●●●●○ Level 4 · Science S4.6

Atoms, bonding and the periodic table

What atoms are made of, how they are arranged, and how they join.

Look inside the atom, follow how the picture of the atom changed, and learn why the periodic table has the shape it has. Then see how atoms join in salts, molecules, diamond and metals, and why each kind of bond gives a material its properties.

YOU ARE READY FOR THIS BOOK IF

You can name five elements and say whether each one is a metal.

One step up	S5.5 Bonding and structure
This book	**S4.6 Atoms, bonding and the periodic table**
One step down	S3.6 Elements, mixtures, reactions and acids

Contents

S4.6.1 Inside the atom

S4.6.2 How the model of the atom changed

S4.6.3 Isotopes

S4.6.4 Electron shells

S4.6.5 The periodic table

S4.6.6 Ionic bonding

S4.6.7 Covalent bonding

S4.6.8 Metals and alloys

Key words, A to Z

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S4.6.1 CHAPTER 1

Inside the atom

An atom is too small to see. How do we know what is inside it?

YOUR GUESS

Pick one before you read on. It is fine to be wrong.

- ☐ **A** Nothing is inside. An atom is the smallest thing there is.
- ☐ **B** A tiny centre called the nucleus, with even tinier electrons outside it.
- ☐ **C** One kind of particle, and it is positive.

IF THIS FEELS HARD, READ THIS FIRST

- Level 3, Particles, S3.5.1. It shows that everything is made of tiny particles.
- Level 3, Elements, mixtures, reactions and acids, S3.6.1. It says that an element has only one kind of atom.

BY THE END YOU CAN

- Give the charge, mass and place of protons, neutrons and electrons
- Work out the number of each particle from atomic and mass numbers

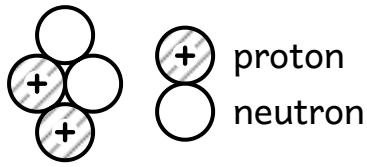
Everything around you is made of atoms. They are very small. More than a million atoms side by side would fit across 1 mm. No ordinary microscope can show one.

Scientists found what is inside an atom by experiments, and the next chapter tells how. This chapter gives the result. An atom has a tiny centre called the **nucleus**. Even smaller particles called **electrons** move outside it.

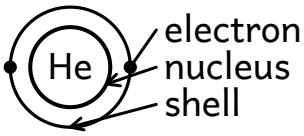
The nucleus holds two kinds of particle. A **proton** has a positive charge. A **neutron** has no charge. An electron has a negative charge.

DRAW IT FIRST

Build *a* helium *atom*



1 Start with the nucleus. Helium has 2 protons and 2 neutrons, packed tightly together.



2 Add the electrons. Two of them move round the nucleus on *a* shell. The picture is *a* model, and the shell is not *a* real ring.

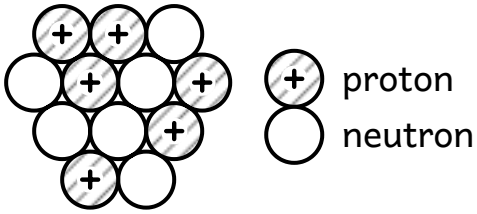
Charge and mass are the two things that tell the particles apart. Scientists compare them with *a* proton, so the numbers stay small. These are relative values, not kilograms.

Particle	Charge	Mass
proton	+1	1
neutron	0	1
electron	−1	≈ 0

Protons and neutrons are in the nucleus. Electrons are outside it. The sign ≈ means about. An electron has about $^{1}/_{1840}$ of the mass of *a* proton.

An electron is so light that we count its mass as almost nothing. Nearly all the mass of an atom is in the nucleus.

A whole atom has no charge. We say it is **neutral**. The protons carry the positive charge and the electrons the negative charge, and the two must cancel. So *a* neutral atom has the same number of protons as electrons. Helium has 2 protons and 2 electrons: +2 and −2 make 0.



A carbon nucleus, enlarged. It has 6 protons and 6 neutrons.

Every atom of one element has the same number of protons. This is the **atomic number**. Carbon always has 6 protons, so its atomic number is 6. An atom with 7 protons is nitrogen, never carbon. The number of protons decides which element an atom is.

The **mass number** is the number of protons plus the number of neutrons. These are the particles in the nucleus. A carbon atom with 6 protons and 6 neutrons has mass number 12. Electrons are left out because their mass is almost nothing.

SEE IT THREE WAYS

As a picture

mass number → 23

atomic number → 11

Na

In words

Chemists write the mass number above the atomic number, to the left of the symbol. This sodium atom has 11 protons and 23 particles in its nucleus.

In symbols

neutrons = mass number − atomic number = 23 − 11 = 12

WORKED EXAMPLE

A sodium atom has atomic number 11 and mass number 23. How many protons, electrons and neutrons does it have?

1. The atomic number is the number of protons. Sodium has 11 protons.
2. An atom is neutral, so it has as many electrons as protons. Sodium has 11 electrons.
3. Neutrons = mass number − atomic number = 23 − 11 = 12.

Answer: 11 protons, 11 electrons and 12 neutrons

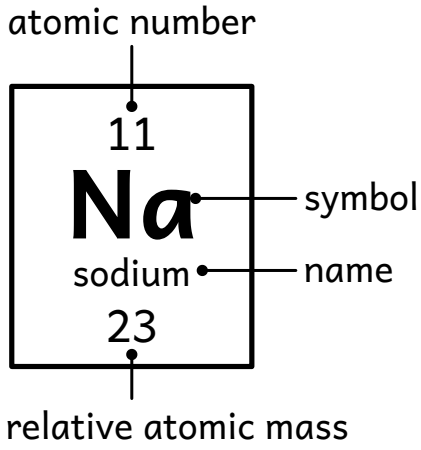
WORKED EXAMPLE

A chlorine atom has atomic number 17 and mass number 35. How many protons, electrons and neutrons does it have?

1. Protons = atomic number = 17.
2. Electrons = protons = 17, because the atom is neutral.
3. Neutrons = mass number − atomic number = 35 − 17 = 18.

Answer: 17 protons, 17 electrons and 18 neutrons

A periodic table shows the same numbers. Each box has the symbol and the name. It also has the atomic number and a number called the relative atomic mass. Chapter 3 explains why that mass is sometimes not a whole number.



The periodic table box for sodium.

TRY IT

Make a paper model of a lithium atom

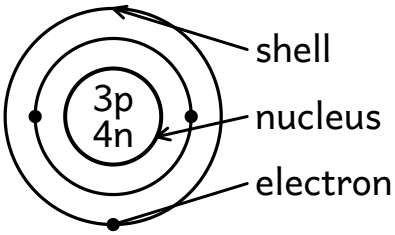
You need: a sheet of paper and a pencil, 3 dark beans or seeds, for protons, 4 light beans, seeds or small stones, for neutrons, 3 tiny seeds or grains of rice, for electrons.

Be safe: Do not eat the beans or seeds you use for the model. Keep small seeds away from young children.

1. Draw a small circle in the middle of the paper. It is the nucleus.
2. Put the 3 dark beans and the 4 light ones inside it. Count them.
3. Draw two rings round the nucleus, one inside the other.
4. Put 2 tiny seeds on the inner ring and 1 on the outer ring.
5. Count the particles in the nucleus. Count the electrons.

What you will see: The nucleus holds 7 beans, which is the mass number. It holds 3 dark beans, which is the atomic number. There are 3 electrons, as many as protons. The model is not to scale. If the nucleus were a bean 1 cm wide, the whole atom would be between 100 m and 1 km across.

If you cannot try it, this is what happens.



A WRONG IDEA MANY PEOPLE HAVE

~~An atom is a solid ball, full all the way through.~~

Why it feels right: A stone feels solid, so it seems that the atoms in it must be solid too.

The test that breaks it: Think of the bean model. If the nucleus is a bean 1 cm wide, the atom is between 100 m and 1 km across. The electrons are tens or hundreds of metres away. Almost all the atom is empty space between the nucleus and the electrons.

What is true: An atom is mostly empty space. A tiny, heavy nucleus sits at the centre. The stone feels solid because of the forces between atoms, not because the atoms are full.

KEY WORDS

nucleus
the tiny centre of an atom, made of protons and neutrons.

proton
a particle in the nucleus with a charge of +1 and a mass of 1.

neutron
a particle in the nucleus with no charge and a mass of 1.

electron
a particle outside the nucleus with a charge of −1 and almost no mass.

neutral
with no overall charge.

atomic number
the number of protons in an atom.

mass number
the number of protons plus the number of neutrons.

BACK TO YOUR GUESS

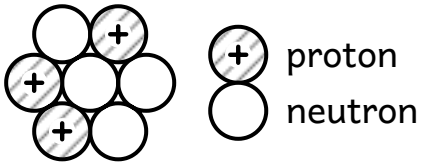
The answer is B: A tiny centre called the nucleus, with even tinier electrons outside it.

An atom has a tiny nucleus made of protons and neutrons. Electrons move outside it. The atom is neutral because the charges cancel.

CHECK YOURSELF

Try each one before you look. A wrong answer tells you where to go next.

1. This is the nucleus of a lithium atom. How many electrons does the whole atom have?



   A 3 electrons

   B 4 electrons

   C 7 electrons

   Answer at the back of the book.

2. Which particle in an atom has no charge?

   A The proton

   B The neutron

   C The electron

   Answer at the back of the book.

3. How does an electron compare with a proton?

   A It has the opposite charge and the same mass.

   B It has the same charge and less mass.

   C It has the opposite charge and much less mass.

   Answer at the back of the book.

4. Where is almost all of the mass of an atom?

   A In the nucleus

   B In the shells with the electrons

   C Spread evenly through the whole atom

   Answer at the back of the book.

5. A fluorine atom has 9 protons and mass number 19. How many neutrons does it have?

   A 19 neutrons

   B 9 neutrons

   C 28 neutrons

   D 10 neutrons

   Answer at the back of the book.

6. Why is a whole atom neutral?

   A The neutrons cancel the charge of the protons.

   B It has as many electrons as protons, and their charges cancel.

   C It has no charged particles at all.

   Answer at the back of the book.

7. A magnesium atom has atomic number 12 and mass number 24. How many neutrons does it have?

   Answer at the back of the book.

8. An atom of silicon has 14 protons and 14 neutrons. What is its mass number?

   Answer at the back of the book.

KEEP IT

Copy this into your exercise book.

An atom has a tiny nucleus of protons (+1) and neutrons (0). Electrons (−1) move outside. Atomic number = protons. Mass number = protons + neutrons. A neutral atom has equal protons and electrons.

