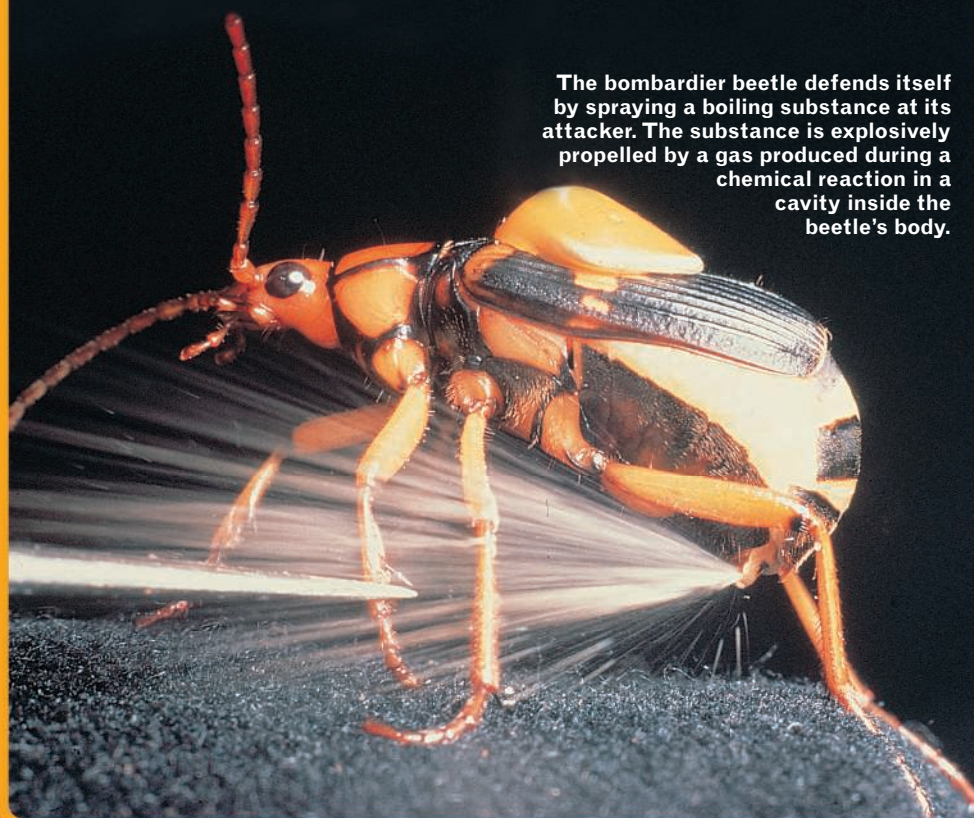


Chemistry — the inside story

2

The air that you breathe, the gunpowder in fireworks and the boiling hot spray discharged by a bombardier beetle are all examples of chemicals. In fact everything around you, including your own body, is entirely composed of chemicals. Chemistry is the study of substances and the way that they behave on their own or when combined with other substances. To understand the behaviour of substances, you need to take a look inside to find out what they are made of.

The bombardier beetle defends itself by spraying a boiling substance at its attacker. The substance is explosively propelled by a gas produced during a chemical reaction in a cavity inside the beetle's body.



Key outcomes

Relate the properties of fundamental groupings of substances to the nature of their constituent particles.

Describe the similar characteristics of groups of elements in the periodic table.

Specify the characteristics, chemical reactions and usefulness to society of groups of similar substances.

Describe the production and uses of substances with unusual and specialised properties.

Think about these

How did a plum pudding help chemists to understand atoms?

Does 'radioactive' always mean 'dangerous'?

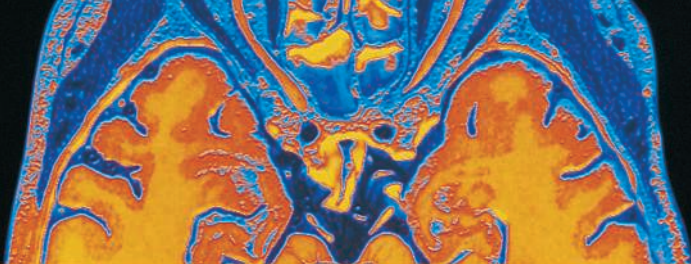
How can we write 'aluminium nitrate' using only four letters?

Who was Dmitri Mendeleev, and how was he able to predict the future?

Are all oxygen atoms the same?

What happens when an atom is split?

Why do we talk about energy levels when describing electrons?



Your Quest

Do you have the inside information?

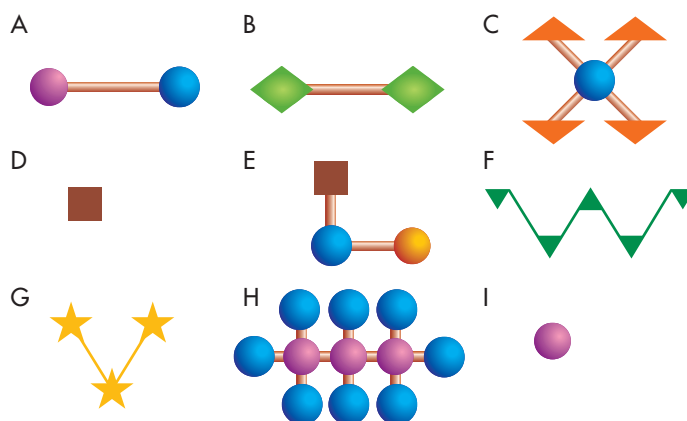
All chemicals — in other words all substances — are made up of tiny particles. These tiny particles are so small that you can't see them, even with the most powerful light microscope. You probably already know quite a lot about the particles inside chemicals. This knowledge is the first step in your quest to find out why chemicals behave the way they do.

THINK

Answer the questions below to find out how much you already know about the inside story on chemicals.

- The substances around you and inside you can be placed into three groups — elements, compounds and mixtures.
 - Which one of these groups contains chemicals that are made up of only one type of atom?
 - Which one of these groups is the least likely to be found naturally in the Earth's crust?
 - What is the difference between a compound and a mixture?
 - Arrange the substances listed below into the three groups of substances to complete the affinity diagram below right.

- Elements, compounds and mixtures are made up of tiny particles called atoms and molecules.
 - How is a molecule different from an atom?
 - List two elements that can be made up of molecules.
 - List two compounds that are made up of molecules.
 - Name one compound that is not made up of molecules.
- Which of the diagrams below represent:
 - an atom of an element?
 - a molecule of an element?
 - a molecule of a compound?



gold blood
carbon dioxide
diamond iron
air sea water
copper chocolate thick shake
table salt
ammonia soil
concentrated hydrochloric acid
pure water calcium
brass
sodium hydroxide oxygen

SUBSTANCES		
elements	compounds	mixtures

Chemical building blocks

How can you describe something that you can't see, hear, feel, touch or smell? That is the problem that scientists are faced with when trying to describe the 'building blocks' that make up all substances.

A history of ideas about the atom

Most of our knowledge about the 'building blocks' of matter is less than one hundred years old. We now know those 'building blocks' as atoms. But the idea that matter was made up of atoms was first

suggested about 2500 years ago by a Greek philosopher named Democritus.

Since then, various theories and models of the atom have been accepted, rejected and modified.

The flowchart below shows how our knowledge about the atom developed.

About 400 BC: Greek philosopher Democritus first suggested that all substances consisted of tiny indestructible particles called atoms.



1808: John Dalton's atomic theory proposed that:

- all matter consisted of tiny particles called atoms
- atoms could not be divided into smaller particles
- atoms of the same element were alike
- atoms combined in simple whole number ratios.

1897: English scientist Sir J. J. Thomson explained that the atom contained negatively charged particles called electrons. His model suggested that atoms were positively charged spheres with negatively charged electrons embedded in them like the fruit in a plum pudding.



1911: Lord Rutherford proposed that the atom consisted mostly of empty space with a dense nucleus containing positively charged protons in the centre. Negatively charged electrons orbited the nucleus. Although Lord Rutherford's model of the atom was essentially the same as today's accepted model, its one flaw was that it proposed that the orbiting electrons would eventually lose energy and spiral in towards the nucleus.

1913: Niels Bohr, a scientist who had studied with Rutherford, modified the model by suggesting that electrons orbit the nucleus at different energy levels. Only electrons with specific amounts of energy could exist at each level. His model proposed that electrons could move from one level to another by gaining or losing 'packets' of energy. Although Bohr's model explained why electrons did not spiral in towards the nucleus, it did not explain all of the known properties of atoms.

1932: Sir James Chadwick discovered that the nucleus contained particles called neutrons, as well as positively charged protons. Neutrons had no electric charge and a mass about the same as a proton.



