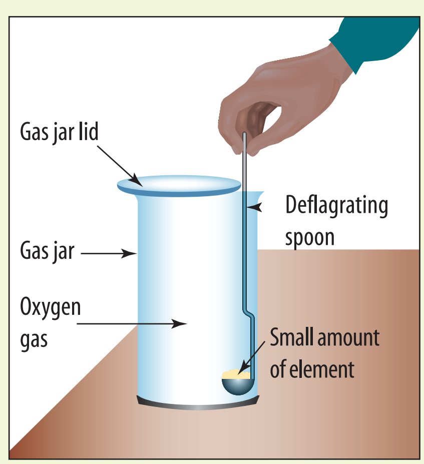
safety glasses, gloves and laboratory coat
1M hydrochloric acid
water
magnesium
iron filings
copper filings
sulfur powder
universal indicator
4 test tubes
4 gas jars filled with oxygen gas
4 deflagrating spoons
dropping pipette
spatula
Bunsen burner, heatproof mat and matches

CAUTION: The heating part of this experiment should be done in a fume cupboard. Safety glasses, gloves and laboratory coats must be worn at all times.

- Place a small quantity of magnesium in a test tube. Add about 2 mL of hydrochloric acid. Record any observations in a suitable table.
- Repeat using the iron filings, copper filings and sulfur powder.
- Place a small amount of magnesium in a deflagrating spoon and heat it. When hot, place it into the gas jar full of oxygen gas. **Do not look directly at the flame**. Record your observations.
- Repeat using the iron and copper filings. Record your observations.
- Repeat using a small amount of sulfur powder. **This part of the experiment must be performed in a fume cupboard**.
- Add about 10 mL of water to each jar and shake. Add 3 drops of universal indicator. Record the colour and determine the pH of the solution.

DISCUSS AND EXPLAIN

1. Use the periodic table to determine which of the elements tested were metals and which were non-metals.
2. Describe any differences between the effect of acids on metals and non-metals.
3. Describe what happened when the metals and non-metals reacted with oxygen.
4. The metal or non-metal oxides formed in the gas jars dissolved in water to form acidic and basic solutions. What type of solution did the metals form? What type of solution did the non-metals form?



Burning sulfur in oxygen in a gas jar

INQUIRY: INVESTIGATION 4.2

Comparing the properties of two metal families

KEY INQUIRY SKILLS:

- planning and conducting
- processing and analysing data and information

Equipment:

small samples of magnesium, iron and copper

'rice grain' equivalent amounts of calcium chloride, magnesium chloride, iron chloride and copper chloride

spatula

5 test tubes and a test-tube rack

electric circuit to measure conductivity (2-volt power supply, 3 connecting leads, 2 alligator clips and a light globe and holder)

2M hydrochloric acid

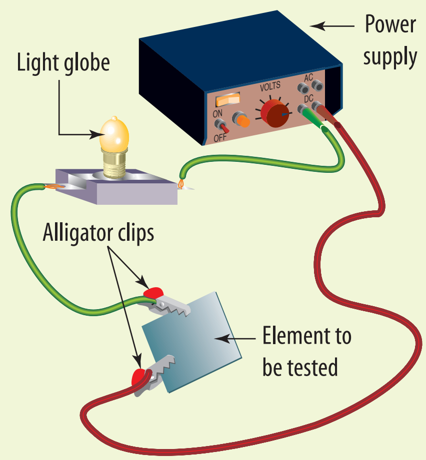
water

matches

stirring rod

safety glasses and laboratory coat

- Record the results of the following experiments in an appropriate table.
- Describe the physical state (solid, liquid or gas) of each of the elements.
- Describe the physical appearance of each of the elements.
- Set up the circuit as shown in the diagram above right and determine whether each of the elements conducts electricity.
- Determine whether any of the elements react with water by placing a small sample in 2 mL of water in a test tube. Record any changes that occur in your table.
- Determine whether the metals react with acid by placing a small sample of each metal in 1 mL of 2M hydrochloric acid in a test tube. If a gas is produced, test it by holding a lit match at the mouth of the test tube. Make sure the test tube is pointed away from you. If hydrogen is present, a 'pop' will be heard.



Circuit used to measure electrical conductivity

If oxygen is present, the match should burn more brightly. If carbon dioxide is present, the match should go out.

Your teacher may show or describe to you how the metal calcium responds to some of the tests described previously.

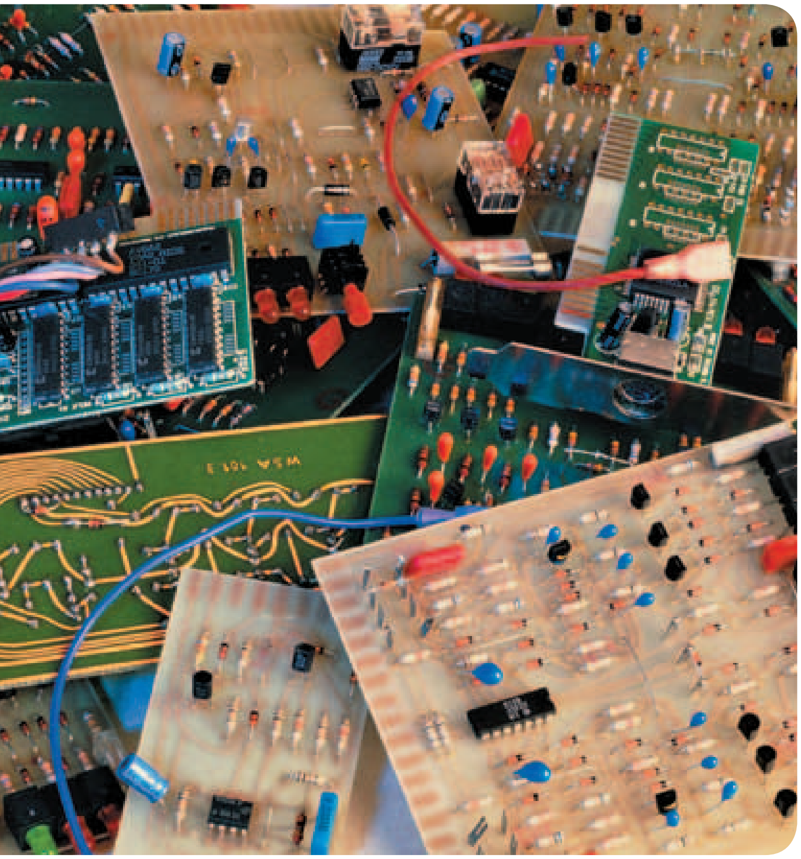
- Add a small amount of each of the metal compounds (magnesium chloride, calcium chloride, iron chloride and copper chloride) to 5 mL of water. Comment on their solubility and the colour of any solution made.

DISCUSS AND EXPLAIN

1. What are the properties of copper and iron? Are there any similarities?
2. What are the properties of calcium and magnesium? Are there any similarities?
3. List the metals in order of reactivity with water and acids. List them in order of most reactive to least reactive.
4. Were there any differences between solubilities of the metal compounds or the colours of the solutions they formed? Describe these differences.
5. Write down the name of the specific group in the periodic table to which each of the elements belong.
6. What could you infer about the properties of elements in the same group? Give reasons for your answer.

METALLOIDS

Some of the elements in the non-metal group look like metals. One example is silicon. While it can be polished like a metal, silicon is a poor conductor of heat and electricity and cannot be bent or made into wire. Those elements that have features of both metals and non-metals are called metalloids. There are eight metalloids altogether: boron, silicon, arsenic, germanium, antimony, polonium, astatine and tellurium.



Metalloids are important materials often used in electronic components of computer circuits.

Following a trend

There are a number of repeating patterns in the periodic table. The most obvious is the change from metals on the left of each period to non-metals on the right. Other patterns exist in the physical and chemical properties of elements in the same group or period. Some of these trends are shown in the table below.

Patterns in the periodic table

Characteristic	Pattern down a group	Pattern across a period
Atomic number and mass number	Increases	Increases
Atomic radius	Increases	Decreases
Melting points	Decreases for groups 1 to 5 and increases for groups 15 to 18	Generally increases then decreases
Reactivity	Metals become more reactive and non-metals become less reactive	Is high, then decreases and then increases. Group 18 elements are inert and do not react.
Metallic character	Increases	Decreases

HOW ABOUT THAT!

Lead poisoning was a common occurrence in ancient Rome because the lead the Romans used to make their water pipes and cooking utensils slowly dissolved into the water. Acute lead poisoning causes mental impairment and personality changes. The effects of lead poisoning are not immediately noticeable. They occur gradually as the amount of lead in the body accumulates over time. Some historians attribute the strange behaviour of several Roman emperors to lead poisoning.

In the Middle Ages, plates, cups and other drinking vessels were often made from pewter, an alloy of lead and tin. The acids in food and drinks caused lead to leach out and cause poisoning.

Until 1986, lead was added to petrol to stop the 'knocking' in car engines. Unleaded fuel was introduced at that time to allow a device called a catalytic converter to prevent pollutants such as nitrous oxides, carbon monoxide and unburnt fuel from being emitted from car exhausts. With lead in the petrol, these devices couldn't work. It was also believed that lead emissions from cars were causing a build-up of lead in the humans in built-up areas.

The word *plumber* is derived from the Latin word *plumbum*, meaning 'lead'. Look up the symbol for lead in the periodic table. Where do you think this symbol came from?