Draw: A sodium atom with its symbol, mass number 23 and atomic number 11, and the number of each particle beside it.

S4.6.2 CHAPTER 2

How the model of the atom changed

How can you find out what is inside something you cannot see?

YOUR GUESS

Pick one before you read on. It is fine to be wrong.

- ☐ **A** Fire small particles at it and watch where they go.
- ☐ **B** Look at it very hard through a strong microscope.
- ☐ **C** Cut it into smaller and smaller pieces.

IF THIS FEELS HARD, READ THIS FIRST

- Level 3, Particles, S3.5.2. It shows how evidence builds a picture of things too small to see.
- Level 3, Particles, S3.5.1. It gives the first picture of matter as tiny particles.

BY THE END YOU CAN

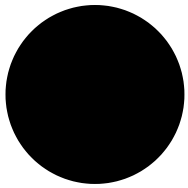
- Describe how the atom model changed from Dalton to Bohr
- Explain how the gold foil experiment showed a tiny nucleus

In Chapter 1 you met the nucleus, the protons, the neutrons and the electrons. Nobody has seen an atom as a tiny ball with a nucleus in it. So how do we know?

A **model** is a picture or an idea that explains what we measure. A good model matches all the **evidence**, which means the results of careful experiments. When a new result does not fit, the model is changed or replaced. This is how the model of the atom grew.

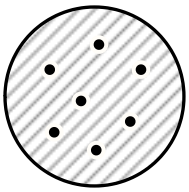
DRAW IT FIRST

Four models of the atom



Dalton

1 Dalton, about 1803: an atom is a tiny solid ball that cannot be split.

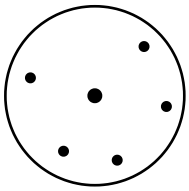


Plum pudding

positive charge

electron

2 Thomson, 1897: he found electrons, so an atom is a positive ball with electrons in it.

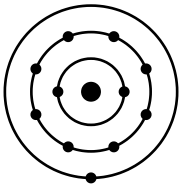


Nuclear

nucleus

electron

3 Rutherford, with Geiger and Marsden, 1911: a tiny positive nucleus, with the electrons far outside it.



Bohr

nucleus

electron

shell

4 Bohr, 1913: the electrons move on fixed shells round the nucleus.

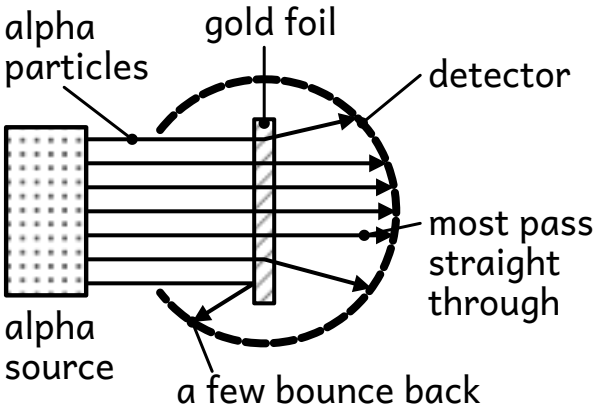
John Dalton said that each element is made of its own kind of atom. He pictured atoms as tiny, solid spheres. This fitted what chemists knew about how elements join to make compounds.

In 1897 J. J. Thomson showed that atoms contain electrons. Electrons are far lighter than atoms and have a negative charge. So an atom could not be a solid ball

that cannot be split.

Atoms are neutral, so Thomson pictured a ball of positive charge with the electrons spread through it. People called it the **plum pudding model**.

About 1909 Hans Geiger and Ernest Marsden, who worked with Ernest Rutherford, ran an experiment. They fired alpha particles at very thin gold foil. An ***alpha particle*** is a small, fast particle with a positive charge. It comes from some radioactive substances.



The gold foil experiment. The detector shows where each alpha particle goes.

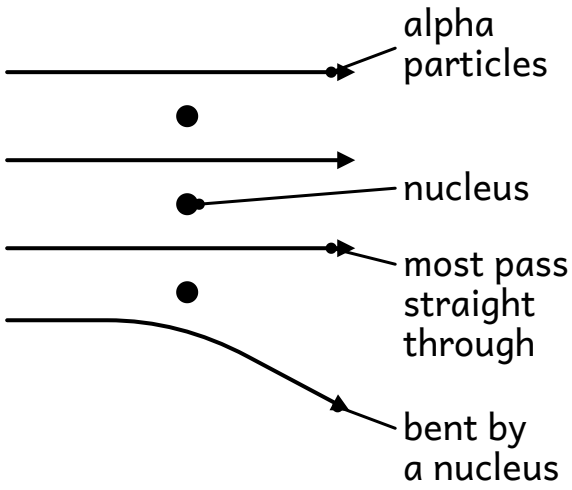
If an atom were a plum pudding, the alpha particles should all pass through with only a tiny bend. The results were different.

Result	Share
straight through	most
bent a little	some
turned back	1 in 8 000

About 1 alpha particle in 8 000 was turned back by more than a right angle. Geiger and Marsden measured this with platinum foil; gold gave the same pattern.

Each result said something about the atom. Most alpha particles went straight through, so most of an atom must be empty space. Some bent, so there is a small place where positive charge is packed. Like charges repel, so a positive particle that passes close is pushed aside.

A very few bounced back. Only something heavy and positive, in a tiny space, could do that. Rutherford called this centre the nucleus. The model with a nucleus is the **nuclear model**.



Zoomed in. A path bends only when it passes close to a nucleus.

WORKED EXAMPLE

Suppose about 1 alpha particle in 8 000 bounces back. In one run 16 000 alpha particles hit the foil. About how many bounce back?

1. The share that bounces back is 1 in 8 000.
2. Count how many groups of 8 000 are in 16 000.
3. 16 000 ÷ 8 000 = 2.

Answer: About 2 bounce back

An atom is between 10 000 and 100 000 times wider than its nucleus. The next example uses the top of that range, which keeps the numbers round.

WORKED EXAMPLE

Suppose an atom is 100 000 times wider than its nucleus. Draw the nucleus 2 mm wide. How wide, in metres, must the atom be on the same scale?

1. The atom is 100 000 times wider, so multiply the width of the nucleus by 100 000.
2. 2 mm × 100 000 = 200 000 mm.
3. There are 1 000 mm in 1 m, so 200 000 mm ÷ 1 000 = 200 m.

Answer: 200 m

The nuclear model had a gap. It did not say why the electrons stay out in space. In 1913 Niels Bohr pictured the electrons on fixed shells, each at a set distance from the nucleus. His model fitted the light that hydrogen atoms give out, and it is the picture we use for chemistry.

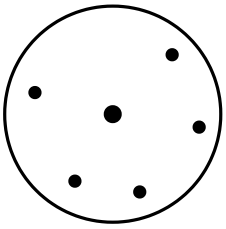
One more step came in 1932. Scientists knew the charge of the nucleus but its mass was too big. A helium nucleus has twice the charge of hydrogen, but four times the mass. James Chadwick found the **neutron**, a particle with no charge and the same mass as a proton. It filled the gap.

Year	Scientist	Idea
1803	Dalton	solid ball
1897	Thomson	electrons
1911	Rutherford	nucleus
1913	Bohr	shells
1932	Chadwick	neutron

Each step came from new evidence that the old model could not explain.

SEE IT THREE WAYS

As a picture



- nucleus
- electron

In words

The gold foil results fit one picture: a tiny, heavy, positive nucleus, and empty space all round it. Nothing else explains a few bounces among thousands of straight paths.

In symbols

Most go straight: empty space. Some bend: a small positive centre. A few bounce back: the centre is heavy.

TRY IT

Find a hidden cup by rolling marbles

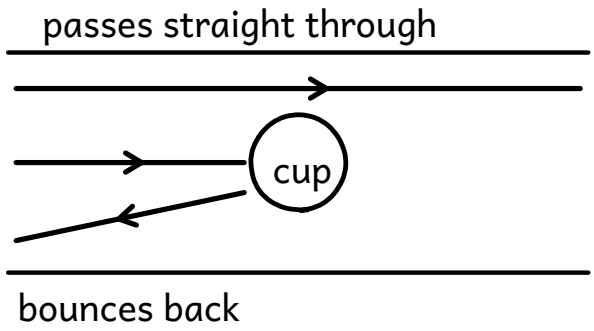
You need: a long cardboard box with both short ends cut open, and its lid, a small cup or a bottle top, about 20 marbles or small round stones, a flat floor, paper and a pencil for a tally.

Be safe: An adult cuts the box. Roll the marbles on a floor away from stairs, and pick up every marble when you finish, so nobody slips.

1. Stand the cup upside down in the middle of the box, and close the lid. Do not look at it again.
2. Lay the box on the floor. Roll a marble through it from one end, aiming at a different place each time.
3. Make a tally. Mark each marble as straight through, bent, or bounced back.
4. After 20 marbles, look at your tally. Which kind was most common?
5. Open the lid. Compare the cup with what your tally told you.

What you will see: Most marbles go straight through, because most of the box is empty. A few hit the cup and bounce away. The more marbles that hit, the wider the cup must be. Scientists found the nucleus in the same way, but with alpha particles.

If you cannot try it, this is what happens.



A WRONG IDEA MANY PEOPLE HAVE

~~The Bohr model shows what an atom really looks like.~~

Why it feels right: Almost every book draws an atom with a nucleus and neat rings of electrons, so the picture seems to be a photograph.

The test that breaks it: Ask what each picture can explain. The shell picture explains the periodic table and bonding well. It cannot tell you where one electron is, and the rings are not real rings.

What is true: The Bohr model is a model. It is useful because it explains a lot, but electrons are not little balls on rings. Models are kept while they work and replaced when new evidence needs a better one.

KEY WORDS

model
a picture or idea that explains what we measure.

evidence
the results of careful experiments.

alpha particle
a small, fast, positive particle given out by some radioactive substances.

plum pudding model
the atom as a positive ball with electrons spread through it.

nuclear model
the atom as a tiny positive nucleus with electrons far outside it.

BACK TO YOUR GUESS

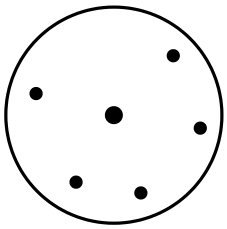
The answer is A: Fire small particles at it and watch where they go.

Scientists fired fast particles at a thin sheet of gold. Where the particles went showed what is inside the atoms. A microscope cannot show an atom, and cutting never reaches inside it.

CHECK YOURSELF

Try each one before you look. A wrong answer tells you where to go next.