The current model

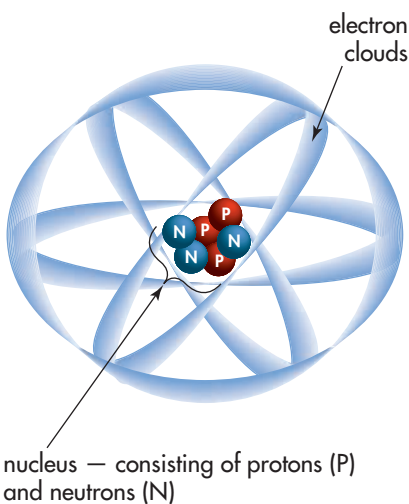
The model of the atom accepted today consists of a tiny, dense **nucleus**, made up of **protons** and **neutrons**, which is surrounded by **electrons**. It provides us with an explanation of many observable phenomena. However, it is likely that the model will continue to change or become more detailed as scientists continue with their research.

The key features of the current model of the atom are:

- An atom contains a positively charged nucleus. Negatively charged electrons surround the nucleus. The regions containing electrons are commonly referred to as electron clouds.
- The nucleus is very small and dense and contains protons and neutrons. Protons are positively charged and neutrons have no electric charge. These particles are held together by very large **nuclear forces**. The nucleus makes up almost all of the mass of an atom. In 1971, it was demonstrated that

protons and neutrons were made up of even smaller particles called quarks.

- An electron has about $\frac{1}{1800}$ of the mass of a proton or a neutron.
- The negative charge of an electron is equal in size to the positive charge of a proton.
- The number of electrons in an atom is equal to the number of protons in its nucleus. This means that an atom is electrically neutral.



A simplified sketch of the currently accepted structure of an atom

sciFacts

Lord Rutherford's model of the atom was based on experiments in which he fired

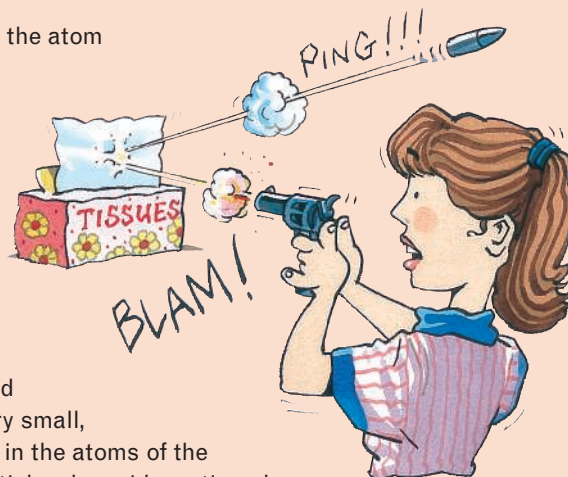
tiny positive alpha particles at very thin sheets of gold foil.

Most of the particles went straight through the gold foil and very few were reflected back.

He explained that the few particles that were reflected back were repelled by a very small,

positively charged nucleus in the atoms of the gold. Most of the alpha particles, he said, continued through the foil because each gold atom consists mainly of empty space. Lord Rutherford said later that his observations were

about as credible as if you had fired a 16-inch shell at a piece of tissue paper and it came back and hit you!



activities

REMEMBER

- 1 Describe, with the aid of a labelled diagram, the modern view of the structure of the atom.
- 2 Name the three important particles that make up an atom.
- 3 How are protons different from neutrons? How are they similar?
- 4 Describe the differences between protons and electrons.

THINK

- 5 Is the current model of the atom a theory or a fact? Explain your answer.
- 6 Was John Dalton's statement that atoms are indivisible correct? Explain.

INVESTIGATE

- 7 Find out more about one of the following scientists and describe their contributions to our knowledge about the structure of the atom. In your report you need to include:
 - full name, place of birth, date of birth and death
 - a brief description of the type of work the scientist did in his/her lifetime
 - their contribution to our understanding of the structure of the atom
 - the technology available to the scientist that enabled him/her to make the discovery
 - a description of how relevant the scientist's theory is to today's understanding of the structure of the atom.

Choose from: John Dalton, Sir William Ramsay, Marie Curie, J. J. Thomson, Henry Moseley, Max Planck, Eugen Goldstein, Lord Rutherford, Frederick Soddy, Sir James Chadwick, Niels Bohr, Louis de Broglie.

- 8 Dalton stated that atoms were indivisible, that is, they were the smallest particle possible. However, today we know of many particles smaller than neutrons and protons. Find out more about some of these particles and how they are investigated.

Searching for patterns

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 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.



The periodic table. At the time of publication, elements with atomic numbers up to 116 have been discovered. The properties of elements with atomic numbers of 117 and 118 have been predicted, just as Mendeleev made predictions about the properties of elements over 100 years ago. However, these 'missing' elements are yet to be produced. The scientists who claimed to have produced element 118 in 1999 have since withdrawn that claim.

	Group I	Group II							
	1.0		Relative atomic mass						
			Symbol						
			Atomic number						
Period 1	1 H Hydrogen								
Period 2	6.9 Li Lithium 3	9.0 Be Beryllium 4							
Period 3	23.0 Na Sodium 11	24.3 Mg Magnesium 12							
Period 4	39.1 K Potassium 19	40.1 Ca Calcium 20	45.0 Sc Scandium 21	47.9 Ti Titanium 22	50.9 V Vanadium 23	52.0 Cr Chromium 24	54.9 Mn Manganese 25	55.8 Fe Iron 26	58.9 Co Cobalt 27
Period 5	85.5 Rb Rubidium 37	87.6 Sr Strontium 38	88.9 Y Yttrium 39	91.2 Zr Zirconium 40	92.9 Nb Niobium 41	95.9 Mo Molybdenum 42	(99) Tc Technetium 43	101.1 Ru Ruthenium 44	102.9 Rh Rhodium 45
Period 6	132.9 Cs Caesium 55	137.3 Ba Barium 56	138.9 La* Lanthanum 57	178.5 Hf Hafnium 72	181.0 Ta Tantalum 73	183.9 W Tungsten 74	186.2 Re Rhenium 75	190.2 Os Osmium 76	192.2 Ir Iridium 77
Period 7	(223) Fr Francium 87	(226) Ra Radium 88	(227) Ac** Actinium 89	(261) Rf Rutherfordium 104	(262) Db Dubnium 105	(266) Sg Seaborgium 106	(264) Bh Bohrium 107	(269) Hs Hassium 108	(268) Mt Meitnerium 109

The group number corresponds to the number of electrons in the outer shell.

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

Legend



liquid at room temperature



gas at room temperature

All other naturally occurring elements are solid at room temperature.

*Lanthanides 58–71

140.1 Ce Cerium 58	140.9 Pr Praseodymium 59	144.2 Nd Neodymium 60	(147) Pm Promethium 61	150.4 Sm Samarium 62
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**Actinides 90–103

232.0 Th Thorium 90	(231) Pa Protactinium 91	238.1 U Uranium 92	(237) Np Neptunium 93	(242) Pu Plutonium 94
------------------------------	-----------------------------------	-----------------------------	--------------------------------	--------------------------------

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**.

			Group III	Group IV	Group V	Group VI	Group VII	Group VIII
								4.0 He Helium 2
			10.8 B Boron 5	12.0 C Carbon 6	14.0 N Nitrogen 7	16.0 O Oxygen 8	19.0 F Fluorine 9	20.2 Ne Neon 10
			27.0 Al Aluminium 13	28.1 Si Silicon 14	31.0 P Phosphorus 15	32.1 S Sulfur 16	35.5 Cl Chlorine 17	39.9 Ar Argon 18
58.7 Ni Nickel 28	63.5 Cu Copper 29	65.4 Zn Zinc 30	69.7 Ga Gallium 31	72.6 Ge Germanium 32	74.9 As Arsenic 33	79.0 Se Selenium 34	79.9 Br Bromine 35	83.8 Kr Krypton 36
106.4 Pd Palladium 46	107.9 Ag Silver 47	112.4 Cd Cadmium 48	114.8 In Indium 49	118.7 Sn Tin 50	121.8 Sb Antimony 51	127.6 Te Tellurium 52	126.9 I Iodine 53	131.3 Xe Xenon 54
195.1 Pt Platinum 78	197.0 Au Gold 79	200.6 Hg Mercury 80	204.4 Tl Thallium 81	207.2 Pb Lead 82	209.0 Bi Bismuth 83	(210) Po Polonium 84	(210) At Astatine 85	(222) Rn Radon 86
(269) Uun Ununnilium 110	(272) Uuu Unununium 111	(277) Uub Ununbium 112	(284) Uut Ununtrium 113	(285) Uuq Ununquadium 114	(288) Uup Ununpentium 115	(289) Uuh Ununhexium 116	Uus 117	Uuo 118

Lanthanides (cont.)