Unleaded petrol was introduced to Australia in 1986 to reduce the amount of pollutants coming out of car exhausts.

UNDERSTANDING AND INQUIRING

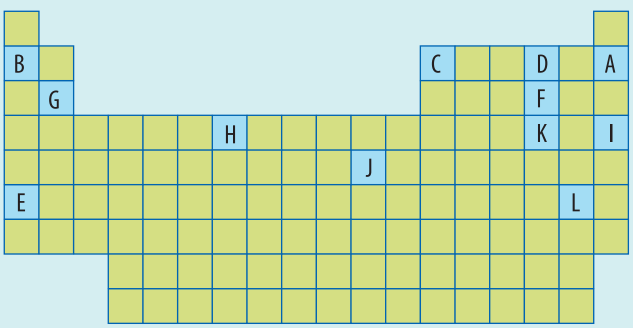
REMEMBER

1 State whether the following statements are true or false.
   (a) The noble gases are found in group 18.
   (b) The non-metals are found in the upper right-hand side of the periodic table.
   (c) There are more metals than non-metals.
   (d) Few elements are found naturally as liquids.

2 What is the name of the element in:
   (a) group 2, period 3
   (b) group 17, period 2
   (c) group 1, period 4
   (d) group 18, period 3?

3 Draw an outline of the periodic table showing where you would find the following elements: the noble gases, the alkali metals, the alkaline earth metals, the halogens and the transition metals.

4 In the outline of the periodic table shown below, some of the elements have been replaced by letters. Using the correct chemical symbols, write down which of these elements fit the following categories.



Use this outline of the periodic table to answer question 4.

   (a) Two elements that are gases at room temperature
   (b) Two elements that are metals
   (c) Two elements that are transition elements
   (d) An element that is a noble gas
   (e) Two elements that are in the same group
   (f) Two elements that are in the same period
   (g) The elements that are alkali metals
   (h) The element that is a halogen

5 What is the difference between the mass number and the relative atomic mass of an element?

6 Describe what happens to the metallic character of the elements as you go across the periodic table.

7 Construct a table showing the name, mass number, atomic number, and number of protons, neutrons and electrons of the following elements.
   (a) $^{12}_{6}C$
   (b) $^{65}_{30}Zn$
   (c) $^{40}_{18}Ar$
   (d) $^{197}_{79}Au$
   (e) $^{238}_{92}U$

THINK

8 Explain how Mendeleev was able to predict the properties of elements even before they were discovered.

9 At room temperature, which group of the periodic table consists exclusively of gases?

10 Compose a rhyme, poem or song that can help you learn the names of the first 20 elements of the periodic table in order.

DESIGN AND CREATE

11 Design and create a poster, multimedia presentation or web page about one of the groups of the periodic table of elements. Include images of each of the elements in the group and a list of the properties that the elements have in common.

INVESTIGATE

12 The elements with atomic numbers greater than 92 have been artificially created in laboratories. Find out how they are made and named, and describe some of their common properties.

13 It is said that the stars are the 'element factories of the universe'; that is, stars make the elements. Do some research and find out how the stars make elements.

14 Find out which single element makes up about three-quarters of the mass of the universe.

15 Choose an element and research the following information about it:
- when it was discovered
- who discovered it
- how it is found in nature
- its properties and uses.

eBook*plus*

16 Test your ability to classify elements by completing the **Time Out: 'Periodic Table'** interactivity. **int-0758**

17 To find out more about the elements of the periodic table and its history use the **Periodic table** weblink in your eBookPLUS.

work sheets
4.1 Periodic table
4.2 Elements and atomic numbers

4.2 SCIENCE UNDERSTANDING

Small but important

When atoms come into contact with one another, they often join together to form **molecules**. Other atoms join together to form giant **crystals** that contain billions of atoms. It is the electrons in each atom that account for the chemical behaviour of all matter, because they form the outermost part of the atom.

Shells of electrons

Drawing an accurate picture of an atom using a diagram is difficult because electrons cannot be observed like most particles. Their exact location within the atom is never known — they tend to behave like a 'cloud' of negative charge. Furthermore, an atom is many times larger than its nucleus so it is not possible to draw a diagram to scale. Nonetheless, diagrams are useful because they help us to understand how atoms combine.

An **electron shell diagram** is a simplified model of an atom. In these diagrams the nucleus of the atom, containing protons and neutrons, is drawn in the middle. Electrons are arranged in a series of energy levels around the nucleus. These energy levels are called **shells** and are drawn as concentric rings around the nucleus. The electrons in the inner shells are more strongly attracted to the nucleus than those in the outer shells.

Each shell contains a limited number of electrons. The first (or K) shell holds a maximum of two electrons. The second (or L) shell holds up to eight electrons. The third (M) shell holds up to 18 electrons. The fourth (N) shell holds up to 32 electrons. The maximum number of electrons in each shell can be calculated using the rule below:

the **nth shell** holds a maximum of **$2n^2$** electrons.

For example, the fourth shell holds a maximum of 2×4^2, which equals 32 electrons.

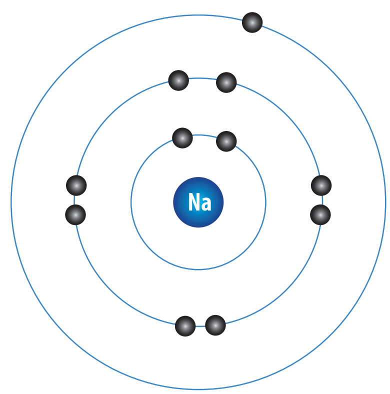
ELECTRONIC CONFIGURATION

The **electronic configuration** of an element is an ordered list of the number of electrons in each shell. The electronic configuration is determined from the atomic number of the element, which is the same as the number of protons in the nucleus of each atom. In a **neutral** atom, the total number of electrons is the same as the number of protons.

To work out the electronic configuration of a particular atom, you need to remember that electrons occupy the innermost shells first. Once the first two shells are filled, the remaining electrons begin to fill the third shell. For example, the element sodium has an atomic number of 11. Each atom has 11 protons and 11 electrons. The electrons will fill the two innermost shells first — two in the first shell and eight in the second shell. That accounts for ten. The remaining electron must be in the third shell because the first two have already been filled.

The electronic configuration of an atom is written by showing the number of electrons in each shell separated by commas. For example:

sodium   2, 8, 1.



An electron shell diagram of a sodium atom

The periodic table explained

When Mendeleev and Meyer grouped elements on the basis of their similar chemical properties, they were not aware of the existence of electrons. We can now explain many of their observations using our understanding of electron shells.

Atoms in the same group of the periodic table have similar properties because they have the same number of electrons in their outer shells. (The outer shell is the last shell to be filled by electrons.) The number of electrons in the outer shell relates to the group number in the periodic table. Hence, all elements in group 1 have one electron in their outer shell and all elements in group 18 (with the exception of helium) have eight electrons in their outer shell.

FILLING UP IN TURN

The largest atoms contain up to seven shells of electrons. Thus, there are seven periods (rows) in the periodic table. (Look at the periodic table in section 4.1 to confirm this.) The period number tells you the number of shells containing electrons. The first shell can hold up to two electrons, so there are two elements in the first period (with hydrogen containing one electron in the first shell and helium containing two electrons in the first shell). The second shell holds up to eight electrons, so there are eight elements in the second period.

Even though the third shell can hold up to 18 electrons, there are only eight elements in the third period. This is because the outer shell of an atom can never hold more than eight electrons as the atom would then become unstable. Therefore, while the third shell is yet to be filled, electrons begin to fill the fourth shell in both potassium and calcium atoms. This stabilises the atoms because the third shell is no longer the outer shell. The filling of the third shell resumes in the block of elements from scandium to zinc (the transition metals). Once the third shell is full, the fourth shell continues to fill from gallium to xenon.

Element	Symbol	Atomic number	Electronic configuration
Oxygen	O	8	2, 6
Fluorine	F	9	2, 7
Neon	Ne	10	2, 8
Sodium	Na	11	2, 8, 1
Magnesium	Mg	12	2, 8, 2
Sulfur	S	16	2, 8, 6
Chlorine	Cl	17	2, 8, 7
Argon	Ar	18	2, 8, 8
Potassium	K	19	2, 8, 8, 1

Note that the fourth shell of the potassium atom begins filling before the third shell is full.

INQUIRY: INVESTIGATION 4.3

Flame tests

KEY INQUIRY SKILLS:

- planning and conducting
- processing and analysing data and information

Equipment:

safety glasses and laboratory coat
2M hydrochloric acid
Bunsen burner, heatproof mat and matches
5 evaporating dishes
barium carbonate
sodium carbonate
copper carbonate
potassium carbonate
strontium carbonate
10 mL measuring cylinder
spatula

CAUTION: Laboratory coats and safety glasses must be worn at all times.

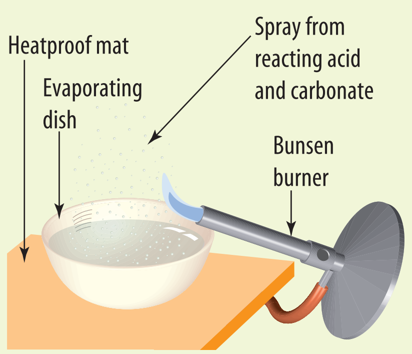
- Place 10 mL of 2M hydrochloric acid in an evaporating dish and place the dish on the heatproof mat.
- Add a spatula full of the barium carbonate to the evaporating dish.
- Carefully hold the lit Bunsen burner at an angle over the spray produced by the reacting acid and carbonate as shown in the diagram below. Observe the change in the colour of the flame.
- Repeat using the other carbonates. Use a different evaporating dish each time.