1. Which model of the atom is this?



● nucleus
• electron

A The plum pudding model of Thomson

B The solid ball of Dalton

C The nuclear model of Rutherford

D The shell model of Bohr

Answer at the back of the book.

2. Which model did the gold foil results replace?

A The solid ball of Dalton

B The plum pudding model

C The shell model of Bohr

Answer at the back of the book.

3. Most alpha particles went straight through the gold foil. What does this show?

A Most of an atom is empty space.

B Atoms are solid, and alpha particles are very strong.

C Gold atoms have no charge.

Answer at the back of the book.

4. A few alpha particles were turned back. What does this show?

   A The electrons pushed the alpha particles back.

   B The gold foil was too thick for the alpha particles.

   C An atom has a tiny, heavy, positive nucleus.

   Answer at the back of the book.

5. What was new in the model of Niels Bohr?

   A The electrons are spread through a positive ball.

   B The electrons move on fixed shells.

   C The nucleus holds neutrons.

   Answer at the back of the book.

6. Why did scientists need a new particle, the neutron?

   A The neutron holds the electrons on their shells.

   B The nucleus needed more positive charge.

   C The nucleus had more mass than its protons could explain.

   Answer at the back of the book.

7. **From an earlier chapter**

   Which particles are in the nucleus of an atom?

   A Protons and neutrons

   B Protons and electrons

   C Protons only

   Answer at the back of the book.

8. Suppose 1 alpha particle in 8 000 bounces back. A run sends 24 000 alpha particles at the foil. About how many bounce back?

   Answer at the back of the book.

9. A nucleus is drawn 3 mm wide. Suppose the atom is 100 000 times wider than its nucleus. How wide, in metres, is the atom on the same scale?

   Answer at the back of the book.

KEEP IT

Copy this into your exercise book.

A model explains the evidence and changes when new evidence does not fit. Gold foil: most alpha particles pass through, a few bounce back. So atoms are mostly empty space with a tiny, dense, positive nucleus.

Draw: The gold foil experiment: a beam, the foil, and three paths: straight, bent and back.

S4.6.3 CHAPTER 3

Isotopes

> **Atoms have a whole number of particles. So why is the mass of chlorine in the periodic table 35.5?**

YOUR GUESS

Pick one before you read on. It is fine to be wrong.

- ☐ **A** Some chlorine atoms have half a proton.
- ☐ **B** Chlorine atoms differ in mass, and 35.5 is the mean of them.
- ☐ **C** The mass was measured badly, so it is only a guess.

IF THIS FEELS HARD, READ THIS FIRST

- Level 3, Elements, mixtures, reactions and acids, S3.6.1. It says that an element has only one kind of atom.
- Level 3, Elements, mixtures, reactions and acids, S3.6.2. It shows what a mixture is, which helps with a mixture of isotopes.

BY THE END YOU CAN

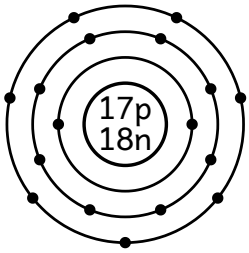
- Explain what isotopes are and why they react the same way
- Calculate relative atomic mass from isotope amounts

The number of protons decides which element an atom is. But the number of neutrons can change. Atoms of one element are not all the same.

Isotopes are atoms of the same element with the same number of protons and different numbers of neutrons. They have the same atomic number and different mass numbers.

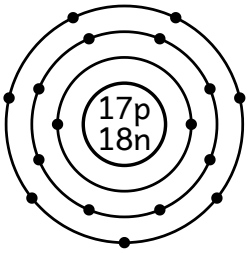
DRAW IT FIRST

Two isotopes of chlorine

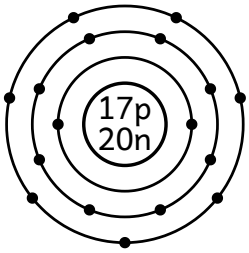


chlorine 35

1 Chlorine 35 has 17 protons, 18 neutrons and 17 electrons. Its mass number is 35.

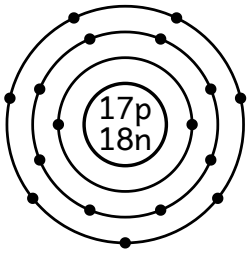


chlorine 35

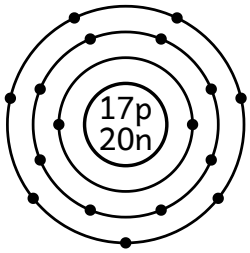


chlorine 37

2 Chlorine 37 has 17 protons, 20 neutrons and 17 electrons. Its mass number is 37.



chlorine 35

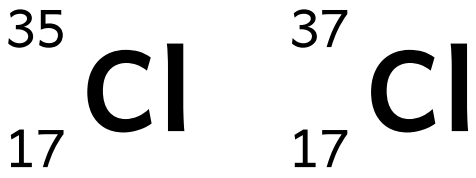


chlorine 37

same protons and electrons

3 The two atoms have the same protons and the same electrons. Only the neutrons differ.

We write the element and its mass number in words: chlorine 35 and chlorine 37. Chemists also write the numbers beside the symbol, as you saw in Chapter 1.



The top numbers differ. The bottom numbers are the same.

Hydrogen has three well known isotopes. Most hydrogen atoms have no neutron at all.

Isotope	Neutrons
hydrogen 1	0
hydrogen 2	1
hydrogen 3	2

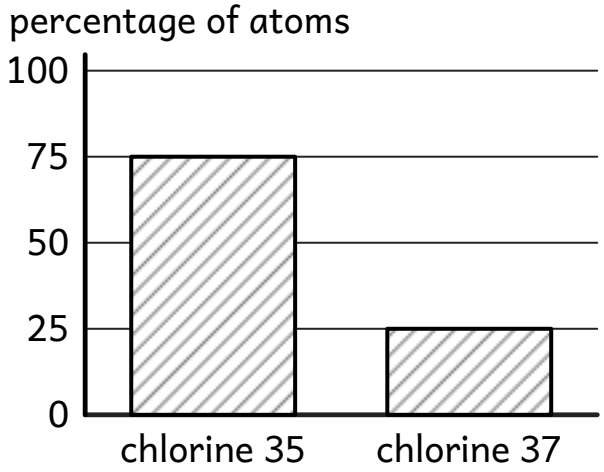
Every hydrogen atom has 1 proton and 1 electron. Hydrogen 3 is unstable, so it is radioactive.

Why do isotopes react in the same way? A chemical reaction is about electrons, above all the outer ones. Isotopes of an element have the same number of electrons. So they react the same way.

The extra neutrons add mass. They do not change the electrons, so isotopes take part in the same reactions. Isotopes do differ in a few things that depend on mass, such as density. A few isotopes are also unstable. That is a topic of its own.

Now look again at the periodic table box. The number at the bottom of the box is the **relative atomic mass**. It is the mean mass of the atoms of an element, on a scale where a carbon 12 atom is exactly 12.

It is a mean because a sample of an element holds a mixture of isotopes. The mean depends on how much of each isotope there is. This amount is its ***abundance***, often written as a percentage of all the atoms.



Out of every 100 chlorine atoms, about 75 are chlorine 35 and 25 are chlorine 37.

Take 100 chlorine atoms. Find their total mass, then divide by 100. Chlorine 35 is more common, so it pulls the mean closer to 35 than to 37. Counting this way is called a weighted mean.

WORKED EXAMPLE

Chlorine is 75% chlorine 35 and 25% chlorine 37. Find its relative atomic mass.

1. Think of 100 atoms: 75 have mass number 35 and 25 have mass number 37.
2. Total mass = 75 × 35 + 25 × 37 = 2 625 + 925 = 3 550.
3. Mean mass = 3 550 ÷ 100 = 35.5.

Answer: 35.5

No single chlorine atom has a mass of 35.5. It is the mean, like a class where the mean number of children in a family is 2.4.

WORKED EXAMPLE

Magnesium is 79% magnesium 24, 10% magnesium 25 and 11% magnesium 26. Find its relative atomic mass to one decimal place.

1. In 100 atoms, 79 have mass number 24, 10 have 25 and 11 have 26.
2. Total mass = 79 × 24 + 10 × 25 + 11 × 26 = 1 896 + 250 + 286 = 2 432.
3. Mean mass = 2 432 ÷ 100 = 24.32, which is 24.3 to one decimal place.

Answer: 24.3

TRY IT

Find a mean with paper pieces

You need: a sheet of paper, torn into 20 small pieces, a pencil, a cup or bowl.

1. On 15 pieces write the number 35. On the other 5 pieces write 37.
2. Mix the pieces in the cup. Each piece stands for one chlorine atom.
3. Add up all the numbers on the 20 pieces.
4. Divide the total by 20.
5. Look through the pieces. Is there one with your answer written on it?

What you will see: The total is 710. Divide by 20 and you get 35.5. Not one piece has 35.5 on it. The mean is a number for the whole mixture, not for any one atom.

If you cannot try it, this is what happens.

Number	Pieces
35	15
37	5

A WRONG IDEA MANY PEOPLE HAVE

~~Isotopes of an element react in different ways, because they have different masses.~~

Why it feels right: Atoms with a different mass number look like different atoms, so it seems they should behave differently.

The test that breaks it: Look at what a reaction needs. Chlorine 35 and chlorine 37 both have 17 electrons, with 7 in the outer shell. Both gain one electron to react with sodium, in the same way.

What is true: Isotopes of one element react the same way, because they have the same electrons. Only properties that depend on mass, such as density, differ, and some isotopes are radioactive.

KEY WORDS

isotopes
atoms of one element with the same number of protons and different numbers of neutrons.

relative atomic mass
the mean mass of the atoms of an element, on a scale where a carbon 12 atom is exactly 12.

abundance
how much of an isotope there is, often as a percentage of all the atoms.

BACK TO YOUR GUESS

The answer is B: Chlorine atoms differ in mass, and 35.5 is the mean of them.

Chlorine is a mixture of two kinds of atom with different masses. The relative atomic mass, 35.5, is the mean of all of them.

CHECK YOURSELF

Try each one before you look. A wrong answer tells you where to go next.

1. Carbon has atoms with 6, 7 and 8 neutrons. What is the same in all of these atoms?

    A The number of neutrons

    B The mass number

    C The number of protons

    Answer at the back of the book.

2. Why do isotopes of an element react in the same way?

    A They have the same mass.

    B They have the same number of neutrons.

    C They are not really different atoms.

    D They have the same number of electrons.

    Answer at the back of the book.

3. A neon atom has 10 protons and mass number 22. How many neutrons does it have?

    A 12 neutrons

    B 22 neutrons

    C 10 neutrons

    Answer at the back of the book.