152.0 Eu Europium 63	157.3 Gd Gadolinium 64	158.9 Tb Terbium 65	162.5 Dy Dysprosium 66	164.9 Ho Holmium 67	167.3 Er Erbium 68	168.9 Tm Thulium 69	173.0 Yb Ytterbium 70	175.0 Lu Lutetium 71
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Actinides (cont.)

(243) Am Americium 95	(247) Cm Curium 96	(245) Bk Berkelium 97	(251) Cf Californium 98	(254) Es Einsteinium 99	(253) Fm Fermium 100	(256) Md Mendelevium 101	(254) No Nobelium 102	(257) Lr Lawrencium 103
--------------------------------	-----------------------------	--------------------------------	----------------------------------	----------------------------------	-------------------------------	-----------------------------------	--------------------------------	----------------------------------

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 uncanny 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 on pages 34–5 includes the **names**, **symbols** and **atomic numbers** of all the known 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.

Properties of eka-silicon and germanium

Properties of eka-silicon as predicted by Mendeleev	Properties of germanium which was 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

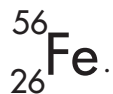
Counting sub-atomic particles

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:



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

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



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 I elements are known as the **alkali metals**. The alkali metals all react strongly with water to form basic solutions.
- Group II elements are referred to as the **alkaline earth metals**.
- Group VII elements are known as the **halogens**. The halogens are brightly coloured elements. Chlorine is green, bromine is red-brown and iodine is silvery-purple.
- Group VIII 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.



Illuminated signs use tubes filled with the noble gas neon.

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**. Examples of these elements include silicon, boron and germanium.

experiment

> CHEMICAL PROPERTIES OF METALS AND NON-METALS

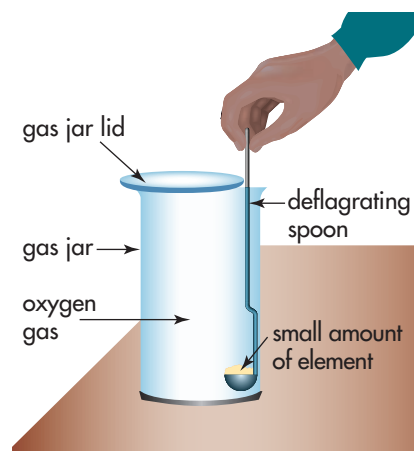
You will need:

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.
- 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

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.

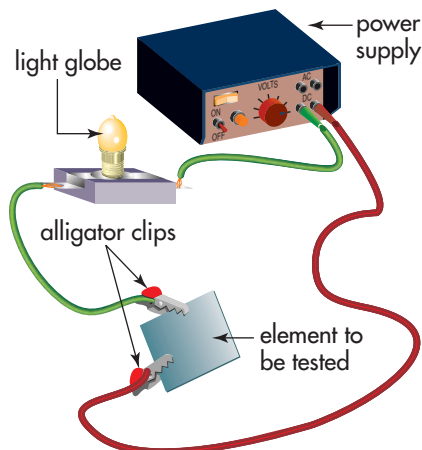


experiment

> COMPARING THE PROPERTIES OF TWO METAL FAMILIES

You will need:

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



Circuit used to measure electrical conductivity

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.

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.

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

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 on the right.

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 I to V and increases for groups V to VIII	generally increases then decreases
reactivity	metals become more reactive and non-metals become less reactive	is high, then decreases and then increases. Group VIII elements are inert and do not react.
metallic character	increases	decreases

REMEMBER

- 1 State whether the following statements are true or false.
 - (a) The noble gases are found in group VIII.
 - (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 II, period 3?
 - (b) group VII, period 2?
 - (c) group I, period 4?
 - (d) group VIII, 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.

[illegible]

- (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) ${}^{12}_{6}\text{C}$
 - (b) ${}^{65}_{30}\text{Zn}$
 - (c) ${}^{40}_{18}\text{Ar}$
 - (d) ${}^{197}_{79}\text{Au}$
 - (e) ${}^{238}_{92}\text{U}$.

8 Why is it useful to display the elements as a periodic table rather than as a list?

- 9** Think of a rhyme, poem or song that can help you learn the names of the first 20 elements in order.

10 Scientists have created all the elements beyond element 92. Find out how they have been made.

- 11** 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.
- 12** 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.

Inside the nucleus

At the centre of every atom is a tiny, solid core called the nucleus. Within the nucleus, protons and neutrons are usually held together by incredibly strong forces. Some of the mysteries of radioactivity can be unravelled by taking a closer look inside the nucleus.

Counting neutrons

All atoms of a particular element have the same number of protons. However, often the number of neutrons in atoms of the same element is different. Such atoms have the same atomic numbers but different mass numbers. Atoms of the same element with different mass numbers are called **isotopes**. Most elements exist as two or more isotopes. These isotopes all have the same chemical properties, but slightly different masses.

Some examples of stable and radioactive isotopes

Element	Symbol	Number of protons	Number of neutrons	Stable or radioactive
carbon-12	C	6	6	stable
carbon-14	C	6	8	radioactive
uranium-235	U	92	235	radioactive
uranium-238	U	92	238	stable

In most atoms, the protons and neutrons found in the nucleus are held together very strongly. The nuclei of these atoms are said to be **stable**. However, in some atoms the neutrons and protons in the nucleus are not held together strongly. These nuclei are **unstable**. Consequently, some isotopes of elements are stable and some are unstable. Isotopes that are unstable decay to form other elements. These isotopes are said to be radioactive and are called radioactive isotopes, or **radioisotopes**. For example, two isotopes of carbon, carbon-12 and carbon-14, have identical chemical properties. However, the nucleus of carbon-14 is not stable and disintegrates naturally. Carbon-12 is a stable isotope while carbon-14 is a radioactive isotope.

Natural radioactivity is radioactivity emitted from matter without energy being supplied to atoms. There are about 50 isotopes that emit radioactivity naturally. They exist in the air, in water, in living things and in the ground. Most radioactive isotopes (about 2000 in total) are made radioactive artificially by bombarding their atoms with sub-atomic particles like protons and neutrons.

Three of a kind

The energy emitted by radioactive substances is called **nuclear radiation** because it comes from the nucleus. Lord Rutherford showed that there were three different types of nuclear radiation: **alpha particles**, **beta particles** and **gamma rays**.

Alpha particles are helium nuclei that contain two protons and two neutrons. Alpha particles are positively charged. They cannot travel easily through materials and can be stopped by a sheet of paper or human skin. They pose little hazard to the external body but can cause serious damage if breathed in, eaten or injected. The symbol for alpha particles is α .

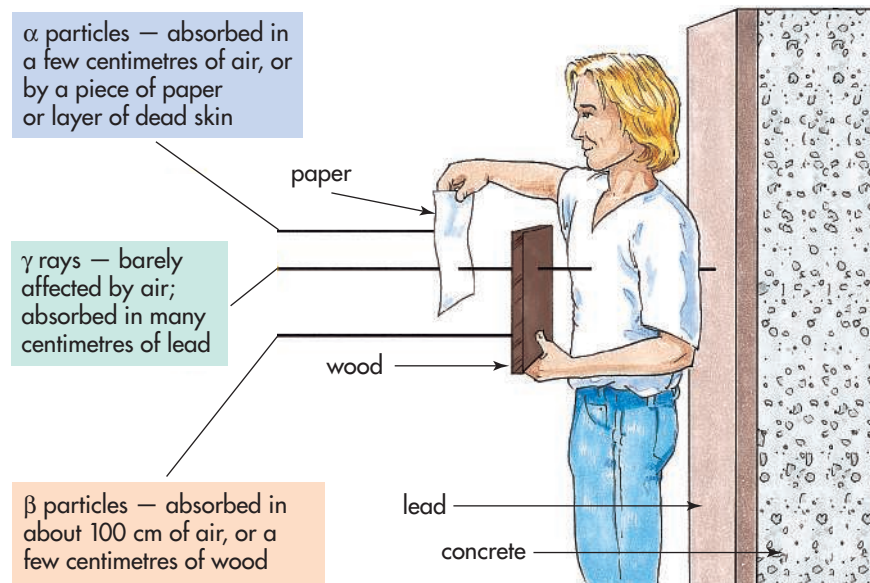
Beta particles are the same size and mass as electrons, can have a negative or positive electric charge and can travel at speeds as high as 99 per cent of the speed of light. Beta particles can penetrate human skin and damage living tissue, but they can not penetrate thin layers of plastic, wood or aluminium. The symbol for beta particles is β .