DISCUSS AND EXPLAIN

1 Record the colours produced by the different carbonates in a suitable table.

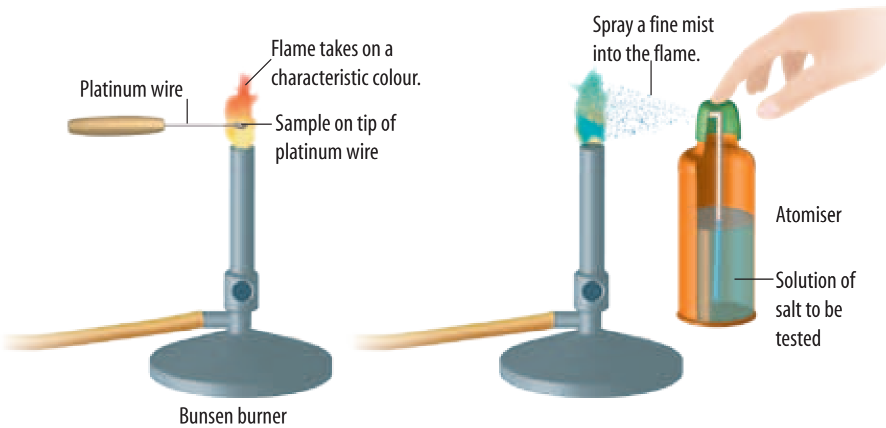
2 Flame tests provide evidence that electrons do actually occupy different energy levels. Why do elements produce different colours?

3 Is it the metal part of the compound or the carbonate part (carbon and oxygen) that produces the colour? How do you know?

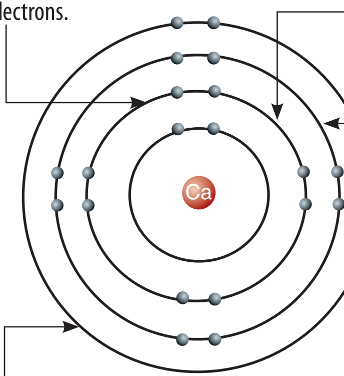


Upwardly mobile electrons

If enough energy is supplied to an atom, electrons can move from one shell (or energy level) to another (higher) energy level. This may occur when atoms are heated by a flame. When electrons move between energy levels, they either absorb or emit an amount of energy related to the difference in energy between the energy levels. Electrons returning to a lower energy level emit this energy in the form of light. The size of the difference in energy levels determines the colour of the light. Thus, flame colours can be used to identify elements.



Various metal ions produce characteristic colours when they are volatilised in a flame.



A calcium atom has 20 electrons.

UNDERSTANDING AND INQUIRING

REMEMBER

1 What is the name given to the different energy levels that electrons can be found in?

2 How many electrons are needed to fill:
(a) the first shell
(b) the second shell
(c) the third shell
(d) the fourth shell?

3 What is meant by the term *outer shell*?

4 What information about the electron arrangement is given by the group number of an element?

5 What information about the electron arrangement is given by the period number of an element?

THINK

6 Name the elements that have an electron arrangement of:
(a) 2, 4
(b) 2, 8, 5
(c) 2
(d) 2, 8, 8, 2.

7 Write the electron arrangement for each of the following elements.
(a) Boron
(b) Neon
(c) Potassium
(d) Fluorine
(e) Silicon

8 (a) If an element has one electron in its outer shell, is it a metal or a non-metal? Explain your answer.
(b) If an element has seven electrons in its outer shell, is it a metal or a non-metal? Explain your answer.
(c) What is special about elements that have eight electrons in their outer shell?

9 What experimental evidence is there to show that electron shells actually exist?

INVESTIGATE

10 The electron arrangement of elements is more complex than the explanation given here. Find out about subshells and orbitals and how they are involved in determining how electrons are arranged in atoms.

11 A lithium atom has three protons, two neutrons and three electrons. Make a 3-dimensional model of this atom.

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12 Use the **Shell-shocked?** interactivity to create a model of the electron shell of an atom and show its energy levels. **int-0676**

work sheets
4.3 Electron shells
4.4 The structure of the atom

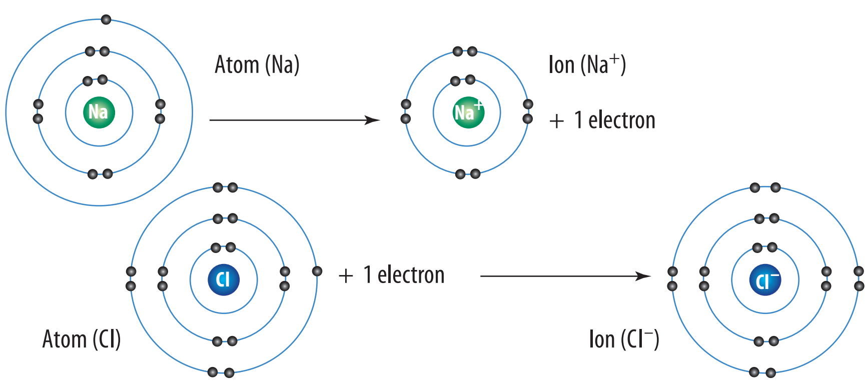
4.3 SCIENCE UNDERSTANDING

When atoms meet

Knowledge of the electron shell structures of atoms helps us to understand how compounds like sodium chloride (table salt) form. When atoms react with each other to form compounds, it is the electrons in the outer shell that are important in determining the type of reaction which occurs.

It's great to be noble

In 1919, Irving Langmuir suggested that the noble gases do not react to form compounds because they have a stable electronic configuration of eight electrons in their outer shell. Most other atoms react because their electron arrangements are less stable than those of the noble gases. The atoms become more stable when they attain an electron arrangement that is the same as that of the noble gases. Chemical reactions can allow atoms to obtain this arrangement. The table in section 4.2 shows that the electron arrangements of the two noble gases neon and argon show eight electrons in their outer shells. The atoms of the other elements must gain or lose electrons to attain full outer shells. In this way they become more stable, ending up with the electron arrangement of the nearest noble gas in the periodic table.



How sodium and chlorine atoms form ions

Some gain, some lose

Atoms that have lost or gained electrons and therefore carry an electric charge are called **ions**. Metal atoms, such as sodium, magnesium and potassium, have a small number of outer shell electrons. They form ions by losing the few electrons that they have in their outer shell. This means that metal ions have more protons than electrons and so the ions are positively charged. For example, the magnesium atom loses its two outer shell electrons to become a positively charged magnesium ion.

The symbol for the magnesium ion is Mg^{2+}. The '2+' means that two electrons have been lost to form the ion. Positively charged ions are called **cations**.

Non-metal atoms form ions by gaining electrons to fill their outer shell. In these ions there are more electrons than protons, so they are negatively charged. For example, the chlorine atom gains one electron to fill its outer shell, becoming a negatively charged chloride ion. Its symbol is Cl^-. The '–' means that one electron has been gained to form the ion. Negatively charged ions are called **anions**.

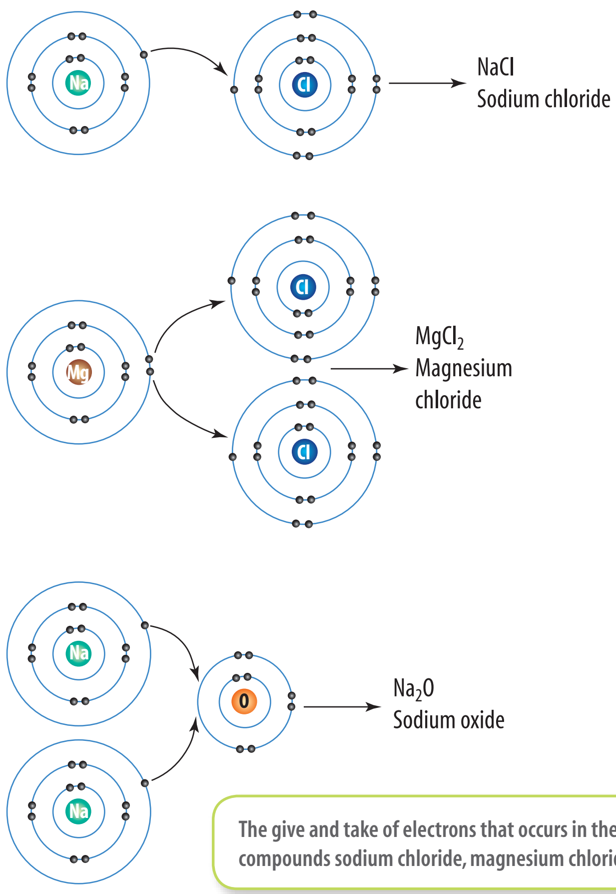
The diagram on the left shows how sodium and chlorine atoms lose and gain electrons respectively to form ions. Note that the sodium atom becomes a sodium ion and that the chlorine atom becomes a chlor*ide* ion. (When non-metals form ions, the suffix '-ide' is used.)