4. The relative atomic mass of chlorine is 35.5. What does this tell us?

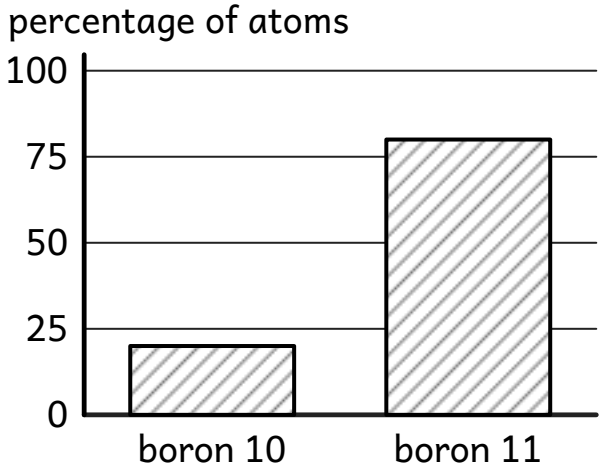
    A Every chlorine atom has a mass of 35.5.

    B It is the mean mass of chlorine atoms, which are a mixture of isotopes.

    C Chlorine atoms each hold a half neutron.

    Answer at the back of the book.

5. Boron is 20% boron 10 and 80% boron 11. What is its relative atomic mass?



A 10.5

B 11

C 10.8

Answer at the back of the book.

6. How do you work out a relative atomic mass from the isotopes?

A Multiply each mass number by its percentage, add, and divide by the total of the percentages.

B Add the mass numbers and divide by how many isotopes there are.

C Use the mass number of the most common isotope.

Answer at the back of the book.

7. **From an earlier chapter**

Which model of the atom first put electrons on fixed shells?

A The nuclear model of Rutherford

B The shell model of Bohr

C The plum pudding model of Thomson

Answer at the back of the book.

8. An atom of potassium 41 has atomic number 19. How many neutrons does it have?

Answer at the back of the book.

9. Element X has two isotopes. 75% of its atoms have mass number 20 and 25% have mass number 22. What is its relative atomic mass?

   Answer at the back of the book.

KEEP IT

Copy this into your exercise book.

Isotopes: same protons, different neutrons, so the same reactions. Relative atomic mass is a weighted mean: add mass × percentage for each isotope, then divide by 100. Chlorine: 35.5.

Draw: Two chlorine atoms with 17p and 18n, and 17p and 20n, and the sum that gives 35.5.

S4.6.4 CHAPTER 4

Electron shells

Sodium has 11 electrons. How are they arranged round the nucleus?

YOUR GUESS

Pick one before you read on. It is fine to be wrong.

- ☐ **A** All 11 are on one shell.
- ☐ **B** 2 on the first shell, 8 on the second and 1 on the third.
- ☐ **C** They are spread evenly, one on each of 11 shells.

IF THIS FEELS HARD, READ THIS FIRST

- Level 3, Particles, S3.5.1. It gives the picture of matter as tiny particles that this chapter builds on.

BY THE END YOU CAN

- Write electron arrangements for the first 20 elements
- Link an element's group and period to its electrons

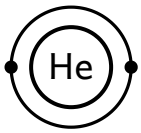
In the model of Bohr, the electrons of an atom move on shells. Each **shell** is at its own distance from the nucleus. The shell nearest the nucleus is shell 1.

A shell can hold only so many electrons. Electrons go into the shell nearest the nucleus first. When it is full, the next one starts. The outermost shell that has electrons is the **outer shell**.

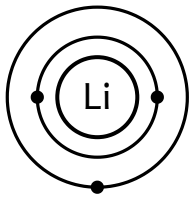
For the first 20 elements the shells fill to 2, 8 and 8. Then shell 4 starts: potassium puts 1 electron on it and calcium puts 2. This rule works well for these elements. In bigger atoms the third shell can hold more than 8. Shell 4 can hold more too, so the pattern is more complex.

DRAW IT FIRST

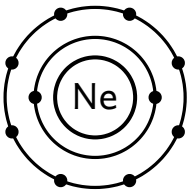
Filling the shells



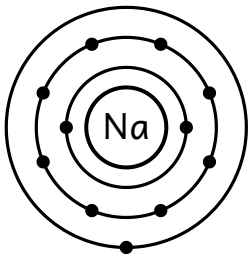
1 Helium has 2 electrons. They fill shell 1.



2 Lithium has 3 electrons. Two fill shell 1 and the third starts shell 2.



3 Neon has 10 electrons. Two fill shell 1 and eight fill shell 2.



4 Sodium has 11 electrons. Shells 1 and 2 are full, so the last electron starts shell 3.

We write an **<u>electron arrangement</u>** as the numbers on each shell, from the inside, with commas. Sodium is 2, 8, 1. The numbers always add up to the number of electrons, which is the atomic number.

Atom	Electrons	Per shell
H	1	1
He	2	2
Li	3	2, 1
Be	4	2, 2
B	5	2, 3
C	6	2, 4
N	7	2, 5
O	8	2, 6
F	9	2, 7
Ne	10	2, 8

The electron arrangements of the first ten elements. Hydrogen has 1 electron, so its arrangement is 1.

Atom	Electrons	Per shell
Na	11	2, 8, 1
Mg	12	2, 8, 2
Al	13	2, 8, 3
Si	14	2, 8, 4
P	15	2, 8, 5
S	16	2, 8, 6
Cl	17	2, 8, 7
Ar	18	2, 8, 8
K	19	2, 8, 8, 1
Ca	20	2, 8, 8, 2

Elements 11 to 20. Argon finishes shell 3 with 8. Potassium starts shell 4, and calcium adds a second electron to it.

Look at the periodic table with these arrangements in mind. A column is a **group**. A row is a **period**. The table is laid out so that elements in one group have the same number of outer electrons.

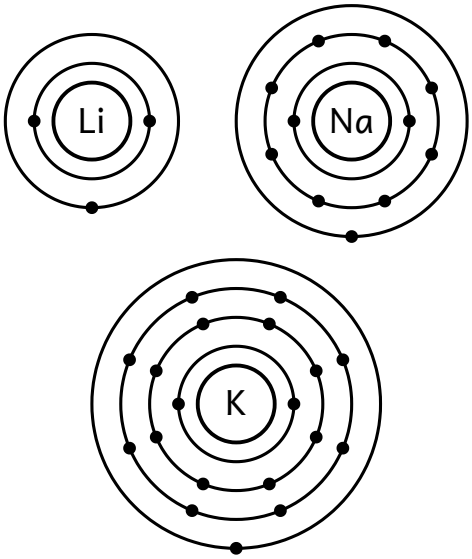
	group							
	1	2	3	4	5	6	7	0
1	H							He
2	Li	Be	B	C	N	O	F	Ne
3	Na	Mg	Al	Si	P	S	Cl	Ar
4	K	Ca						

The numbers down the left side are the periods. Sodium is hatched.

The **group number** is the number of electrons in the outer shell. Sodium has 1 outer electron, so it is in group 1. Sulfur is 2, 8, 6, so it is in group 6. Group 0 is different: its elements have a full outer shell, which is 2 for helium and 8 for the others.

Many tables number the columns 1 to 18 instead. Then group 6 is group 16, group 7 is group 17 and group 0 is group 18. This book uses 1 to 7 and 0.

The **period number** is the number of shells. Sodium has 3 shells, so it is in period 3. Lithium has 2 shells, so it is in period 2.



one outer electron each

Group 1: one outer electron each, on a different shell. Lithium is in period 2, sodium in period 3 and potassium in period 4.

WORKED EXAMPLE

Phosphorus has atomic number 15. Write its electron arrangement.

1. A neutral atom has 15 electrons.
2. Shell 1 takes 2, which leaves 13. Shell 2 takes 8, which leaves 5.
3. The last 5 go in shell 3. The arrangement is 2, 8, 5.

Answer: 2, 8, 5

WORKED EXAMPLE

Calcium has atomic number 20. Write its electron arrangement, then give its group and its period.

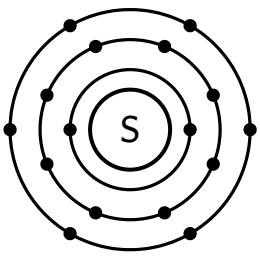
1. A neutral atom has 20 electrons. Fill the shells in turn: 2, 8, 8. That uses 18.
2. Shell 4 takes the last 2. The arrangement is 2, 8, 8, 2.
3. The group is the outer electrons: 2. The period is the number of shells: 4.

Answer: 2, 8, 8, 2, group 2, period 4

Helium, neon and argon are in group 0. Their outer shells are full. This is why they hardly ever react. A full outer shell is a very steady arrangement.

SEE IT THREE WAYS

As a picture



In words

Sulfur has 16 electrons. They fill shell 1, then shell 2, and the last 6 go in shell 3. Six outer electrons put sulfur in group 6. Three shells put it in period 3.

In symbols

Arrangement 2, 8, 6: group 6, period 3

TRY IT

Fill the shells with seeds

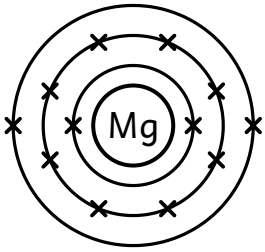
You need: a sheet of paper and a pencil, a plate, a bowl, a cup and a small lid, to draw round, about 20 small seeds or beans.

Be safe: Do not eat the seeds or beans you use for the model. Keep small seeds away from young children.

1. Draw round the plate, the bowl, the cup and the lid, one inside another, to make four rings. The lid is the middle.
2. Choose an element, for example magnesium, which has 12 electrons.
3. Put the seeds on the rings one at a time, starting at the inner ring. Put 2 on ring 1 and 8 on ring 2.
4. Put what is left on ring 3. Count the seeds on each ring.
5. Try chlorine with 17 electrons, then calcium with 20 electrons.

What you will see: Magnesium comes out as 2, 8, 2. The outer ring has 2 seeds, so magnesium is in group 2. It uses 3 rings, so it is in period 3. When a ring is full you must start the next one.

If you cannot try it, this is what happens.



A WRONG IDEA MANY PEOPLE HAVE

~~The group number tells you how many shells an atom has.~~

Why it feels right: Both groups and periods are small whole numbers, so they are often mixed up.

The test that breaks it: Take sodium. It is in group 1, but its arrangement is 2, 8, 1, which has three numbers. Count the shells and you get 3.

What is true: The group number is the number of outer electrons. The period number is the number of shells. Sodium is group 1 and period 3.