The National Medical Cyclotron in Sydney is used to make radioisotopes for use in hospitals.

Gamma rays are not particles, but bursts of energy released after alpha or beta particles are emitted. Gamma rays travel at the speed of light and are highly penetrating.

They can cause serious and permanent damage to living tissue and can be stopped only by a thick shield of lead or concrete. The symbol given to gamma rays is γ .



The different penetrating powers of alpha (α), beta (β) and gamma (γ) radiation

sciFacts

French physicist Henri Becquerel accidentally discovered radioactivity while investigating the fluorescence of uranium salts in 1896. When he developed a photographic plate that had been in a drawer near his bench top, he found that it had been fogged up by radiation from the uranium salts.

This effect of radioactivity is now used in a protective device worn by people who work with radioactive materials. The 'fogging' of the film in this device measures the amount of radioactivity they have been exposed to.

Becquerel was the first scientist to report the effects of radioactivity on living tissue. He suffered from burns on his skin as a result of carrying a small quantity of the element radium in his pocket.

activities

REMEMBER

- How are isotopes of the same element different from each other?
- Why are the isotopes of some elements radioactive?
- Write down the type of nuclear radiation described by the following statements.
 - a radioactive particle that has the same size and mass as an electron
 - a radioactive particle that is made up of two protons and two neutrons
 - the type of radiation that can penetrate the human body and can be stopped only by a thick shield of lead or concrete
 - a radioactive particle that can travel almost at the speed of light

USING DATA

- A scientist wished to determine the type of radiation emitted by

a radioisotope. She had three materials (paper, plastic and lead) and an instrument called a Geiger counter, which detects nuclear radiation. She covered the radioisotope with each of the three materials and measured the radiation that passed through each material. The results of her experiment are shown in the table below.

Results of radioactivity experiment

Material	Effect on Geiger counter readings
paper	no effect on readings
plastic	readings fell by two-thirds
lead	large fall in readings

What type of nuclear radiation does this radioisotope emit? Explain your answer.

THINK

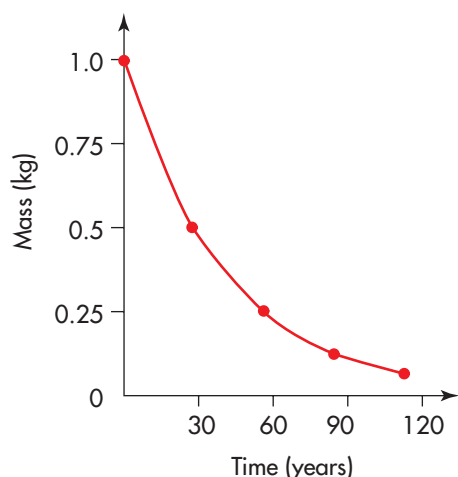
- About 0.01 per cent of the potassium in your body is the radioisotope $^{40}_{19}\text{K}$.
 - How many protons and neutrons are in each atom of this radioisotope?
 - The stable nuclei of potassium atoms have one less neutron than the nuclei of potassium's unstable radioisotope. Write down the complete symbol for the stable isotope of potassium.
- Are the atoms $^{230}_{93}\text{X}$ and $^{239}_{94}\text{Y}$ isotopes of the same element? Explain.
- An atom of uranium-238 ($^{238}_{92}\text{U}$) decays by emitting a single radioactive particle. The atom formed as a result of the decay is thorium-234 ($^{234}_{90}\text{Th}$). What type of radioactive particle is emitted? Explain how you got your answer.

Using radioactivity

In 1903, Marie Curie, her husband Pierre, and Henri Becquerel were awarded the Nobel Prize in Physics for their discovery of radioactivity and their work on uranium. Little did they know that their discoveries and investigations would change the course of history. They could not have imagined that their work would lead to the development of nuclear weapons capable of killing millions of people, nuclear power plants that generate electricity, and radioactive isotopes that can be used to treat cancers and detect life-threatening illnesses.

The lives and half-lives of radioisotopes

The nuclei of different radioactive substances decay at different rates. Some radioisotopes decay in a few seconds, while others take thousands of years. The time taken for half of all the nuclei in a sample of a radioisotope to disintegrate or decay is known as its **half-life**.



A graph showing the radioactive decay of strontium-90, which has a half-life of 28 years

What's the use?

Radioisotopes are used in industry and research, and also have medical applications. They can be used as radioactive 'tracers' to follow the movement of substances through liquids (for example, sediment movement in rivers and the movement of substances in the blood).

Naturally occurring radioisotopes can be used to calculate the age of samples from archaeological sites. The radioisotope of carbon, for example, occurs naturally in the atmosphere as a component of carbon dioxide. During photosynthesis, plants take in carbon dioxide. The element carbon, including the radioisotope carbon-14, becomes part of the plant's cells and part of the cells of animals that consume the plants. When the plant dies, it takes in no more carbon-14. The carbon-14 that is already present begins to decay. Knowing that the half-life of carbon-14 is 5730 years, it is possible to estimate the age of a dead plant or animal by measuring how much of the carbon in its remains is radioactive. Materials excavated from archaeological sites often include organic carbon. It is possible to test how much carbon-14 remains in these samples, and from this information calculate how old the samples are. This technique is called **radiocarbon dating**.

Radioactive isotopes are also used in smoke detectors, soil analysis, pollution testing, measuring the thickness of objects and criminology.

Radioisotopes and nuclear power

The radioactive properties of uranium are used in the generation of electricity in **nuclear reactors**. Uranium is an element that occurs naturally in most rocks, although usually in very small amounts.



A nuclear power plant

Australia is one of several countries that have large high-grade deposits of uranium. Uranium is converted to uranium dioxide and then sealed in rods, called **fuel rods**. The uranium undergoes a **fission** reaction in the reactor when neutrons are fired at the radioactive uranium. This causes the uranium nuclei to split and form two new elements, releasing neutrons, radiation and heat in the process. This heat energy is used to heat water to produce steam, which is used to turn the turbines that generate the electricity.

Fast breeders

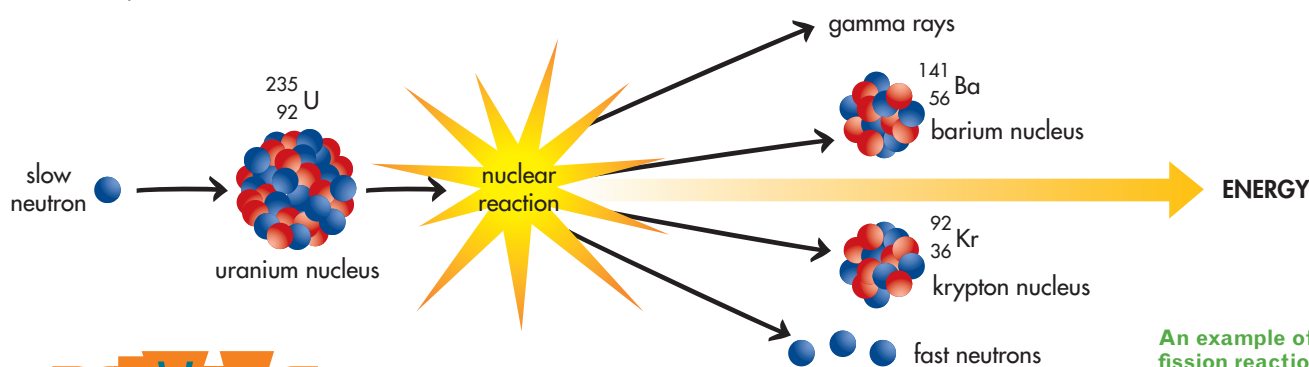
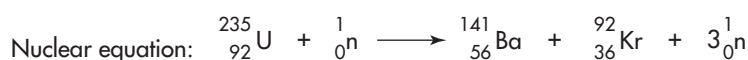
In some countries fast breeder reactors use the artificial radioisotope plutonium-239 as a fuel. Plutonium-239 is made by bombarding uranium-238 with fast moving neutrons (that's why the term 'fast breeder' is used). The plutonium-239 produced is also used to produce nuclear weapons.

Nuclear waste

The used fuel rods in a nuclear reactor are radioactive and contain a mixture of radioisotopes. Some of the waste radioisotopes have

half-lives of only minutes, while others have half-lives of thousands of years. These waste products are currently sealed in steel containers or glass blocks and stored in power stations or buried deep at sea or underground away from ground water. There is, however, still no permanent solution to the problem of disposing of nuclear waste.

It has been suggested that nuclear waste should be sent by rocket to the sun or into outer space. However, the risk of a rocket carrying nuclear waste exploding before leaving the Earth's atmosphere makes that solution very risky.