It's a game of give and take

Compounds such as sodium chloride, copper sulfate, calcium carbonate and sodium hydrogen carbonate all form when atoms come in contact with each other and lose or gain electrons. Compounds formed in this way are called **ionic compounds**.

Ionic compounds form when metal and non-metal atoms combine. A sodium atom loses an electron to form an ion and a chlorine atom gains an electron to form an ion. The electrons are transferred from one atom to the other, and the oppositely charged ions that form attract each other and form a compound. This electrical force of attraction between the ions is called an **ionic bond**.

The diagram below shows some examples of the transfer of electrons that occurs when ionic compounds are formed. Note that more than two atoms may be involved to ensure that all the elements achieve eight electrons in their outer shell. For example, when magnesium reacts with chlorine to form magnesium chloride, each magnesium atom loses two electrons. Since each chlorine atom needs to gain only one electron, a magnesium atom gives one electron to each of two chlorine atoms. The resulting Mg^{2+} and Cl^- ions are attracted to each other to form the compound $MgCl_2$.



The give and take of electrons that occurs in the formation of the ionic compounds sodium chloride, magnesium chloride and sodium oxide

What do ionic compounds have in common?

Ionic compounds have the following properties.

- They are made up of positive and negative ions.
- They are usually solids at room temperature.
- They normally have very high melting points because the electrostatic force of attraction between the ions is very strong.
- They usually dissolve in water to form **aqueous solutions**.
- Their aqueous solutions normally conduct electricity.

WHAT DOES IT MEAN?

The word *aqueous* comes from the Latin word ***aqua***, meaning 'water'. Other words beginning with the prefixes aque- or aqua- relate to water (for example, aqueduct, aquatic, aqualung).

UNDERSTANDING AND INQUIRING

REMEMBER

1 Why do ions form?

2 What is a positively charged ion called?

3 What is a negatively charged ion called?

4 What properties do most ionic compounds have in common?

5 What kinds of elements combine to form ionic compounds?

THINK

6 Write the symbol for the ion formed by each of the following elements. You can turn back to the periodic table in section 4.1.
(a) Sodium (c) Potassium
(b) Nitrogen (d) Fluorine

7 How many electrons have been gained or lost by the following ions?
(a) Pb^{4+} (c) Cr^{3+}
(b) Br^- (d) Se^{2-}

8 Draw diagrams like those on the left to show how each of the following ionic compounds form.
(a) Magnesium fluoride
(b) Lithium chloride
(c) Aluminium sulfide
(d) Calcium oxide

IMAGINE

9 Imagine that you are the outer shell electron of a sodium atom and you are going to form the ionic compound sodium chloride. Describe your experiences in a piece of creative writing. Discuss details such as the physical states and properties of the elements and compound involved, their atomic structure, reasons for forming ions and, finally, the reasons why the ions form the ionic compound.

10 Test your knowledge of what it means to be ionic by completing the **Pass the salt** interactivity.
int-0675

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work sheets
4.5 Ionic bonding
4.6 Writing formulae for ionic compounds
4.7 Electron configurations

4.4 SCIENCE UNDERSTANDING

When sharing works best

Ionic compounds form when atoms lose or gain electrons. Atoms can also achieve stable electronic configurations by sharing electrons with other atoms to gain a full outer shell. When two or more atoms share electrons, a molecule is formed. A chemical bond formed by the sharing of electrons is called a **covalent bond**. The compounds formed are called **covalent** or **molecular compounds**. Non-metal atoms share electrons to form covalent bonds.

Coal contains the element sulfur. When coal is burned to generate electricity, the sulfur reacts with oxygen to produce the covalent compound sulfur dioxide. Sulfur dioxide is a dangerous pollutant that causes respiratory problems. It also contributes to acid rain.

Molecules can be made of more than one type of atom, or made of atoms of the same element. For example, oxygen gas consists of molecules formed when two oxygen atoms share electrons. Individual atoms of oxygen are not stable and become more stable by sharing electrons with each other.

Electron dots: what's the point?

It is possible to draw diagrams to show how elements share electrons to form covalent compounds. These diagrams are called **electron dot diagrams**. They show the symbol for the atom and dots for the electrons in the outer shell of atoms. The table below right shows electron dot diagrams for some elements. Note that the electrons in the diagrams are arranged in four regions around the atom. Wherever possible, they are grouped in pairs.

When elements combine to form covalent compounds, they share electrons in order to achieve a full outer shell with eight electrons. Hydrogen has a full outer shell when it has two electrons but all the other elements in the table need eight electrons to fill the outer shell

The table on the following page shows how some covalent compounds form. The shared electrons are called **bonding electrons**. It is also possible to draw a **structural formula**, where a dash is used to represent these shared electrons. The dash represents the covalent bond and the other electrons need not be drawn. It is also possible for double or triple covalent bonds to form. The way electrons are shared determines the ratio in which elements combine to form a covalent compound. It also determines the **chemical formula** of the compound.

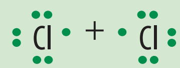
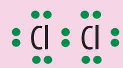
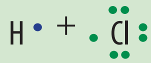
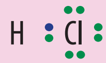
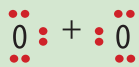
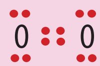
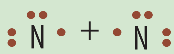
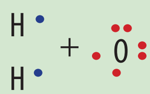
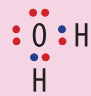
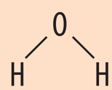
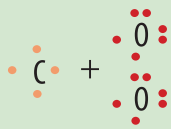
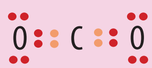
Covalent compounds

Most covalent compounds have the following properties.

- They exist as gases, liquids or solids with low melting points because the forces of attraction between the molecules are weak.
- They generally do not conduct electricity because they are not made up of ions.
- They are usually insoluble in water.

Electron dot diagrams for some elements

Symbol	Electronic configuration	Electron dot diagram
H	1	H •
C	2, 4	• C •
O	2, 6	•• O •
S	2, 8, 6	•• S •
Cl	2, 8, 7	•• Cl •
N	2, 5	•• N •
F	2, 7	•• F ••

Name and formula	Atoms	Compound	Structural formula	Explanation
Chlorine Cl_2			Cl — Cl *Note:* The line represents a sharing of two electrons and is called a single covalent bond.	Each chlorine atom needs to share one electron to gain a full outer shell.
Hydrogen chloride HCl			H — Cl	Both the hydrogen and the chlorine atom need to share one electron to gain a full outer shell.
Oxygen O_2			O═O *Note:* The double line represents a double covalent bond.	Each oxygen atom needs to share two electrons to gain a full outer shell.
Nitrogen N_2			N≡N *Note:* The triple line represents a triple covalent bond.	Each nitrogen atom shares three electrons to gain a full outer shell.
Water H_2O				Each hydrogen atom needs one electron and the oxygen atom needs two electrons to gain a full outer shell.
Carbon dioxide CO_2			O═C═O	Each oxygen atom needs two electrons and the carbon atom needs four electrons to gain a full outer shell.

The formation of covalent molecules

UNDERSTANDING AND INQUIRING

REMEMBER

1 What kinds of elements combine to form covalent compounds?

2 What is a covalent bond?

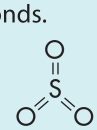
3 What does an element's electron dot diagram represent?

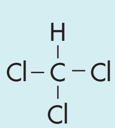
4 What properties do most covalent compounds have in common?

THINK

5 What is the difference between a single covalent and a triple covalent bond, in terms of the number of electrons involved?

6 For the covalent compounds shown below, state whether their bonds are single, double or triple covalent bonds.

(a)  Sulfur trioxide — a gas used to make sulfuric acid

(b)  Chloroform — a liquid once used as an anaesthetic

(c) H−C≡C−H Acetylene — a colourless gas used in welding

7 (a) Draw electron dot diagrams to show how the following covalent compounds form.

(i) Hydrogen fluoride (HF)
(ii) Methane (CH_4)
(iii) Phosphorus chloride (PCl_3)
(iv) Hydrogen sulfide (H_2S)
(v) Tetrachloromethane (CCl_4)
(vi) Ammonia (NH_3)
(vii) Carbon disulfide (CS_2)

(b) What pattern emerges between the structural formula of the compound and the number of electrons involved in bonding?

(c) State whether the covalent bonds in the compounds are single, double or triple bonds.

8 Why don't the noble gases form covalent compounds?

9 Explain why CO_2 (a compound) and O_2 (an element) are both molecules.

INVESTIGATE

10 Silicon dioxide, commonly known as silica or sand, is a hard solid covalent compound with a very high melting point. Find out about its structure.

11 Although carbon and graphite are both made up of carbon atoms, they have very different properties. Investigate their properties and explain why they are so different in terms of their covalent structure.

12 To find out more about atomic structure and bonding, use the **Atomic structures** weblink in your eBookPLUS.

4.5 SCIENCE AS A HUMAN ENDEAVOUR

How reactive?

Have you ever wondered why it is that gold can be found lying near the surface of the Earth and yet we need to mine iron ore and smelt it in large furnaces before we can obtain iron? The answer lies in the reactivity of the metals. Gold is a very unreactive element. It does not combine readily with other elements to form compounds. Most metals are much more reactive than gold.

When the Earth formed, the more reactive metals — including aluminium, copper, zinc and iron — reacted with other elements to form ionic compounds. These compounds are the **mineral ores** from which the metal elements are obtained. Iron ores include haematite (Fe_2O_3), magnetite (Fe_3O_4), siderite ($FeCO_3$), pyrite (FeS_2) and chalcopyrite ($CuFeS_2$).