KEY WORDS

shell
a place at a set distance from the nucleus where electrons move.

outer shell
the outermost shell that holds electrons.

electron arrangement
the number of electrons on each shell, from the inside, such as 2, 8, 1.

group
a column of the periodic table. The number is the outer electrons.

period
a row of the periodic table. The number is the number of shells.

group number
the number of electrons in the outer shell, with group 0 for a full outer shell.

period number
the number of shells in the atom.

BACK TO YOUR GUESS

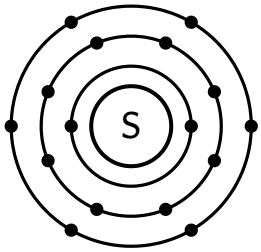
The answer is B: 2 on the first shell, 8 on the second and 1 on the third.

Electrons fill the shells from the inside. The first shell takes 2 and the second takes 8. The last electron goes on a third shell.

CHECK YOURSELF

Try each one before you look. A wrong answer tells you where to go next.

1. This is an atom of sulfur. Which group of the periodic table is it in?



   A Group 3

   B Group 6

   C Group 8

   Answer at the back of the book.

2. An atom has the electron arrangement 2, 8, 3. In which period is it?

   A Period 13

   B Period 2

   C Period 3

   Answer at the back of the book.

3. Fluorine has atomic number 9. What is its electron arrangement?

   A 2, 8

   B 7, 2

   C 9

   D 2, 7

   Answer at the back of the book.

4. Helium has only 2 electrons, yet it is very unreactive. Why?

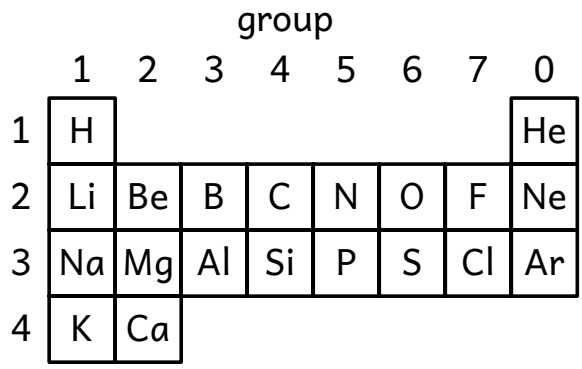
   A Its outer shell is full.

   B It has eight electrons in its outer shell.

   C It has no outer shell.

   Answer at the back of the book.

5. Which element is in group 7 and period 3?



   A Sulfur

   B Chlorine

   C Fluorine

   Answer at the back of the book.

6. What is the most electrons the third shell holds for the first 20 elements?

   A 18 electrons

   B 2 electrons

   C 8 electrons

   Answer at the back of the book.

7. **From an earlier chapter**

   Chlorine 35 and chlorine 37 are isotopes of chlorine, which has atomic number 17. What is the electron arrangement of both?

   A 2, 8, 7

   B 2, 8, 8

   C 2, 8, 9

   Answer at the back of the book.

8. Write the electron arrangement of the atom with atomic number 13. Write it like 2, 8, 1.

   Answer at the back of the book.

9. An atom has 7 electrons. Write its group number and then its period number.

   Answer at the back of the book.

KEEP IT

Copy this into your exercise book.

Shells fill from the inside: 2, 8, 8, then shell 4, for the first 20 elements. Group number = outer electrons (group 0 has a full outer shell). Period number = number of shells. Sodium: 2, 8, 1.

Draw: A sodium atom with its three shells and the numbers 2, 8 and 1, and the words group 1 and period 3.

S4.6.5 CHAPTER 5

The periodic table

How did one chemist predict elements that nobody had found yet?

YOUR GUESS

Pick one before you read on. It is fine to be wrong.

- ☐ **A** He left gaps in his table and worked out what the missing elements would be like.
- ☐ **B** He found the elements first and only then made his table.
- ☐ **C** He guessed, and he was lucky.

IF THIS FEELS HARD, READ THIS FIRST

- Level 3, Elements, mixtures, reactions and acids, S3.6.1. It names the common elements and says what an element is.
- Level 3, Particles, S3.5.3. It explains melting and boiling points, which we compare in this chapter.

BY THE END YOU CAN

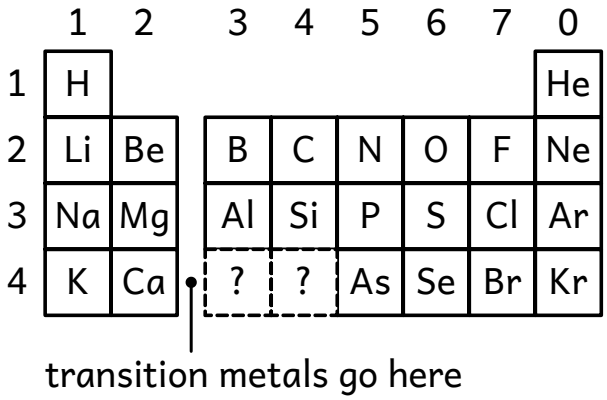
- Explain how Mendeleev arranged the elements and left gaps
- Describe trends in groups 1, 7 and 0

By 1869 chemists knew about 60 elements. They had measured how heavy the atoms of each element are and how each element behaves. Many tried to find a pattern.

Dmitri Mendeleev wrote each element on a card. He put the cards in order of atomic mass, then began a new row whenever the properties began to repeat. Elements with similar properties fell in one column. This was his **periodic table**.

Mendeleev trusted the pattern more than the order of masses. Tellurium has a slightly greater mass than iodine. But iodine behaves like chlorine and bromine, so he put iodine after tellurium so that it sat under them. He swapped the pair.

Some places in his table fitted no known element. Mendeleev did not move the others to close the gap. He left it empty and said an element there had not been found yet. From the elements above and below it, and on each side, he **predicted** its properties.



The modern shape of the table, with two of the gaps that Mendeleev left marked with a question mark. His own table looked different.

The element under silicon he called eka-silicon. The element under aluminium he called eka-aluminium. Within about twenty years gallium and then germanium were found. They fitted his predictions closely.

Value	Mass	Density
predicted	72	5.5 g/cm^3
found	72.6	5.3 g/cm^3

Germanium was found in 1886. The mass has no unit because it is a relative mass.

WORKED EXAMPLE

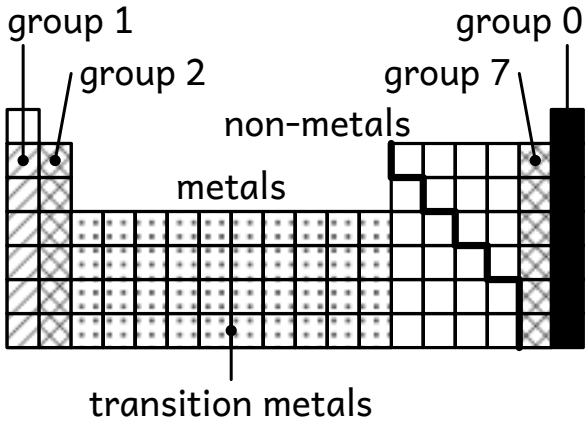
Mendeleev predicted a mass of 72 for the element under silicon. Germanium has a mass of 72.6. By what percentage was his prediction below the real value? Give it to one decimal place.

1. The difference is 72.6 − 72 = 0.6.
2. As a fraction of the real value: 0.6 ÷ 72.6 = 0.0083.
3. As a percentage: 0.0083 × 100 = 0.8% to one decimal place.

Answer: 0.8%

A prediction that comes true is strong evidence. After germanium, most chemists accepted the table. Mendeleev ordered by atomic mass because atoms were not yet known to have protons.

Today the table is ordered by atomic number, which is the number of protons. This removes the need to swap pairs. Tellurium has 52 protons and iodine has 53, so iodine follows tellurium in the order.



The modern table. Most elements are metals. They are on the left of the staircase. Hydrogen, at the top left, is a non-metal. Elements next to the staircase, such as boron, silicon and germanium, are metalloids, with some properties of each. The 28 elements usually printed in two rows below the table, the lanthanides and actinides, are left out.

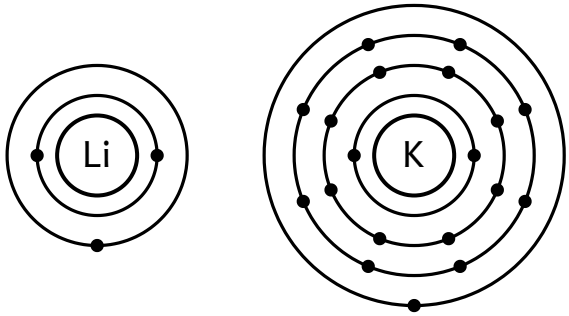
Elements in a group have the same number of outer electrons. This is why they react in a similar way. Within a group the properties change step by step. A step by step change like this is a **trend**.

Group 1 is the **alkali metals**: lithium, sodium and potassium are the first three. They are soft enough to cut with a knife, and they have a low density. They tarnish quickly in air. They react with water to make hydrogen and an alkali. For example: sodium + water → sodium hydroxide + hydrogen.

The trend is that group 1 metals become more reactive going down. Lithium fizzes steadily in water. Sodium melts into a ball and fizzes fast. Potassium reacts so fast that its hydrogen catches fire with a lilac flame. **Reactivity** is how readily an element takes part in reactions.

Be safe. Scientists do these reactions in a laboratory, with shields and a small piece of metal. Group 1 metals burn the skin and can start fires. Never try this at home.

Why does reactivity rise? A group 1 atom reacts by losing its one outer electron. Going down, the outer electron is further from the nucleus, and more inner shells lie between them. The pull of the nucleus on it is weaker. So the electron is lost more easily.



lithium held tightly

potassium held loosely

The outer electron of potassium is far from the nucleus, so it is lost more easily than the outer electron of lithium.

Group 7 is the **halogens**: fluorine, chlorine, bromine and iodine. They are non-metals. Their atoms pair up in molecules of two: F_2, Cl_2, Br_2 and I_2. Their colours get darker going down, and their boiling points rise.

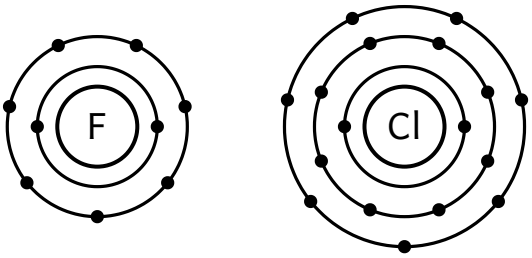
Halogen	Colour	State
fluorine	yellow	gas
chlorine	green	gas
bromine	red-brown	liquid
iodine	dark grey	solid

The state is for room temperature. The yellow of fluorine is pale and the green of chlorine is a yellow green. The colours deepen going down, and the state moves from gas to solid.