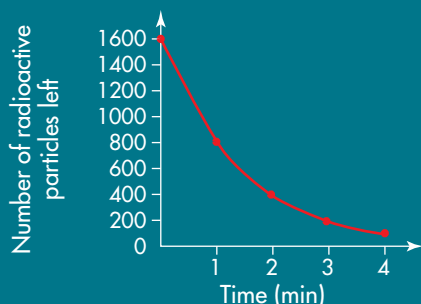


An example of a nuclear fission reaction

activities

USING DATA

- 1 The graph below shows the decay of a radioisotope over four minutes.



Graph of radioactive decay of an isotope

- What is the half-life of this isotope?
- How many radioactive particles would be left after five minutes?
- When the decay takes place in a sealed container, helium gas is collected. Name one type of radiation produced in the decay.

REMEMBER

- What is the name of the nuclear reaction that takes place in nuclear power stations?
- Describe three uses of radioactive elements.

INVESTIGATE

- On a cold spring morning in April 1986, a nuclear reactor at Chernobyl, in what is now Ukraine, exploded and released radioactive gases into the atmosphere. Find out and report on:
 - how the disaster happened
 - how it affected the workers at the power plant and the surrounding towns and villages
 - the attempts to reduce or control the damage caused by the radiation

- the long-term effects of the explosion.

- 5 What is radioactive fallout?

CREATE

- Research the topic 'nuclear reactors' and find out:
 - what they are built from
 - what fuel rods and control rods are
 - what type of nuclear reaction occurs in the reactor
 - how the reactor is kept cool
 - how electricity is generated
 - what kinds of safety features are used.

Use simple materials like cardboard, wire and papier-mâché to build a model that incorporates the information you have found. Ensure that the main parts of your model are labelled.

Health: Radioactivity — a two-edged sword

As far as the human body is concerned, radioactivity is a two-edged sword. On the one hand, radioisotopes can be used to treat cancers and detect life-threatening illnesses. Yet on the other hand, radioisotopes can damage or destroy living tissue, causing serious and often fatal diseases and birth defects.

Radiotherapy in the treatment of cancer

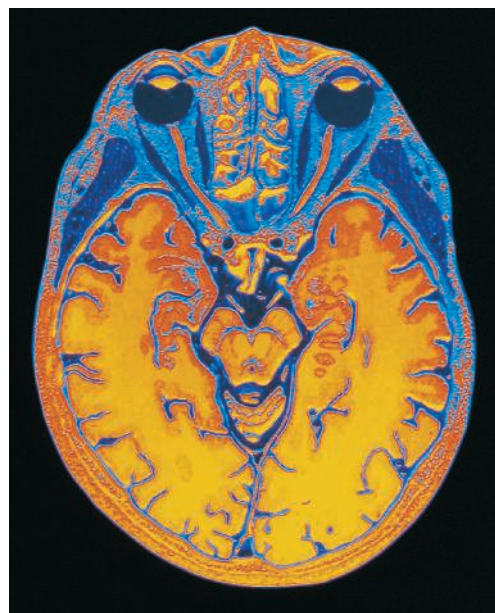
Radiotherapy is the use of radioisotopes, or other radiation such as X-rays, to kill cancer cells or prevent them from multiplying.

It can be targeted at a small area so that surrounding tissue is not damaged. Radiotherapy is often used along with other treatments such as surgery or chemotherapy.

Radiation can be directed at the cancer by a machine like the one below. This method is known as **external radiotherapy**. The other method, known as **internal radiotherapy** or **brachytherapy**, involves placing radioisotopes inside the body at or near the site of the cancer. In some cases both methods are used. The type of treatment depends on the type of cancer, its size and location as well as the general health of the patient.



A patient undergoing a PET scan of her brain



A PET image of the human brain

Radioisotopes in the diagnosis of disease

Radioactive substances may be inserted into the body to detect or identify the cause of disease. The radiation produced by the substance while it is in the part of the body under investigation is measured to diagnose the problem.

Some radioisotopes can be used to obtain images of parts of the body. The gamma rays emitted by these radioisotopes are used to produce the images. PET (positron emission tomography) scans use cameras surrounding the patient to detect gamma rays coming from radioisotopes injected into the body.



Preserving food

If you've ever suffered from food poisoning you will understand why it is necessary to keep food from spoiling. Food in sealed containers can be preserved by exposing it to gamma radiation. The radiation kills the microorganisms in the food and keeps it from spoiling. However, there has been much controversy about the safety of food that has been treated in this way.

Some of the radioisotopes used in the treatment and diagnosis of disease.

Radioisotope	Use	Half-life
phosphorus-32	used to treat leukaemia	14.3 days
cobalt-60	used in radiotherapy for treating cancer	5 years
barium-137	diagnosis of digestive illnesses	2.6 minutes
iodine-123	monitoring of thyroid and adrenal glands, and assessment of damage caused by strokes	13 hours
iodine-131	diagnosis and treatment of thyroid problems	8 days
iron-59	measurement of blood flow and volume	46 days
thallium-201	detection of damaged heart muscles	3 days



Radioactive decay

You will need:
graph paper

- The half-life of the radioisotope iodine-131 is 8 days. Calculate the amount of iodine-131 left after 8, 16, 24, 32, 40, 48, 56, 64, 72 and 80 days if 100 g is given to a patient to treat a thyroid problem. Present your information in a table.
 - Draw a graph showing how the radioisotope decays. Make the horizontal axis represent time and the vertical axis represent the amount of radioisotope left.
- What fraction of the iodine-131 is left after:
 - 8 days?
 - 16 days?
 - 24 days?
 - 80 days?
 - Why is it difficult to store radioisotopes with short half-lives?

The dark side of radioactivity

Nuclear radiation can have a devastating effect on living things. Exposure to large doses of radiation can cause immediate effects like nausea, headaches, vomiting and diarrhoea. Nuclear radiation damages living cells, and too much exposure can lead to diseases like leukaemia and cancer. It can also damage the reproductive mechanisms in cells, including DNA (see chapter 8), leading to birth defects in the offspring of exposed organisms. It is ironic that Marie Curie herself died of leukaemia at the age of 67. Her illness was almost certainly caused by her constant exposure to radioactivity.



Cigarette smoke contains radioactive isotopes, including radium-226, polonium-210 and lead-210. When a smoker inhales, these radioactive isotopes are deposited in the lungs.

activities

REMEMBER

- What is radiotherapy and how does it prevent the spread of cancer through the body?
- How is internal radiotherapy different from external radiotherapy?
- How do radioisotopes used in food preservation stop food from spoiling?

THINK

- Is iodine-131 a more stable radioisotope than barium-137? Explain.
- The use of barium-137 in the diagnosis of digestive illnesses involves the patient drinking it in a

syrup. What property of barium-137 makes its use quite safe?

- Is cobalt-60, used in the treatment of cancer, more likely to be used in external radiotherapy or internal radiotherapy? Use the information in the table to explain your answer.

IMAGINE

- It was Marie Curie who invented the word 'radioactivity' to describe the disintegration of the nucleus. What would Marie Curie really think if she were still alive today and could see both the good and bad effects of radioactivity? Would she be proud? Would she be disappointed? Would she be angry? Imagine that you are Curie and write an open letter explaining your feelings.

INVESTIGATE

- Radiotherapy is an effective method of treating cancer. However, it has a number of side effects. Find out what the side effects are.
- Suppose you have been asked to write a report to discuss the following proposal: 'The use of radioactive elements should be banned in Australia'. Give both sides of the argument, but present a conclusion for or against the proposal. For more information visit the website for this book and click on the Uranium Information Centre weblink (see 'Weblinks', page 305).
You should also search the Internet using keywords such as 'uranium', 'radiation', 'mining', 'nuclear' and 'waste' to find other useful sites.

Small but important

When atoms come in contact with each other, 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:

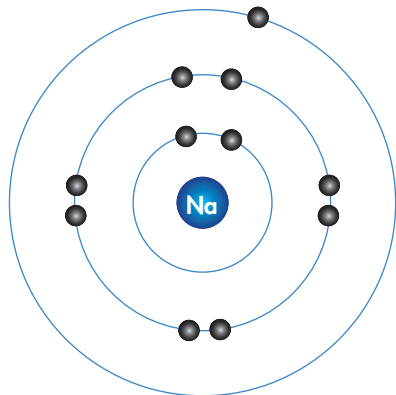
the **n th shell** holds a maximum of **$2n^2$** electrons.

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

To work out the electron arrangement in a particular atom, you need to remember that electrons occupy the two innermost shells first. However, once the first two shells are filled, the remaining electrons must then begin to fill the third shell. For example, the 11th electron in the sodium atom must be in the third shell because the other 10 electrons have filled the first two shells — with two electrons in the first shell and eight in the second shell.