The reactivity of metals is dependent on how easily they are able to give up their outer shell electrons. For example, it is easier for an atom to give up a single electron from an outer shell than to give up two electrons from the outer shell.

Few metals like gold are found as elements; most are found as compounds or ores.

The reactivity of metals can be investigated by observing the reactions of metals with acids. When a metal reacts with hydrochloric acid, it reacts according to the equation:

metal + hydrochloric acid → salt + hydrogen gas.

In these reactions electrons are transferred away from the metal atoms to the hydrogen in the acid, forming positive metal ions and hydrogen gas. The metal is said to have displaced the hydrogen from the acid. For this reason, these reactions are also **displacement reactions**.

Metals in ancient times

The most powerful ancient civilisations succeeded and prospered because they developed better weapons than their enemies by using metals such as copper, tin and iron. The Mesopotamians, who occupied a large region of the Middle East, learned almost five thousand years ago how to separate copper and tin from their ores using a process

INQUIRY: INVESTIGATION 4.4

Investigating reactivity

KEY INQUIRY SKILLS:

- planning and conducting
- processing and analysing data and information

Equipment:

5 test tubes and a test-tube rack
safety glasses
1 cm × 4 cm piece of magnesium ribbon (or equivalent amount)
1 cm × 4 cm piece of zinc, copper, aluminium and iron
1M hydrochloric acid
measuring cylinder, small funnel, thermometer and steel wool

CAUTION: Wear safety glasses.

- Polish each of the metal pieces with the steel wool.
- Pour 10 mL of acid into each test tube. Measure and record the temperature.
- Add one metal to each of the test tubes. Look for the presence of bubbles on the surface of the metals. Arrange the test tubes in order of increasing bubble production and record your observations.

DISCUSS AND EXPLAIN

1 List the metals in order of increasing reactivity.
2 Discuss the limitations of this experiment.

called **smelting**. Smelting is a chemical process in which carbon reacts with molten ore to separate the relatively pure metal from it. In ancient times, charcoal was used in furnaces to provide the carbon. They combined molten copper and tin to produce an **alloy** known as **bronze**, which was resistant to corrosion and harder than both copper and tin. The ancient Egyptians, Persians and Chinese also used bronze in weapons, ornaments, statues and tools.

The ancient Romans used the smelting process to separate iron from iron ore. They strengthened it by pounding it with a hammer and used it to produce weapons, shields and armour that was harder and stronger than brass. The use of iron weapons allowed the Roman legions to rule the Mediterranean world and beyond for over four hundred years.

The gladius (a short iron sword), together with a long iron shield, gave the Roman army a huge advantage over its enemies. The shields were often used by groups of soldiers to form a protective wall and roof known as a *testudo* (tortoise) around themselves.

HOW ABOUT THAT!

The activity series

The **activity series** places the elements in decreasing order of reactivity:

Li → K → Na → Ca → Mg → Al → Mn → Cr → Zn → Fe → Ni → Sn → Pb → H → Cu → Hg → Ag → Au → Pt.

In order to react with acid and release hydrogen gas, the metal must be before hydrogen in the activity series.

Lithium, potassium, sodium and calcium are the most reactive metals. They will react with water to produce hydrogen gas. Magnesium through to lead will react with acid to form hydrogen gas, but copper, mercury and silver will not. Gold and platinum are even less reactive than copper and silver. Most of the elements at the top of the activity series were discovered much later than those at the bottom. Gold, silver, mercury and copper were all discovered over 2000 years ago. Potassium, sodium and calcium were not discovered until 1808. Why do you think this is so?

INQUIRY: INVESTIGATION 4.5

Quantified reactivity

KEY INQUIRY SKILLS:

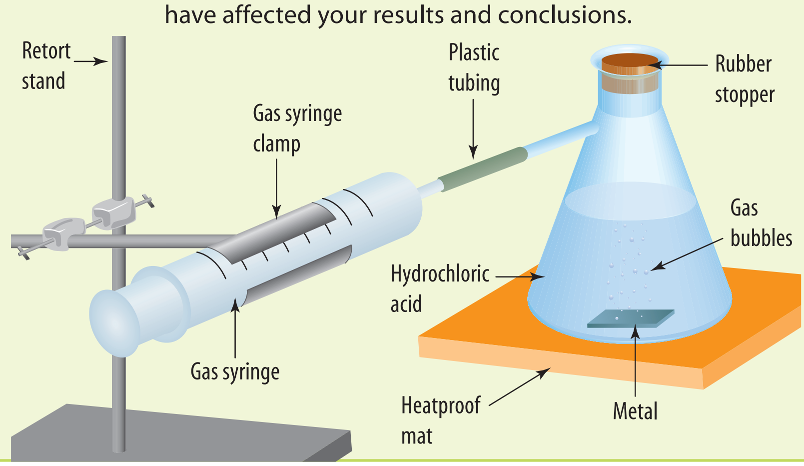
- planning and conducting
- processing and analysing data and information

Equipment:

safety glasses, heatproof mat, steel wool and gas syringe
1 cm × 4 cm piece of zinc, copper, aluminium and iron
1 cm × 4 cm piece of magnesium ribbon (or equivalent amount)
1M hydrochloric acid
retort stand, bosshead and gas syringe clamp
1 cm × 6 cm length of plastic tubing
250 mL side arm conical flask
rubber stopper to fit conical flask
stopwatch or clock with second hand
50 mL measuring cylinder
distilled water

CAUTION: Wear safety glasses.

- Polish each of the metal pieces with the steel wool.
- Mount the gas syringe in the clamp as shown in the diagram at right. Your teacher will tell you if the syringe needs to be lubricated. Push the plunger fully in and attach the plastic tubing to the nozzle.
- Pour 50 mL of acid into the flask.
- Connect the other end of the plastic tubing to the conical flask.
- Place one of the pieces of metal in the conical flask and quickly seal with the rubber stopper.
- Have one student act as a timer and another as a recorder.
- As soon as the metal is dropped in, start timing.



- Using a suitable table, record the volume of the gas in the syringe every 30 seconds until gas is no longer produced, the syringe is full or 10 minutes has passed, whichever occurs first.
- Repeat the procedure with the other metals, taking care to rinse out the flask carefully each time with distilled water.
- In your workbook, plot the results for all of the metals on one set of axes. Put the volume of gas on the vertical axis and time on the horizontal axis.

DISCUSS AND EXPLAIN

1 Use your graph to list the five metals in increasing order of reactivity and explain your reasoning.
2 Write a word equation for the reaction of each of the metals with the acid. If no reaction occurred, write 'no reaction'.
3 Write an equation using formulae for the reaction of each of the metals with the acid. If no reaction occurred, write 'no reaction'.
4 To which general reaction type or types do reactions between metals and acids belong?
5 Some of the variables in this investigation were not carefully controlled. List them and explain how this may have affected your results and conclusions.

UNDERSTANDING AND INQUIRING

REMEMBER

1 Name the gas produced in the reaction of metals with hydrochloric acid.
2 Why is iron usually found in the form of a compound in the Earth's crust?

THINK

3 Explain why the reactivity of metals decreases from left to right across the periods of the periodic table.

INVESTIGATE

4 Design and carry out an experiment that investigates the reactivity of alloys, such as stainless steel and brass. Compare these results with those obtained for the metal elements.
5 Research and report on the science of metallurgy and the role of metallurgists in the mining industry.

CREATE

6 When scientists attend conferences they often present the results of their investigations as a poster. A poster can describe their work with photographs, drawings and concise written summaries. Present the findings of your investigation into the reactivity of metals as a poster to display in your classroom.

4.6 SCIENCE UNDERSTANDING

Finding the right formula

Most of the chemicals used in your school science laboratory are identified by both a name and a formula. Most people are able to recognise the formula of common compounds such as water (H_2O) and carbon dioxide (CO_2). A chemical formula (plural *formulae*) is a shorthand way of writing the name of an element or compound. It tells us the number and type of atoms that make up an element or compound. Writing the correct formula is of paramount importance in chemistry. Most chemical problems cannot be solved without the knowledge of chemical formulae.

It's elementary

Often the formula of a substance is simply the symbol for the element. Metals such as iron and copper, which contain only one type of atom, are identified simply by the symbol for that element (for example, Fe and Cu). Noble gases such as neon (Ne) have a similar formula.

Some non-metal elements such as hydrogen, oxygen and nitrogen exist as simple molecules. These molecules form when atoms of the same non-metal join together by covalent bonds. For example, the formula for the element hydrogen is H_2, indicating that two hydrogen atoms are joined together to make each molecule of hydrogen. A **molecular formula** is a way of describing the number and type of atoms that join to form a molecule.

Some common non-metal molecules and their molecular formulae

Name	Formula
Hydrogen	H_2
Nitrogen	N_2
Chlorine	Cl_2
Bromine	Br_2
Oxygen	O_2
Sulfur	S_2
Phosphorus	P_2

Formulae of compounds

The formula of a compound shows the symbols of the elements that have combined to make the compound and the ratio in which the atoms have joined together. For example, the chemical formula for the covalent compound methane, a constituent of natural gas, is CH_4 — one carbon atom for every four hydrogen atoms. The formula for the ionic compound calcium chloride, which is used as a drying agent, is $CaCl_2$ — two chlorine ions for every calcium ion.