Halogen	Boils at
fluorine	−188 °C
chlorine	−34 °C
bromine	59 °C
iodine	184 °C

Boiling points rise going down group 7.

Going down group 7 the halogens become less reactive. A halogen atom reacts by gaining one electron. Further down, the outer shell is further from the nucleus and more shielded. The nucleus pulls an incoming electron less strongly, so the electron is gained less easily.



fluorine
pulls strongly

chlorine
pulls less

A space in the outer shell of fluorine is close to the nucleus. The same space in chlorine is further away.

Be safe. Chlorine and bromine are poisonous, and fluorine is far worse. They are handled only in laboratories with extraction. Do not look for them at home.

Group 0 is the **noble gases**: helium, neon, argon and krypton. Each has a full outer shell. They do not need to gain, lose or share electrons, so they are very unreactive. Only a few compounds of the heavier noble gases, such as krypton, are known. Their atoms stay single, not joined in molecules.

Noble gas	Boils at
helium	−269 °C
neon	−246 °C
argon	−186 °C
krypton	−153 °C

All are gases at room temperature. Boiling points rise going down group 0.

WORKED EXAMPLE

Argon boils at −186 °C and krypton at −153 °C. By how many degrees is the boiling point of krypton higher?

1. Subtract the lower boiling point from the higher one.
2. −153 − (−186) = −153 + 186.
3. Krypton is 33 °C higher.

Answer: 33 °C

TRY IT

Sort the elements like Mendeleev

You need: a sheet of paper, torn into 18 cards, a pencil, the table of electron arrangements in Chapter 4, a flat table or floor.

1. Write on each card a symbol from Li to Ca: that is elements 3 to 20. Write its outer electrons, from Chapter 4.
2. Put the cards in order of atomic number, from lithium.
3. Start a new row after each card with 8 outer electrons: after neon, and after argon.
4. Slide the rows so that cards with the same number of outer electrons are in one column.
5. Look down the columns. Which cards are together?

What you will see: Each column holds elements with the same outer electrons. Lithium, sodium and potassium are together in group 1. Fluorine and chlorine are together in group 7. Neon and argon are together in group 0. Their properties are alike too. The order of atomic number makes the pattern appear.

If you cannot try it, this is what happens.

	1	2	3	4	5	6	7	0
1	H							He
2	Li	Be	B	C	N	O	F	Ne
3	Na	Mg	Al	Si	P	S	Cl	Ar
4	K	Ca						

A WRONG IDEA MANY PEOPLE HAVE

~~Every group becomes more reactive going down.~~

Why it feels right: Group 1 does, and the dramatic reactions of potassium are the ones people remember.

The test that breaks it: Check group 7. Fluorine reacts with almost everything, and iodine reacts slowly. Going down, the halogens become less reactive, not more.

What is true: Metals lose electrons, and that is easier when the outer electron is further from the nucleus. Non-metals gain electrons, and that is harder when the shell is further away. So group 1 rises and group 7 falls.

KEY WORDS

periodic table
the elements in order of atomic number, in rows and columns so that similar elements are in one column.

predicted
said before it is found, from a pattern.

trend
a change that goes step by step down a group or along a period.

alkali metals
the metals of group 1.

reactivity
how readily an element takes part in reactions.

halogens
the non-metals of group 7.

noble gases
the unreactive gases of group 0.

BACK TO YOUR GUESS

The answer is A: He left gaps in his table and worked out what the missing elements would be like.

Mendeleev left gaps where no known element fitted the pattern. From the elements round each gap he predicted the missing element. Later it was found, and the predictions held.

CHECK YOURSELF

Try each one before you look. A wrong answer tells you where to go next.

1. How did Mendeleev arrange the elements?

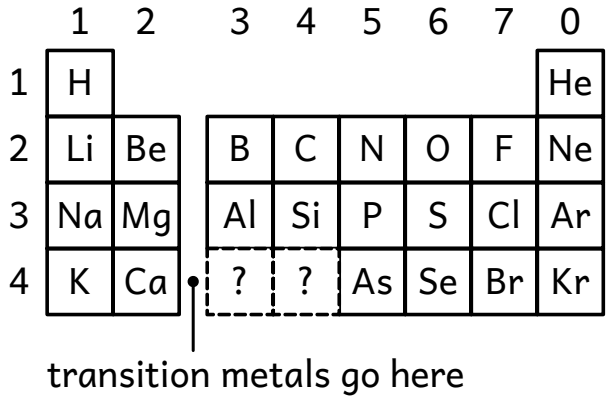
   A By the number of protons, in columns of similar elements

   B By the order in which they were found

   C By atomic mass, in columns of similar elements

   Answer at the back of the book.

2. This table has two gaps, marked with a question mark. Mendeleev left a gap under silicon. What did he predict about the missing element?



   A It would be a soft metal like sodium.

   B It would behave like silicon, the element above it.

   C It would be unreactive like argon.

   Answer at the back of the book.

3. Going down the alkali metals and going down the halogens, how does reactivity change?

    A It rises for the alkali metals and falls for the halogens.

    B It rises in both groups.

    C It falls for the alkali metals and rises for the halogens.

    Answer at the back of the book.

4. Why is potassium more reactive than lithium?

    A It has more outer electrons to lose.

    B Its nucleus holds the outer electron more strongly.

    C Its outer electron is further from the nucleus, so it is lost more easily.

    Answer at the back of the book.

5. Chlorine is more reactive than bromine. Why?

    A Chlorine has fewer outer electrons.

    B Its outer shell is closer to the nucleus, so it pulls an extra electron in more strongly.

    C Chlorine atoms are heavier.

    Answer at the back of the book.

6. Why is argon unreactive?

    A Its outer shell is full, so it has no need to gain, lose or share electrons.

    B It has one outer electron, which is held very tightly.

    C Its atoms are too small to react.

    Answer at the back of the book.

7. **From an earlier chapter**

   An atom has the electron arrangement 2, 8, 7. Which group is it in?

   A Group 3

   B Group 7

   C Group 8

   Answer at the back of the book.

8. Neon boils at −246 °C and krypton boils at −153 °C. By how many degrees is the boiling point of krypton higher?

   Answer at the back of the book.

9. Chlorine boils at −34 °C and iodine boils at 184 °C. By how many degrees is the boiling point of iodine higher?

   Answer at the back of the book.

KEEP IT

Copy this into your exercise book.

Mendeleev ordered by atomic mass, grouped by properties, swapped pairs and left gaps. Today: atomic number. Group 1 reacts more going down. Group 7 reacts less. Group 0 is unreactive, with a full outer shell.

Draw: The table shape with group 1, group 7 and group 0 marked, and an arrow down each for the trend.

S4.6.6 CHAPTER 6

Ionic bonding

Why does salt stay solid in a pan that is hot enough to boil water dry?

YOUR GUESS

Pick one before you read on. It is fine to be wrong.

- [ ] **A** The particles of salt hardly attract one another.
- [ ] **B** The particles of salt attract one another very strongly.
- [ ] **C** Salt is made of single atoms, which cannot melt.

IF THIS FEELS HARD, READ THIS FIRST

- Level 3, Elements, mixtures, reactions and acids, S3.6.1. It says that a compound has elements joined together, such as salt.
- Level 3, Particles, S3.5.3. It explains melting and the high melting point of a solid whose particles hold tight.
- Level 3, Electricity and magnetism, S3.10.5. It shows that unlike charges attract and like charges repel.

BY THE END YOU CAN

- Draw dot and cross diagrams for ions such as sodium chloride
- Explain why ionic compounds have high melting points and conduct when molten

Table salt is sodium chloride. It melts at 801 °C, and water boils at 100 °C. Something holds the particles of salt together very firmly. That something is called a bond.

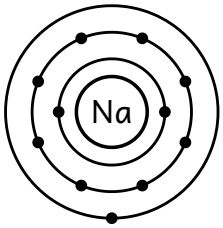
Atoms bond so that each ends with a full outer shell, the arrangement of a noble gas. Metals have few outer electrons, and non-metals have almost a full shell. An

atom of a metal can lose its outer electrons. An atom of a non-metal can gain them.

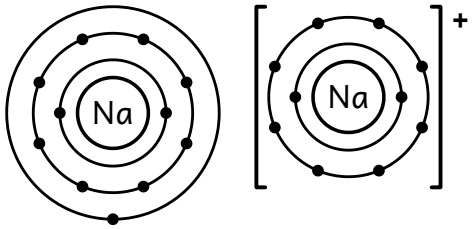
An **ion** is an atom, or a group of atoms, with an electric charge. An atom that loses electrons has more protons than electrons, so it becomes a positive ion. An atom that gains electrons becomes a negative ion.

DRAW IT FIRST

A sodium atom becomes a sodium ion



1 A sodium atom has 11 protons and 11 electrons, arranged 2, 8, 1. It is neutral.



loses 1 electron

2 It loses its one outer electron. Now it has 11 protons (+11) and 10 electrons (−10). The ion has a charge of +1 and the arrangement 2, 8, the same as neon.

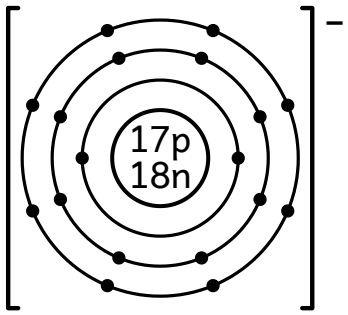
We write the charge as a small raised mark: Na^+. A magnesium atom loses 2 electrons, so its ion is Mg^{2+}. A chlorine atom gains 1 electron, so its ion is Cl^-. An oxygen atom gains 2, so its ion is O^{2-}.

WORKED EXAMPLE

A chloride ion has 17 protons and 18 electrons. What is its charge?

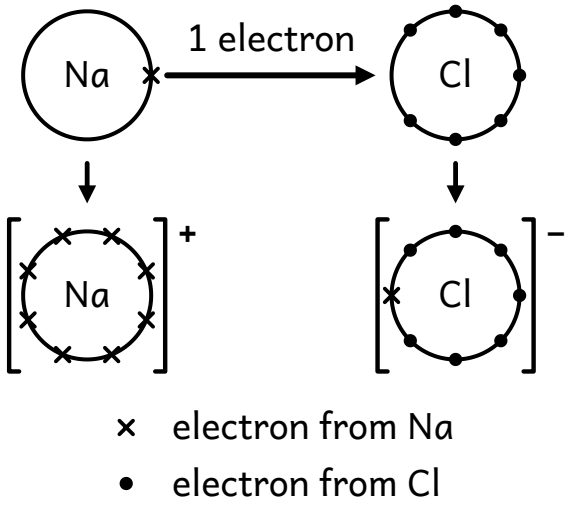
1. Charge = protons − electrons.
2. Charge = 17 − 18.
3. Charge = −1. The ion is negative, so we write Cl^-.