The electron arrangement of an atom can be written by showing the number of electrons in each shell separated by commas. For example:

sodium 2, 8, 1
oxygen 2, 6.



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 is the same as the group number in the periodic table. Hence, all elements in group I have one electron in their outer shell and all elements in group VIII (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 on pages 34–5 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.

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.

experiment

> FLAME TESTS

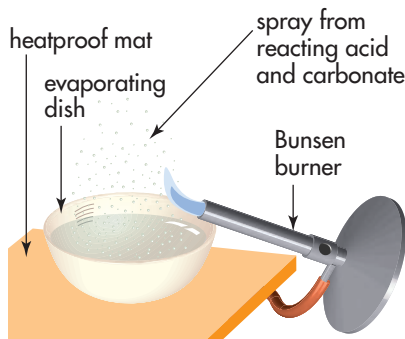
You will need:

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 on the right. Observe the change in the colour of the flame.

- Repeat using the other carbonates. Use a different evaporating dish each time.
- Record the colours produced by the different carbonates in a suitable table.
 - Flame tests provide evidence that electrons do actually occupy different energy levels. Why do elements produce different colours?
 - Is it the metal part of the compound or the carbonate part (carbon and oxygen) that produces the colour? How do you know?



activities

REMEMBER

- What is the name given to the different energy levels that electrons can be found in?
- How many electrons are needed to fill:
 - the first shell?
 - the second shell?
 - the third shell?
 - the fourth shell?
- What is meant by the term 'outer shell'?
- What is the maximum number of electrons allowed in the outer shell of an atom?
- What information about the electron arrangement is given by the group number of an element?
- What information about the electron arrangement is given by the period number of an element?

THINK

- Name the elements that have an electron arrangement of:
 - 2, 4
 - 2, 8, 5
 - 2, 8, 8, 2
 - 2, 8, 8, 2
- Write the electron arrangement for each of the following elements:
 - boron
 - neon
 - potassium
 - fluorine
 - silicon
- If an element has one electron in its outer shell, is it a metal or a non-metal? Explain your answer.
 - If an element has seven electrons in its outer shell, is it a metal or a non-metal? Explain your answer.
 - What is special about elements that have eight electrons in their outer shell?
- What experimental evidence is there to show that electron shells actually exist?

INVESTIGATE

- 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.

When atoms meet . . .

When we use salt to add flavour to a meal, we are adding a **compound** formed from two poisonous elements, sodium and chlorine. This compound has physical and chemical properties that are quite different from its constituent elements.

It's the outer shell that counts



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.

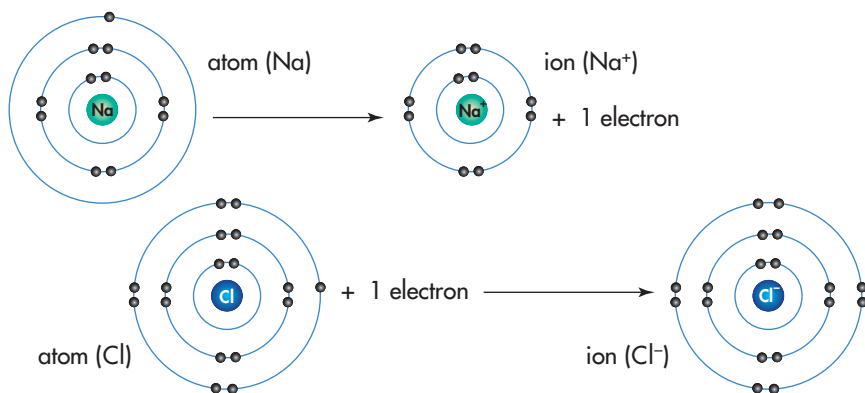
It's great to be noble

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 the noble gases. Chemical reactions can allow atoms to obtain this arrangement. The table below shows the electron arrangement of a few elements.

Notice how 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.

The electron arrangement of some elements

Element	O	F	Ne	Na	Mg	S	Cl	Ar	K
Electron arrangement	2, 6	2, 7	2, 8	2, 8, 1	2, 8, 2	2, 8, 6	2, 8, 7	2, 8, 8	2, 8, 8, 1



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**.

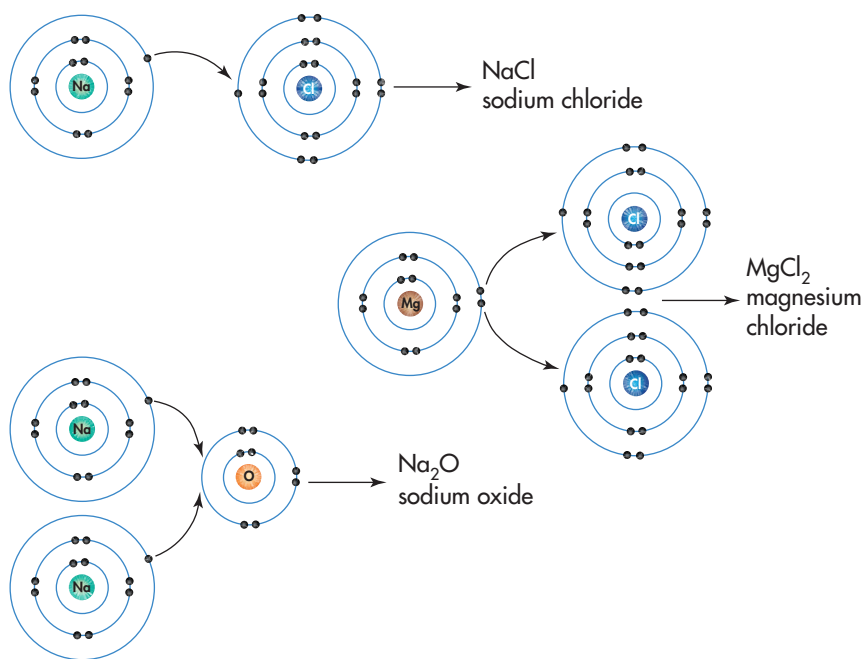
The diagram on the left shows how sodium and chlorine atoms lose and gain electrons respectively to form ions. Note that the sodium atom becomes a sodium ion and that the chlorine atom becomes a chloride ion. (When non-metals form ions, the suffix '-ide' is used.)

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.

REMEMBER

- 1 What is an ion?
- 2 Why do ions form?
- 3 What is a positively charged ion called?
- 4 What is a negatively charged ion called?
- 5 What properties do most ionic compounds have in common?
- 6 What kinds of elements combine to form ionic compounds?

THINK

- 7 Write the symbol for the ion formed by each of the following elements. You can turn back to the periodic table on pages 34–5.
 - (a) sodium
 - (b) nitrogen
 - (c) potassium
 - (d) fluorine
- 8 How many electrons have been gained or lost by the following ions?
 - (a) Pb^{4+}
 - (b) Br^-
 - (c) Cr^{3+}
 - (d) Se^{2-}
- 9 Name the ions in 'Think' question 8.
- 10 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

- 11 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.

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.

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.



Coal contains the element sulfur. When coal is burnt 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.

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 on the 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 opposite 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

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•

which elements combine to form a covalent compound. It also determines the **chemical formula** of the compound.

sciFacts

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 .

Name and formula	Atoms	Compound	Structural formula	Explanation
Chlorine Cl_2			$\text{Cl} - \text{Cl}$ <i>Note: The line represents a sharing of two electrons and is called a single covalent bond.</i>	Each chlorine atom needs to share one electron to gain a full outer shell.
Hydrogen chloride HCl	$\text{H} \cdot + \cdot \ddot{\text{Cl}}:$	$\text{H} : \ddot{\text{Cl}}:$	$\text{H} - \text{Cl}$	Both the hydrogen and the chlorine atom need to share one electron to gain a full outer shell.
Oxygen O_2			$\text{O} = \text{O}$ <i>Note: The double line represents a double covalent bond.</i>	Each oxygen atom needs to share two electrons to gain a full outer shell.
Nitrogen N_2			$\text{N} \equiv \text{N}$ <i>Note: The triple line represents a triple covalent bond.</i>	Each nitrogen atom shares three electrons to gain a full outer shell.
Water H_2O	$\text{H} \cdot + \cdot \ddot{\text{O}}:$			Each hydrogen atom needs one electron and the oxygen atom needs two electrons to gain a full outer shell.
Carbon dioxide CO_2			$\text{O} = \text{C} = \text{O}$	Each oxygen atom needs two electrons and the carbon atom needs four electrons to gain a full outer shell.

The formation of covalent molecules

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.