Valency: formulae made easy

Knowledge of the **valency** of an element is essential if we wish to write formulae correctly.

The valency of an element is equal to the number of electrons that each atom needs to gain, lose or share to fill its outer shell. For example, the chlorine atom has only seven electrons in its outer shell, which can hold eight electrons. By gaining one electron, its outer shell becomes full. Chlorine therefore has a valency of one. The magnesium atom has two electrons in its outer shell. By losing two electrons, it is left with a full outer shell. Magnesium therefore has a valency of two.

A simple guide to remembering the valency of many elements is to remember to which group in the periodic table they belong. The number of outer shell electrons allows you to work out the number of electrons required to fill the outer shell. The table below provides a simple guide to the valency of many elements.

Valency of groups in the periodic table

Group	Valency
Group 1	1
Group 2	2
Group 13	3
Group 14	4
Group 15	3
Group 16	2
Group 17	1

Writing formulae for covalent compounds

To write the formula of a non-metal compound made up of only two elements, use the valency of each element and follow the steps shown below.

EXAMPLE 1

Write the formula for carbon dioxide.

Step 1 *Determine the valency of the elements involved.*

Carbon has a valency of four; oxygen a valency of two. (That is, carbon needs to share four electrons, while oxygen needs to share two electrons.)

Step 2 *Determine the ratio of atoms that need to combine so that each atom can share the same number of electrons.*

A ratio of one carbon atom to two oxygen atoms would result in both sharing four electrons.

Step 3 *Write the formula using the symbols of the elements and writing the ratios as subscripts next to the element. (The number 1 can be left out as writing the symbol for the element assumes that one atom is present.)*

The formula for carbon dioxide is CO_2.

EXAMPLE 2

Write the formula for phosphorus chloride.

Step 1 *Determine the valency of the elements involved.*

Phosphorus has a valency of three; chlorine has a valency of one.

Step 2 *Determine the ratio of atoms that need to combine so that each atom can share the same number of electrons.*

A ratio of one phosphorus atom to three chlorine atoms would result in both sharing three electrons.

Step 3 *Write the formula using the symbols of the elements and writing the ratios as subscripts next to the element.*

The formula for phosphorus chloride is PCl_3.

EXAMPLE 3

Write the formula for hydrogen oxide (water).

Step 1 *Determine the valency of the elements involved.*

Hydrogen has a valency of one; oxygen has a valency of two.

Step 2 *Determine the ratio of atoms that need to combine so that each element can share the same number of electrons.*

A ratio of two hydrogen atoms to one oxygen atom would result in both sharing two electrons.

Step 3 *Write the formula using the symbols of the elements and writing the ratios as subscripts next to the element.*

The formula for hydrogen oxide is H_2O.

Writing formulae for ionic compounds

The formulae for ionic compounds can be written from knowledge of the ions involved in making up the compound. In ionic compounds, metal ions combine with non-metal ions. The tables below and on the following page list common positive and negative ions and their names.

Metal atoms usually form positive ions. The number of positive charges on the ion is called the **electrovalency** of the ion. For example, a sodium ion has one positive charge (Na^+), the calcium ion has two positive charges (Ca^{2+}) and the aluminium ion has three positive charges (Al^{3+}). Note that, in the table below, some of the transition metals have more than one valency (e.g. iron). The Roman numerals in brackets after iron and copper identify the valency.

Electrovalencies of some common positive ions

Number of positive charges in each element		
+1	+2	+3
Hydrogen (H^+)	Calcium (Ca^{2+})	Aluminium (Al^{3+})
Potassium (K^+)	Copper(II) (Cu^{2+})	Iron(III) (Fe^{3+})
Silver (Ag^+)	Iron(II) (Fe^{2+})	
Sodium (Na^+)	Lead (Pb^{2+})	
Ammonium (NH_4^+)	Magnesium (Mg^{2+})	
	Zinc (Zn^{2+})	

Non-metals usually form negative ions. The number of negative charges in the ion is the electrovalency of the ion. For example, chloride has one negative charge (Cl^-), oxide has two negative charges (O^{2-}) and phosphorus has three negative charges (P^{3-}). There are also some more complex negative ions called **molecular ions**, such as hydroxide ions (OH^-) and sulfate ions (SO_4^{2-}). These groups of atoms have an overall negative charge and are treated as a single entity. Note that the hydrogen ion, although a non-metal ion, exists as a positive ion.

Electrovalencies of some common negative ions

Number of negative charges in each element		
−1	−2	−3
Bromide (Br^-)	Carbonate (CO_3^{2-})	Phosphate (PO_4^{3-})
Chloride (Cl^-)	Oxide (O^{2-})	Nitride (N^{3-})
Hydrogen carbonate (HCO_3^-)	Sulfate (SO_4^{2-})	
Hydroxide (OH^-)	Sulfide (S^{2-})	
Iodide (I^-)		
Nitrate (NO_3^-)		

The following examples show how the formulae for ionic compounds are determined.

EXAMPLE 1

Write the formula for sodium chloride.

Step 1 *Determine the electrovalency of the ions that comprise the compound and write down their symbols.*

The symbol for the sodium ion is Na^+ and the symbol for the chloride ion is Cl^-.

Step 2 *Determine the ratio of ions required in order to achieve electrical neutrality. (Remember compounds have no overall charge.)*

The ratio of negative to positive charges for sodium and chloride ions is 1 : 1. That is, it takes one negatively charged chloride ion to balance the charge of the positively charged sodium ion.

Step 3 *Write the formula for the compound using the numbers in the ratios as subscripts. (Remember the number 1 does not need to be included.)*

The formula for the compound is NaCl.

EXAMPLE 2

Write the formula for aluminium oxide.

Step 1 *Determine the electrovalency of the ions that comprise the compound and write down their symbols.*

The symbol for the aluminium ion is Al^{3+} and the symbol for the oxide ion is O^{2-}.

Step 2 *Determine the ratio of ions required in order to achieve electrical neutrality. (Remember compounds have no overall charge.)*

The ratio of negative to positive charges for aluminium and oxide ions is 2 : 3. That is, it takes three negatively charged oxide ions to balance the charge of the two positively charged aluminium ions.

Step 3 *Write the formula for the compound using the numbers in the ratios as subscripts.*

The formula for the compound aluminium oxide is Al_2O_3.

EXAMPLE 3

Write the formula for calcium phosphate.

Step 1 *Determine the electrovalency of the ions that comprise the compound and write down their symbols.*

The symbol for the calcium ion is Ca^{2+} and the symbol for the phosphate ion is PO_4^{3-}.

Step 2 *Determine the ratio of ions required in order to achieve electrical neutrality. (Remember compounds have no overall charge.)*

The ratio of negative to positive charges for calcium and phosphate ions is 3 : 2. That is, it takes two negatively charged phosphate ions to balance the charge of the three positively charged calcium ions.

Step 3 *Write the formula for the compound using the numbers in the ratios as subscripts.*

The formula for the compound calcium phosphate is $Ca_3(PO_4)_2$.

Note the use of brackets in the formula to show that more than one molecular ion is needed to balance the electric charge.

INQUIRY: INVESTIGATION 4.6

The ionic compound formula game

Equipment:

a set of playing cards with the name and valency of each of the positive and negative ions listed in the tables in this section that list electrovalencies. You will need four identical cards for each ion.

- Organise a group of four students to play the card game. The aim of this game is to collect as many cards as possible by producing compounds with their correct chemical formulae.
- Shuffle the cards and then distribute them to the players.
- The dealer puts down one card.
- The rest of the players then try to produce a chemical formula using their cards. The first person to come up with a correct chemical formula wins the hand and keeps the cards. They are put aside until the end of the game. The dealer will decide the winner of the hand.
- The person to the left of the dealer then puts down one of their cards.
- The other players in the game now try to produce a chemical formula using the cards they have in their hands. Again, the person to come up with a correct chemical formula wins that hand and the cards are put aside until the end of the game.
- The game continues moving to the next person until no one is able to produce a chemical formula. The game stops at this point.
- Each player then counts the number of cards they have produced formulae with. The winner is the person with the most cards.

DISCUSS AND EXPLAIN

1 Write a list of the formulae and the name of the compounds formed.

2 What is the best strategy to win the game?

3 Did you find the game useful in learning the formulae of compounds? Explain.

UNDERSTANDING AND INQUIRING

REMEMBER

1 What is a chemical formula?

2 What is a molecular formula?

3 What does the formula of a compound tell you about the compound?

4 Write the symbols for the following elements: sodium, hydrogen, potassium, lead, chlorine, iodine and sulfur.

5 Which elements are present in each of the following compounds?
(a) HNO_3 (b) $NaHCO_3$ (c) FeS

6 How is the valency of an element determined?

7 How many chlorine (Cl^-) ions would be required to combine with each of the following ions to form an ionic compound?
(a) calcium (Ca^{2+}) (c) silver (Ag^+)
(b) aluminium (Al^{3+})

8 Write down the valencies for the following elements: sodium, hydrogen, lead, chlorine, iodine, magnesium and sulfur.

THINK

9 The ions listed below can combine in many different ways to form 25 different compounds. Write the formulae and names of these compounds.