Answer: The charge is −1



The chloride ion has 17 protons and 18 electrons. Its outer shell is full.

A **dot and cross diagram** shows the outer electrons of the atoms that bond. We draw the electrons of one atom as crosses and those of the other as dots. This only helps us follow them. All electrons are the same.



Sodium chloride. The sodium atom gives its outer electron to the chlorine atom. The sodium ion is drawn with its new outer shell, shell 2, which is full.

The two ions have opposite charges, so they attract one another. The attraction between oppositely charged ions is the **ionic bond**. A compound held together by ionic bonds is an **ionic compound**.

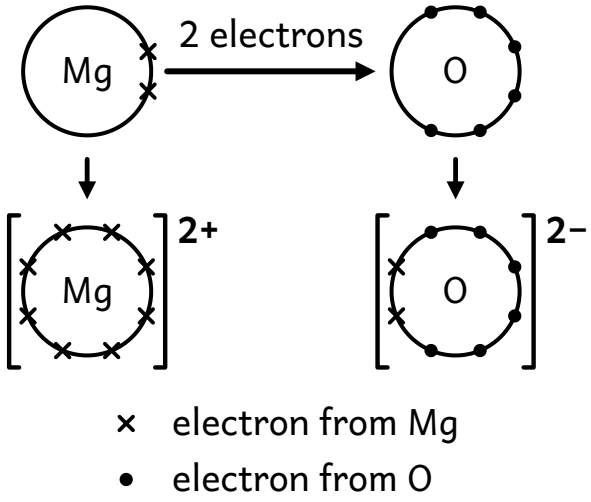
The charges must balance. Magnesium gives 2 electrons. One oxygen atom takes 2. So one Mg^{2+} ion pairs with one O^{2-} ion. In magnesium chloride one Mg^{2+} ion needs two Cl^- ions, because each chlorine takes only 1. This is why its formula is $MgCl_2$.

WORKED EXAMPLE

A magnesium atom is arranged 2, 8, 2. An oxygen atom is arranged 2, 6. How many electrons move from magnesium to oxygen?

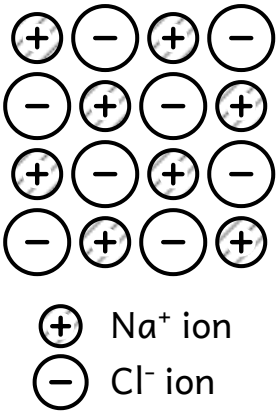
1. Magnesium has 2 outer electrons. A metal loses them all.
2. Oxygen has 6 outer electrons and a full shell holds 8, so it needs 8 − 6 = 2 more.
3. Both say the same: 2 electrons move.

Answer: 2 electrons move



Magnesium oxide. Two electrons move, so the ions have a charge of 2+ and 2−. The magnesium ion is drawn with its new outer shell, shell 2, which is full.

Now think about a crystal of salt. Each Na^+ ion is attracted to every Cl^- ion round it, and each Cl^- ion to every Na^+ ion. The ions sit in a regular pattern that repeats in all directions. It is a **giant ionic lattice**.



A small part of the lattice, in one flat layer. A real crystal has layers above and below too.

Ionic compounds have **high melting points**. To melt a crystal you must pull the ions out of their fixed places. They attract in every direction, so it takes a lot of energy. The attraction is stronger when the charges are bigger.

Compound	Melts at
sodium chloride	801 °C
magnesium oxide	2 850 °C

Magnesium oxide has ions of 2+ and 2−, so its bonds are stronger and it melts at a much higher temperature.

A crystal of salt is hard, but it breaks if you hit it. A blow can slide one layer along another. Then ions with the same charge sit side by side and repel. The crystal splits. We say it is brittle.

Do ionic compounds conduct electricity? A solid does not. A current is a flow of charged particles, and the ions in a solid cannot move. They are fixed in the lattice. Solid salt has no charged particles free to carry a current.

When an ionic compound is **molten**, the ions are free to move. Molten sodium chloride conducts, because the ions carry charge. Dissolved in water the ions are free as well, so salt solution conducts too.

Be safe. Scientists test this in a laboratory. Melting salt needs about 800 °C. Mixing water with a mains supply is deadly. Do not try either at home.

TRY IT

Grow salt crystals and see the cubes

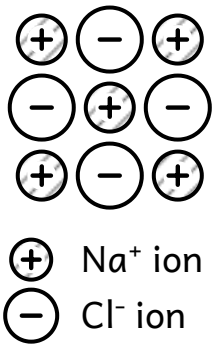
You need: table salt, a spoon and a cup of warm water from a tap, a small dark plate or saucer, a sunny shelf or window ledge, and some days of waiting, a hand lens if you have one, and paper and a pencil.

Be safe: Taste nothing. Warm water from the tap is enough, and an adult should pour any hot water. Keep the plate out of reach of small children.

1. Stir salt into the warm water, a spoon at a time, until no more will dissolve and some stays at the bottom.
2. Pour a thin layer of the clear salty water onto the dark plate. Leave the grains behind.
3. Put the plate in the sun. Leave it for a day or more until the water has dried.
4. Look at the crystals with a hand lens, or very close by eye. Draw one.
5. Look at some grains of dry table salt as well. Compare the shapes.

What you will see: Many of the crystals are tiny cubes or boxes with flat faces and square corners. The ions sit in a regular pattern, so the crystals have regular shapes. Salt that dissolved was ions moving free in water. As the water went, they fell back into the lattice.

If you cannot try it, this is what happens.



A WRONG IDEA MANY PEOPLE HAVE

~~**Sodium chloride is made of molecules, each with one sodium and one chlorine atom.**~~

Why it feels right: The formula NaCl looks like a small unit, like the formula of water.

The test that breaks it: Look at the lattice picture. Pick any Na^+ ion and count the Cl^- ions touching it. There are several. No pair stands apart as a molecule.

What is true: Salt is a giant lattice of ions. The formula NaCl only gives the ratio of the ions, which is one sodium to one chlorine.

KEY WORDS

ion
an atom, or a group of atoms, with an electric charge.

dot and cross diagram
a drawing of outer electrons, with the electrons of one atom as crosses and of the other as dots.

ionic bond
the attraction between oppositely charged ions.

ionic compound
a compound held together by ionic bonds.

giant ionic lattice
a regular pattern of ions that repeats in all directions.

high melting points
melting points far above those of most things at home.

molten
melted, as a liquid.

BACK TO YOUR GUESS

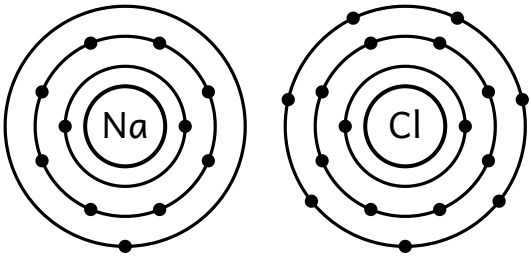
The answer is B: The particles of salt attract one another very strongly.

Salt is made of ions with opposite charges. They attract one another very strongly in every direction, so it takes a very high temperature to pull them apart.

CHECK YOURSELF

Try each one before you look. A wrong answer tells you where to go next.

1. A sodium atom and a chlorine atom meet. What happens to the outer electron of sodium?



   A It is shared with the chlorine atom.

   B It moves to the chlorine atom.

   C It stays, and the chlorine atom gives one away.

   Answer at the back of the book.

2. A magnesium atom loses 2 electrons. What is the ion?

   A Mg^{2+}

   B Mg^{+}

   C Mg^{2-}

   Answer at the back of the book.

3. An oxygen atom is arranged 2, 6. Which ion does it form?

   A O^{6+}

   B O^{2-}

   C O^{2+}

   Answer at the back of the book.

4. Why does sodium chloride have a high melting point?

   A It is made of molecules that are very heavy.

   B It has strong bonds between pairs of atoms inside each molecule.

   C Strong forces between oppositely charged ions act in every direction.

   Answer at the back of the book.

5. Which of these conducts electricity?

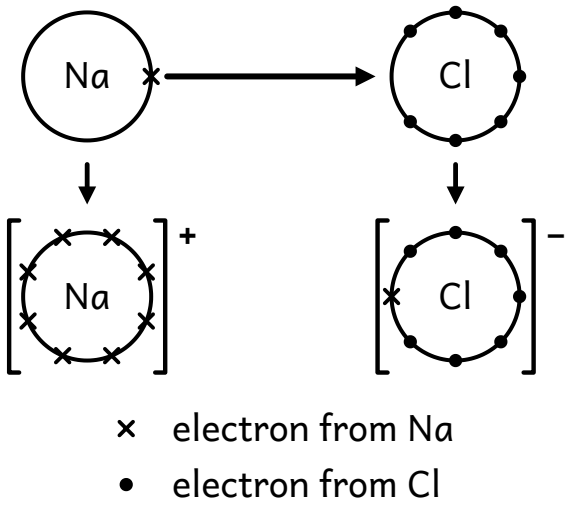
   A Molten sodium chloride

   B Solid sodium chloride

   C Solid magnesium oxide

   Answer at the back of the book.

6. This diagram shows an ionic bond between sodium and chlorine. How many electrons move from sodium to chlorine?



   A 7 electrons

   B 8 electrons

   C 1 electron

   Answer at the back of the book.

7. **From an earlier chapter**

   Chlorine, bromine and iodine are halogens. Which of these is the most reactive?

   A Iodine

   B Chlorine

   C Bromine

   Answer at the back of the book.

8. A magnesium ion, Mg^{2+}, has 12 protons. How many electrons does it have?

   Answer at the back of the book.

9. Oxygen is in group 6. How many electrons does one atom gain to get a full outer shell?

   Answer at the back of the book.

KEEP IT

Copy this into your exercise book.

A metal atom loses electrons and a non-metal atom gains them, so both ions have full outer shells. Oppositely charged ions attract in a giant lattice: high melting point, and it conducts only when molten or dissolved.

Draw: Sodium chloride as a dot and cross diagram. Na gives one electron to Cl. Draw both ions in brackets with their charges.

S4.6.7 CHAPTER 7

Covalent bonding

> **A diamond is the hardest natural material. Pencil lead is made of the same atoms. Why is it so soft?**

YOUR GUESS

Pick one before you read on. It is fine to be wrong.

- ☐ **A** Diamond is carbon and pencil lead is another element.
- ☐ **B** Both are carbon, but the atoms are joined in different patterns.
- ☐ **C** Diamond has heavier atoms than pencil lead.