Drawing electron dot diagrams for covalent compounds

- Draw electron dot diagrams like those in the table above for the following covalent compounds: hydrogen fluoride (HF), methane (CH_4), phosphorus chloride (PCl_3) and hydrogen sulfide (H_2S).

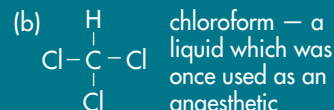
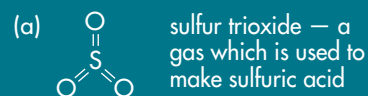
1. What pattern emerges between the structural formula of the compound and the number of electrons involved in bonding?
2. State whether the covalent bonds in the compounds are single, double or triple bonds.

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 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.



- 7 Draw electron dot diagrams to show how the following covalent compounds form.
 - (a) tetrachloromethane (CCl_4)
 - (b) ammonia (NH_3)
 - (c) carbon disulfide (CS_2)
- 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.

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 like 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 (e.g. 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.

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.

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_8
phosphorus	P_4

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 I	1
group II	2
group III	3
group IV	4
group V	3
group VI	2
group VII	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 table below and the table on page 54 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 $\text{Ca}_3(\text{PO}_4)_2$.
- Note the use of brackets in the formula to show that more than one molecular ion is needed to balance the electric charge.

The ionic compound formula game

You will need:

a set of playing cards with the name and valency of each of the positive and negative ions listed in the tables on pages 53 and 54. 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 the cards they have in their hands. 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.
- Write a list of the formulae and the name of the compounds formed.
 - What is the best strategy to win the game?
 - Did you find the game useful in learning the formulae of compounds? Explain.

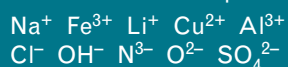
activities

REMEMBER

- What is a chemical formula?
- What is a molecular formula?
- What does the formula of a compound tell you about the compound?
- Write the symbols for the following elements: sodium, hydrogen, potassium, lead, chlorine, iodine and sulfur.
- Which elements are present in each of the following compounds?
 - HNO_3
 - NaHCO_3
 - FeS
- How is the valency of an element determined?
- How many chlorine (Cl^-) ions would be required to combine with each of the following ions to form an ionic compound?
 - calcium (Ca^{2+})
 - aluminium (Al^{3+})
 - silver (Ag^+)
- Write down the valencies for the following elements: sodium, hydrogen, lead, chlorine, iodine, magnesium and sulfur.

THINK

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



- The chloride ion has the same valency as the sodium ion. However, it has a different electrovalency. Why?
- Write a formula for each of the following.
 - oxygen gas
 - chlorine gas
 - lead
 - nitrogen oxide
 - zinc oxide
 - potassium sulfate
 - calcium hydroxide
- Name the following compounds.
 - NH_4Cl
 - KI
 - $\text{Al}(\text{NO}_3)_3$
 - $\text{Fe}(\text{OH})_3$
 - KHCO_3
 - MgCO_3
 - HNO_3
- Explain why group VIII is not listed in the table on page 52.

IMAGINE

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

CREATE

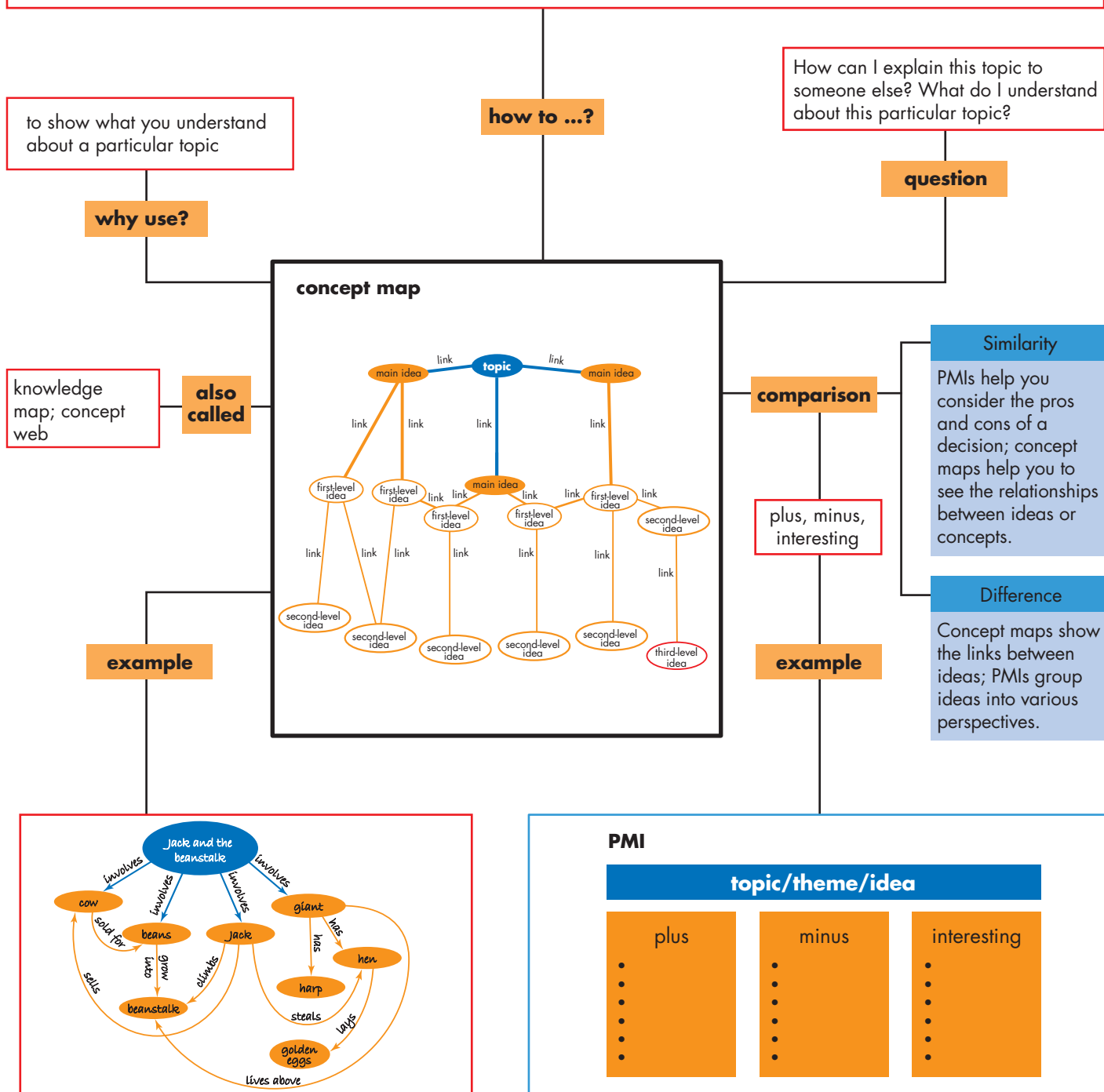
- Create your own ionic compound formula game. It could be an improved version of the game in the 'Try this' above. However, it does not have to be a card game.

Thinking tools:

Concept maps and Plus, minus, interesting

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.



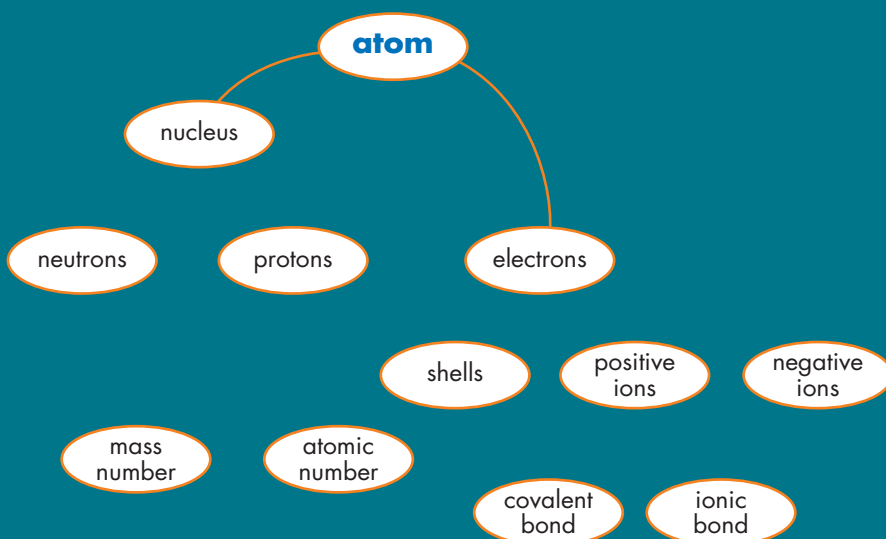
Adapted with permission from Hawker Brownlow Education © 2005 modellearning.com *Thinking Skills and EyeQ: Visual Tools for Raising Intelligence* by Ian Harris, Oliver Caviglioli and Bill Tindall

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 on the right into your workbook and complete it by adding the 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 Construct a concept map of ideas associated with radioactivity.