Na^+ Fe^{3+} Li^+ Cu^{2+} Al^{3+}

Cl^- OH^- N^{3-} O^{2-} SO_4^{2-}

10 The chloride ion has the same valency as the sodium ion. However, it has a different electrovalency. Why?

11 Write a formula for each of the following.
(a) Oxygen gas (e) Zinc oxide
(b) Chlorine gas (f) Potassium sulfate
(c) Lead (g) Calcium hydroxide
(d) Nitrogen oxide

12 Name the following compounds.
(a) NH_4Cl (e) $KHCO_3$
(b) KI (f) $MgCO_3$
(c) $Al(NO_3)_3$ (g) HNO_3
(d) $Fe(OH)_3$

13 Explain why group 18 is not listed in the table in this section showing valency of groups in the periodic table.

IMAGINE

14 Imagine that there was no recognised system for naming elements and compounds. Describe some of the problems this would lead to.

CREATE

15 Create your own ionic compound formula game. It could be an improved version of Investigation 4.6 above; however, it does not have to be a card game.

16 Use the **Chemical formulae** weblink in your eBookPLUS and take the quiz to check your understanding of how chemical formulae are written.

eBook*plus*

work sheets
4.8 Covalent bonding
4.9 Chemical formulae

Concepts and mind maps

1. On small pieces of paper, write down all the ideas you can think of about a particular topic.
2. Select the most important ideas and arrange them under your topic. Link these main ideas to your topic and write the relationship along the link.
3. Choose ideas related to your main ideas and arrange them in order of importance under your main ideas, adding links and relationships.
4. When you have placed all of your ideas, try to find links between the branches and write in the relationships.

how to ...?

question

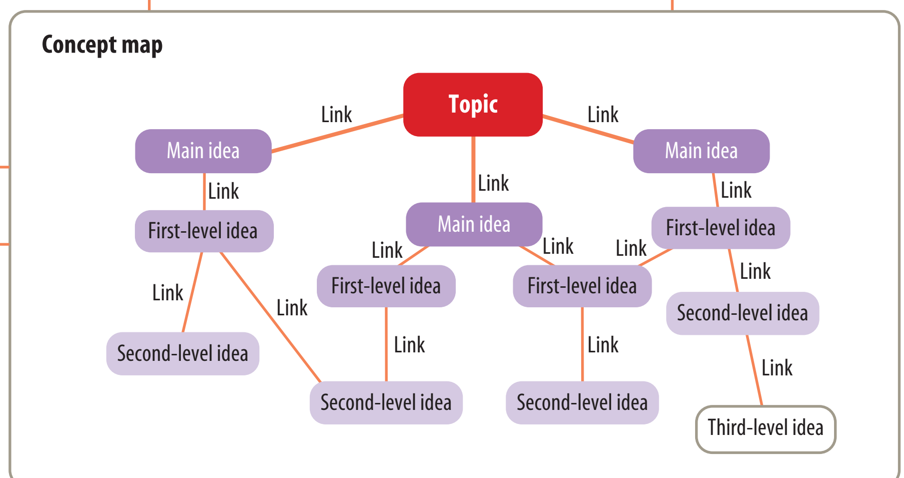
How can I explain this topic to someone else?
What do I understand about this particular topic?

why use?

To show what you understand about a particular topic

also called

Knowledge map; concept web



comparison

Similarity

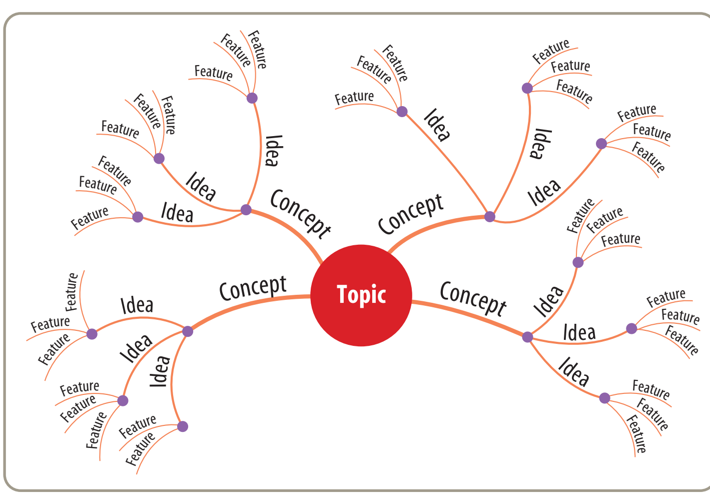
Both show graphically the structure of a topic in a hierarchical way.

Difference

Concept maps explain the relationship between the parts or elements with statements on the links.

Mind map

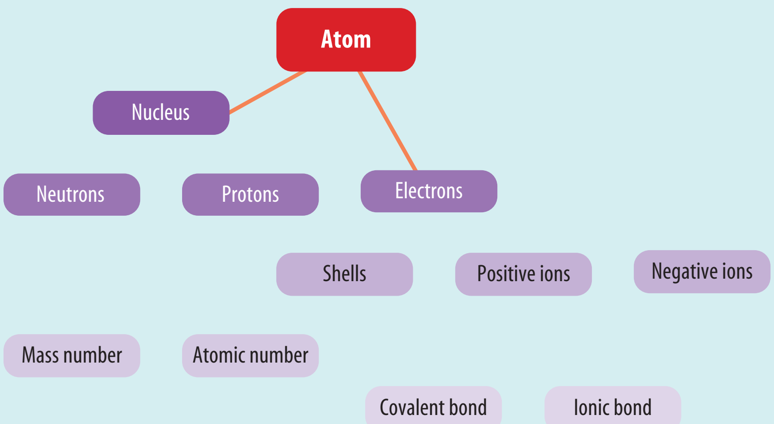
example



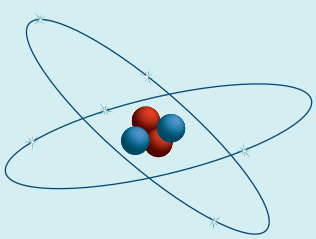
UNDERSTANDING AND INQUIRING

THINK AND CREATE

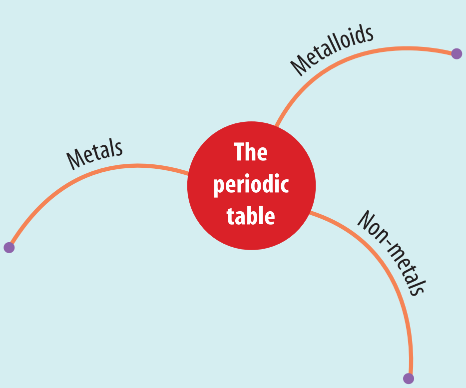
1 A concept map can be used to illustrate some of the important ideas associated with the atom and the links between the ideas.
   (a) Copy the concept map below into your workbook and complete it by adding links between the ideas.
   (b) Construct your own concept map to show how ideas about what is inside substances are linked. Begin by working in a group to brainstorm the main ideas of the topic.



2 Create a concept map to illustrate ideas and links related to
   (a) the structure of the atom
   (b) the periodic table.

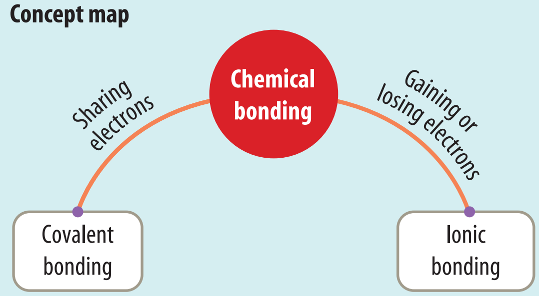


3 A mind map is similar to a concept map, but doesn't explain the links between the major concepts and ideas. Complete the mind map below to represent your knowledge of metals, non-metals and metalloids.

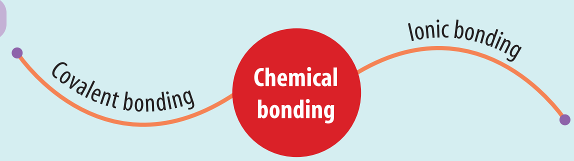


4 In a small group, brainstorm a list of important words, concepts and ideas associated with covalent bonding and ionic bonding. Use the list to create either a concept map or a mind map beginning with the term *chemical bonding*.

Concept map



Mind map



HOW ABOUT THAT!

Oxygen gas consists of molecules in which two oxygen atoms share electrons. The formula for oxygen gas is therefore O_2. Ozone gas, which exists naturally in the upper atmosphere, consists of 'triplets' of oxygen atoms sharing electrons. The formula for ozone is therefore O_3.

STUDY CHECKLIST

ATOMS AND THE PERIODIC TABLE

- recall the characteristics and location in the atom of protons, neutrons and electrons
- explain how the electronic structure of the atom determines its position in the periodic table and its properties
- recognise that elements in the same group of the periodic table have similar properties
- recognise that the atomic numbers of elements in the periodic table increase from left to right across each period
- distinguish between the atomic number, mass number and relative atomic mass of an atom
- describe common properties of elements in each of the alkali metals, halogen and noble gas groups of the periodic table
- distinguish between the properties of metals, non-metals and metalloids

ELECTRON SHELLS AND BONDING

- describe the structure of atoms in terms of electron shells
- relate the energy of electrons to shells
- explain the movement of electrons to higher energy levels and the emission of light when they return to a lower level
- describe covalent bonding in terms of the sharing of electrons in the outer shells of atoms
- describe ionic bonding in terms of the formation of ions and relate it to the number of electrons in the outer electron shells of atoms
- relate the reactivity of metals to the shell structure of their atoms and their location in the periodic table

VALENCY AND CHEMICAL FORMULAE

- define the valency of an element as the number of electrons an atom needs to gain, lose or share to fill its outer shell
- relate the valency of an atom to its group in the periodic table
- deduce the formula of a variety of simple covalent and ionic compounds from the valency of their constituent elements

SCIENCE AS A HUMAN ENDEAVOUR

- investigate the development of the periodic table and how this was dependent on experimental evidence at the time
- describe the hazards associated with the use of lead and describe recent attempts to reduce its use
- relate the reactivity of metals to the mining industry
- describe the extraction of copper, tin and iron by ancient civilisations
- describe the uses of bronze and iron by ancient civilisations

ICT

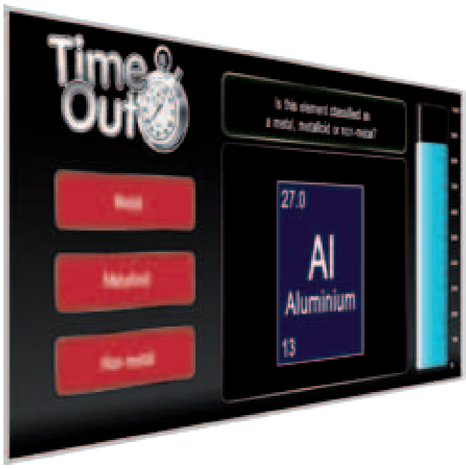
eBookplus **Summary**

INTERACTIVITIES

Time Out: 'Periodic Table'

In this exciting interactivity, test your ability to classify elements from the periodic table before time runs out.

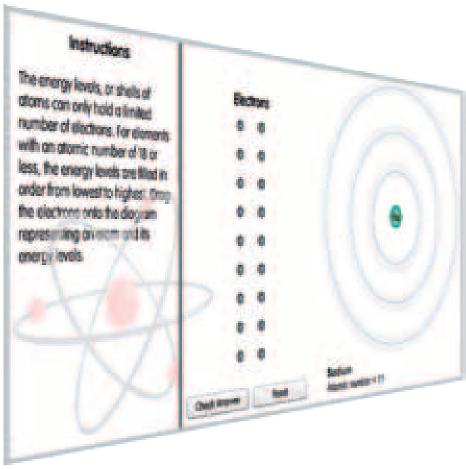
Searchlight ID: int-0758



Shell-shocked?

This interactivity challenges you to create a model of the electron shell of an atom and indicate its energy levels.

Searchlight ID: int-0676



Pass the salt

Use this interactivity to test your knowledge on what it means to be ionic.

Searchlight ID: int-0675

INDIVIDUAL PATHWAYS

eBookplus

Activity 4.1 Revising chemical patterns

Activity 4.2 Investigating chemical patterns

Activity 4.3 Investigating chemical patterns further

LOOKING BACK

1 Explain why it is more useful to display the elements as a periodic table than as a list.

2 The periodic table is an arrangement of all the known elements. What information is given by the group and period numbers on the periodic table?

3 Explain how the periodic table has been helpful to chemists of both the past and present when they are searching for new elements.

4 Explain why water does not appear in the periodic table.

5 Write the atomic number and mass number of the following atoms and then calculate the number of protons, neutrons and electrons they have.
(a) $^{28}_{14}Si$ (b) $^{52}_{24}Cr$ (c) $^{197}_{79}Au$
(d) $^{206}_{82}Pb$ (e) $^{242}_{94}Pu$

6 To which group of elements in the periodic table does the neon used in lighting belong?

7 List five properties that all (or almost all) metals have in common.

8 List five properties that most solid non-metals have in common.

9 As you move down the groups in the periodic table, how does the reactivity change for:
(a) metals
(b) non-metals?

10 As you move across the periodic table, what changes occur in:
(a) atomic number (c) melting points
(b) mass number (d) metallic character?

11 Although they look very different from each other and have very different uses, arsenic, germanium and silicon belong to the group of elements known as metalloids. How are metalloids different from all of the other elements in the periodic table?

12 Copy and complete the following table.

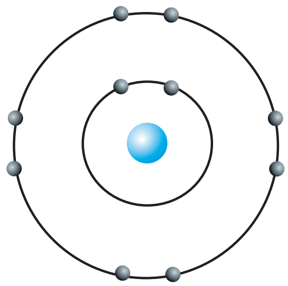
Name	Symbol	Atomic number	Electron configuration
Lithium	Li	3	2, 1
	C	6	
			2, 6
Neon			
	Na		
		13	
			2, 8, 5
Chlorine			
	K		2, 8, 8, 1
	Ca	20	

13 All atoms of the element magnesium have four protons. Eighty per cent of those atoms have four neutrons.
(a) State the atomic number of magnesium.
(b) What is the mass number of most magnesium atoms?
(c) How many electrons orbit a neutral magnesium atom?
(d) Explain why all magnesium atoms don't have the same mass number.

14 Copy and complete the following table.

Ion	Ion symbol	Atomic number	Electron configuration
		3	2
	Na^+		
		12	2, 8, 8,
	N^{3-}		
		9	2, 8
Sulfide			

15 The electron shell diagram below has its first two shells filled. It could represent a neutral atom, a positive ion or a negative ion. Identify the names and symbols of the atom or ion if it represents:
(a) a neutral atom (identify one)
(b) a positive ion (identify two possibilities)
(c) a negative ion (identify two possibilities).



16 Show how the following ionic compounds form.
(a) Lithium fluoride (LiF)
(b) Sodium oxide (Na_2O)

17 Show how the following covalent compounds form.
(a) Hydrogen chloride (HCl)
(b) Ammonia (NH_3)

18 What are the differences between the properties of ionic and covalent compounds?

19 Explain why you are more likely to find pure gold than pure copper in the ground.

20 Explain why metals such as gold, silver and copper were discovered about 2000 years ago while the metals potassium, sodium and calcium were not discovered until about 200 years ago.

21 Write formulae for the following substances.
(a) Oxygen gas
(b) Carbon dioxide gas
(c) Aluminium oxide
(d) Sodium fluoride
(e) Calcium carbonate
(f) Zinc chloride
(g) Iron(III) sulfide
(h) Sulfur dioxide
(i) Carbon
(j) Lead

work sheet 4.10 Chemical patterns: Summary projectsplus

The mystery metal

SEARCHLIGHT ID: PRO-0113

Scenario

Your eccentric aunt loves combing through junk shops in search of overlooked treasures, and every time you spend a day with her she'll make you go into one grubby store smelling of mangy mink coats after another. One day during the school holidays, you are wandering idly in one of these old junk shops while your aunt haggles for an old vase with the owner. You find a lump of metal in a drawer of an old dresser. The shopkeeper says that you can keep it and you put it in your pocket. Occasionally over the next few days you wonder what the metal is. Is it something valuable like platinum, or useful like aluminium? Or is it just an old lump of lead? By the end of the holidays, you've forgotten all about the lump of mystery metal.

When you get back to school, your science teacher announces that everyone in your class is to enter a competition that the Australian Chemistry Teachers' Association is running. The competition needs you to write an online 'Choose your own adventure' story that has a chemistry theme. You and your friends are scratching your heads trying to come up with an idea when, suddenly, you remember that lump of mystery metal you found in the junk shop. Maybe you could use that as the theme for your competition entry . . .

Your task

Either on your own or as part of a group, you will develop a 'Choose your own adventure' (CYOA) story exploring the identification of the mystery metal. You will then create a series of interconnected PowerPoint screens that can be uploaded. A player starting at the first screen will advance through a storyline according to the choices they make at each screen. The choices will relate to various chemical and physical characteristics of the metal. The right sequence of choices will eventually lead to the correct identification of the mystery metal.

Process

- Open the ProjectsPLUS application for this chapter located in your eBookPLUS. Watch the introductory video lesson and then click the 'Start Project' button to set up your project group. You can complete this project individually or invite other members of your class to form a group. Save your settings and the project will be launched.

- Navigate to your Research Forum. Here you will find a number of different headings under which you will organise your research. You may delete those topics that you will not be considering or add your own topics if you find your research going in a different direction.

SUGGESTED SOFTWARE

- ProjectsPLUS
- Word or other word-processing software
- PowerPoint
- Internet access

- Start your research. Make notes of information that you think will be relevant to your project, such as what different metals look like and how metals that look similar can be distinguished from one another. Enter your findings as articles under your topic headings in the Research Forum. You should each find at least three sources (other than the textbook, and at least one offline such as a book or encyclopaedia) to help you discover extra information about the chemistry of metals. You can view and comment on other group members' articles and rate the information they have entered. When your research is complete, print out your Research Report to hand in to your teacher.

- Visit your Media Centre and download the 'Choose your own adventure' PowerPoint template, which you will use to create your project. Your Media Centre also includes weblinks to sites that you might find useful, an example of a scientific CYOA and images that you may find helpful for your project.
- Start creating your Mystery Metal CYOA.

MEDIA CENTRE

Your Media Centre contains:

- a sample rule book
- a selection of useful weblinks
- a selection of images
- an assessment rubric.

Your ProjectsPLUS application is available in this chapter's Student Resources tab inside your eBookPLUS. Visit www.jacplus.com.au to locate your digital resources.