3 Create a PMI on radioactivity using the diagram at right as a starting point.

radioactivity

plus

- can be used to treat cancer
-
-
-
-
-

minus

- radioactive isotopes can be used in nuclear weapons
-
-
-
-
-

interesting

- radioactivity was discovered by accident
-
-
-
-
-

4 A SWOT analysis, like a PMI, is a visual tool that helps you think about different viewpoints related to an issue or topic. Work in a small group to perform a SWOT analysis to represent the positive and negative aspects of one of the following issues. (See page 230 for SWOT 'How to' instructions.)

(a) nuclear power for Australia

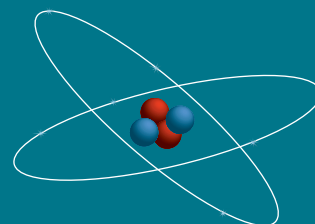
(b) exporting uranium to other countries.

SWOT analysis

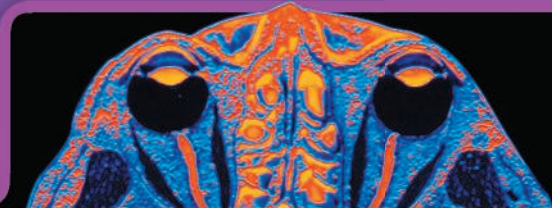
strengths	weaknesses	
opportunities	issue	threats



Radioactive materials are classified as dangerous goods. The international symbol for radioactivity must be displayed wherever they are used.



Looking back

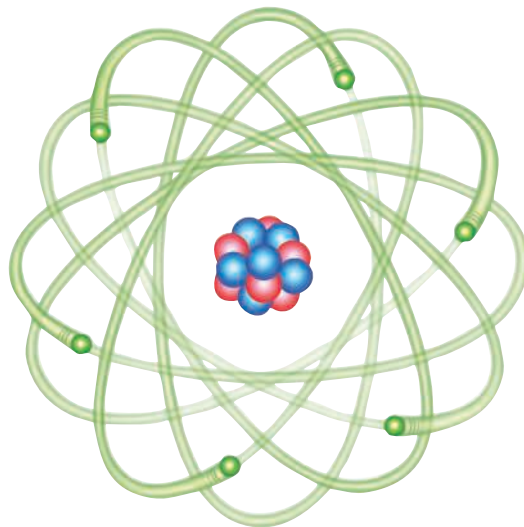


1. Complete the word puzzle below. Use the following clues to find the words. The words may be spelt across, down, diagonally or even backwards.

G	S	A	T	O	M	I	C	R	C	S
R	A	E	P	O	T	O	S	I	N	D
O	G	L	O	B	M	Y	S	G	I	O
U	N	A	I	P	P	I	M	H	Z	I
P	I	L	O	N	M	L	E	T	B	R
S	D	U	R	E	L	A	T	I	V	E
E	N	M	N	G	E	K	A	Y	Y	P
D	O	R	B	O	L	L	L	B	O	K
E	B	O	U	L	B	A	R	I	U	M
G	H	F	G	A	O	S	O	L	I	D
R	V	H	X	H	N	S	S	A	M	H

- The shorthand way of writing the name of an element.
- Most elements in the periodic table are found in this physical state.
- The name given to the rows in the periodic table.
- The name given to the columns in the periodic table.
- The non-metals are found on this side of the periodic table.
- The term given to the average of the masses of the isotopes of an element (three words).
- The term that describes the attraction between two atoms as a result of sharing or transferring electrons.
- The element with the symbol Zn.
- The term that describes an element with the same atomic number but different mass number.
- Group I elements are known as this type of metal.
- The element that has the atomic number 56.
- The term used to describe the shorthand way of writing the name of a compound.
- The name of the scientist who developed the theory of electron shells.
- Each element on the left-hand side of the periodic table is one.
- The name used to describe each of the group VII elements.
- The name given to describe each element in the unreactive group of gases in the periodic table (two words).
- A substance made up of two or more elements chemically combined.

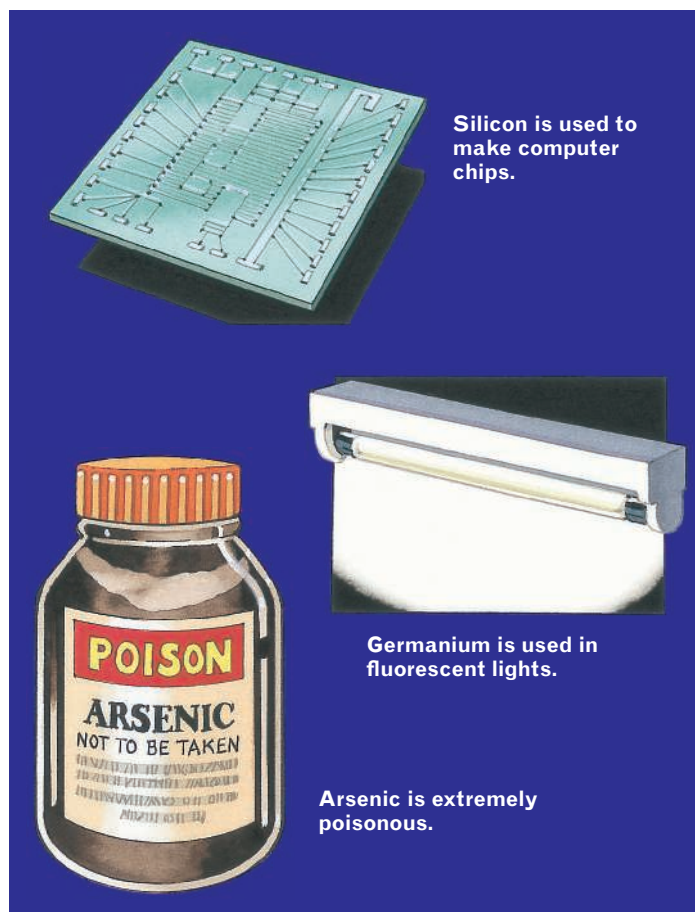
2. The diagram below represents a model of a neutral atom.



- Which two types of particles make up the nucleus of the atom?
 - Which particles are shown orbiting the nucleus in the atom?
 - What features of atoms are not very well represented by this particular model?
 - To which element does this atom belong?
3. Describe the contributions of the following scientists to our understanding of the structure of the atom.
- J. J. Thomson
 - Lord Rutherford
 - Niels Bohr
4. The periodic table is a classification of all the known elements. What information is given by the group and period numbers on 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.
- $^{28}_{14}\text{Si}$
 - $^{52}_{24}\text{Cr}$
 - $^{197}_{79}\text{Au}$
 - $^{206}_{82}\text{Pb}$
 - $^{242}_{94}\text{Pu}$

Eat at Joe's

6. To which group of elements in the periodic table does the neon used in lighting belong?
7. As you move down the groups in the periodic table, how does the reactivity change for:
 - (a) metals?
 - (b) non-metals?
8. As you move across the periodic table, what changes occur in:
 - (a) atomic number?
 - (b) mass number?
 - (c) melting points?
 - (d) metallic character?
9. 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?



10. List the three forms of radioactivity and describe the nature and properties of each of them.
11. Radioisotopes have many uses.
 - (a) What property of radioisotopes makes them useful?
 - (b) Describe some of the beneficial uses of radioisotopes.
 - (c) Some radioisotopes are considered highly dangerous even after thousands of years. Why?
12. Two isotopes of the element carbon found naturally on Earth are carbon-12 and carbon-14.
 - (a) How is every atom of carbon-14 different from every atom of carbon-12?
 - (b) What features and properties do carbon-14 and carbon-12 have in common?
 - (c) Which of the two carbon isotopes is stable?
13. The half-life of strontium-90 is 28 years. If a 400 gram sample of strontium-90 was left to decay, how many grams of the sample would be left after:
 - (a) 28 years?
 - (b) 56 years?
 - (c) 84 years?
14. Explain how it is possible to use carbon-14 to estimate the age of the remains of a dead plant embedded in a rock.
15. Write electron arrangements for the following atoms: helium, silicon, argon, potassium, phosphorus.
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. Write formulae for the following substances:

(a) oxygen gas	(f) zinc chloride
(b) carbon dioxide gas	(g) iron(III) sulfide
(c) aluminium oxide	(h) sulfur dioxide
(d) sodium fluoride	(i) carbon
(e) calcium carbonate	(j) lead.