IF THIS FEELS HARD, READ THIS FIRST

- Level 3, Elements, mixtures, reactions and acids, S3.6.1. It says that a compound has elements joined together, such as water.
- Level 3, Particles, S3.5.3. It explains melting and boiling, which we compare for different bonds.

BY THE END YOU CAN

- Draw dot and cross diagrams for water, methane and oxygen
- Compare simple molecules with giant structures such as diamond and graphite

In the last chapter a metal gave electrons to a non-metal. Two non-metal atoms both need electrons, so neither will give any up. They do something else. They **share** them.

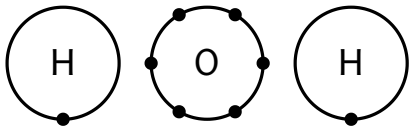
A **covalent bond** is a shared pair of electrons between two atoms. The shared pair counts for both atoms. Each atom ends with a full outer shell: 8, or 2 for hydrogen.

A **molecule** is a small group of atoms joined by covalent bonds. In a water molecule an oxygen atom shares a pair with each of two hydrogen atoms. This is why its

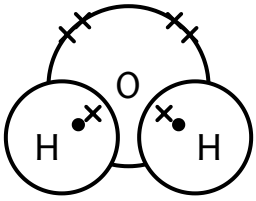
formula is H_2O.

DRAW IT FIRST

Making a water molecule



1 The atoms are apart. Oxygen has 6 outer electrons and needs 2 more. Each hydrogen has 1 and needs 1 more.



× electron from O

• electron from H

2 Oxygen shares one pair with each hydrogen. Now oxygen counts 8 outer electrons, and each hydrogen counts 2.

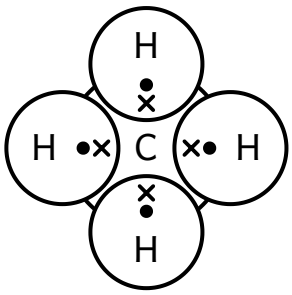
In a dot and cross diagram we draw the outer electrons of the central atom as crosses and the others as dots. The overlap holds the shared pairs. A pair on one atom that is not shared is a **lone pair**.

WORKED EXAMPLE

A carbon atom has 4 outer electrons. Each hydrogen atom shares 1 electron. How many hydrogen atoms bond to one carbon atom to give it a full outer shell?

1. A full outer shell holds 8, so carbon needs 8 − 4 = 4 more electrons.
2. Each hydrogen atom gives one shared electron, so carbon needs 4 hydrogen atoms.
3. The molecule is CH_4, which is called methane.

Answer: 4 hydrogen atoms



× electron from C
• electron from H

Methane, CH_4. Carbon has four shared pairs, so eight electrons round it.

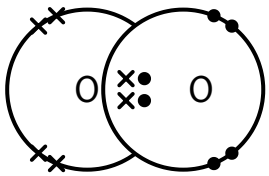
Oxygen gas is made of molecules of two oxygen atoms. Each atom has 6 outer electrons and needs 2 more. So they share two pairs. Two shared pairs make a **double bond**.

WORKED EXAMPLE

Each oxygen atom has 6 outer electrons. In an oxygen molecule, O_2, how many pairs do the two atoms share?

1. Each oxygen needs 8 − 6 = 2 more electrons.
2. A shared pair gives 1 electron to each atom, so each atom needs 2 pairs.
3. The two atoms share 2 pairs, which is a double bond. That is 4 shared electrons.

Answer: 2 pairs

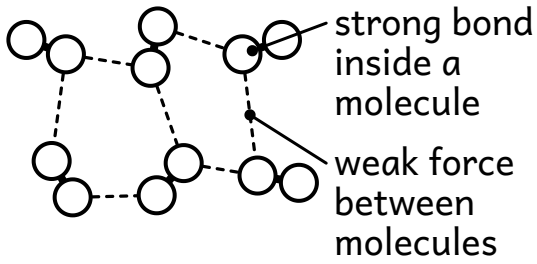


× electron from one O
• electron from the other O

Oxygen, O_2. The double bond is two shared pairs.

The covalent bonds inside a molecule are strong. But a molecule has no charge overall, so the forces between one molecule and the next are weak. A substance

made of small molecules is called a **simple molecule** substance. Water and methane are examples.



Strong bonds inside each molecule. Weak forces between the molecules.

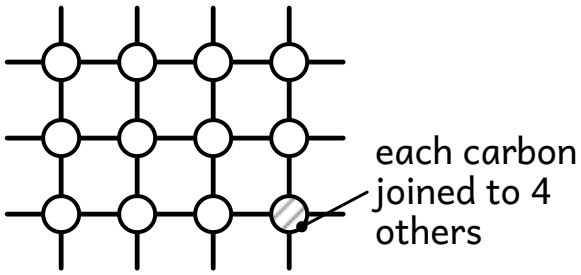
To melt or boil a simple molecule substance you only need to pull the molecules apart. You do not break the bonds inside them. The weak forces need little energy, so these substances have low melting and boiling points. Many are gases or liquids at room temperature.

Substance	Melts at
water	0 °C
methane	−182 °C
oxygen	−219 °C
sodium chloride	801 °C

Three simple molecule substances melt at low temperatures. Salt, an ionic compound, melts at a very high one.

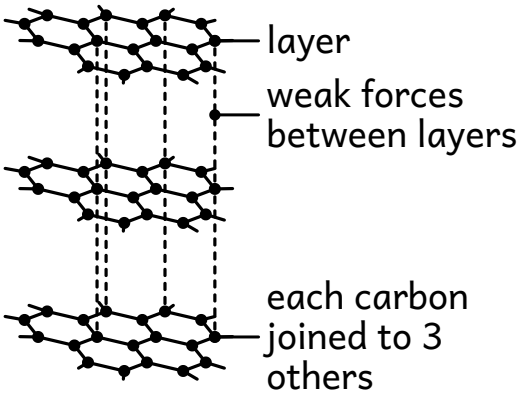
Simple molecule substances do not conduct electricity. A molecule has no charge, and no ions or free electrons carry one. This is true as a solid, as a liquid and as a gas. Pure water conducts only very slightly. Tap water conducts better, because ions are dissolved in it, so water and mains electricity are always dangerous together.

Some covalent substances are not small molecules at all. In a **giant covalent structure** a huge number of atoms, far more than millions, are joined by covalent bonds in one network. Carbon makes two well known examples with very different properties.



Diamond. Every carbon atom is joined to four others. In the real crystal the four bonds point out in three dimensions, to the corners of a pyramid. They are not at right angles, as drawn here.

In diamond each carbon atom shares all four of its outer electrons, in four bonds. The network is strong in every direction. So diamond is very hard and has a very high melting point. No electron is free, so it does not conduct.



Graphite. Each carbon is joined to three others, in flat layers.

In graphite each carbon atom uses only three of its four outer electrons, in three bonds in a flat layer. The layers are held by weak forces, so they slide over each other. This is why graphite is soft and slippery. The pencil lead you write with holds graphite.

The fourth electron of each carbon in graphite is free to move along the layer. A moving electron carries charge, so graphite conducts electricity. It is one of the few non-metals that does. Sand, silicon dioxide, is another giant covalent structure.

Be safe. Scientists test the conduction of graphite with a battery, wires and a bulb. Do not use mains electricity for any test at home.

TRY IT

A dot and cross model of water with seeds

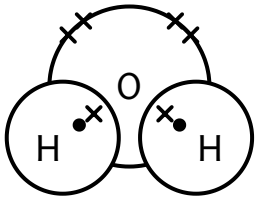
You need: a sheet of paper and a pencil, a cup, to draw round, 6 dark seeds or beans and 2 pale seeds or grains of rice.

Be safe: Do not eat the seeds or beans. Keep small seeds away from young children.

1. Draw round the cup for oxygen. Draw two more circles, one on each side, each overlapping the oxygen circle. They are the hydrogen atoms.
2. Put 6 dark seeds round the oxygen circle. They are the outer electrons of oxygen.
3. Put 1 pale seed in each hydrogen circle. They are the electrons of hydrogen.
4. Slide each pale seed into an overlap. Slide one dark seed from oxygen next to it, so the two make a shared pair.
5. Count the seeds inside each circle, including the overlap.

What you will see: The oxygen circle holds 8 seeds: 6 dark and 2 pale. Each hydrogen circle holds 2 seeds. Each atom has a full outer shell. The two seeds in an overlap count in both circles.

If you cannot try it, this is what happens.



× electron from O

• electron from H

A WRONG IDEA MANY PEOPLE HAVE

~~When water boils, the bonds between the hydrogen and oxygen atoms break.~~

Why it feels right: Boiling is a big change, and it seems that something strong must break.

The test that breaks it: Collect steam on a cold plate. It turns back to liquid water, and the water is just as before. If the atoms had come apart you would have hydrogen and oxygen gas.

What is true: Only the weak forces between the molecules are overcome. The molecules stay whole, and the covalent bonds inside them do not break.

KEY WORDS

covalent bond
a shared pair of electrons between two atoms.

molecule
a small group of atoms joined by covalent bonds.

lone pair
a pair of outer electrons on one atom that is not shared.

double bond
two shared pairs of electrons between two atoms.

simple molecule
a small molecule, with strong bonds inside it and weak forces between molecules.

giant covalent structure
a huge network of atoms joined by covalent bonds.

share
to use a pair of electrons that belongs to two atoms at once.

BACK TO YOUR GUESS

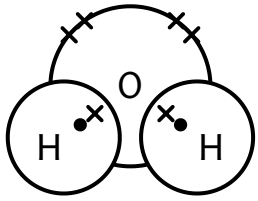
The answer is B: Both are carbon, but the atoms are joined in different patterns.

Diamond and the graphite in pencil lead are both pure carbon. In diamond each atom is joined to four others. In graphite each atom is joined to three, in layers that slide.

CHECK YOURSELF

Try each one before you look. A wrong answer tells you where to go next.

1. This is a water molecule. How many pairs of electrons does the oxygen atom share?



× electron from O
• electron from H

   A 2 pairs
   B 6 pairs
   C 1 pair

   Answer at the back of the book.

2. What is a covalent bond?

   A The attraction between a positive ion and a negative ion
   B A shared pair of electrons between two atoms
   C A force between two molecules

   Answer at the back of the book.

3. Why do substances made of small molecules melt at low temperatures?

   A The covalent bonds inside the molecules are weak.
   B The molecules are very light.
   C Only the weak forces between the molecules must be overcome.

   Answer at the back of the book.

4. Why does graphite conduct electricity but diamond does not?

   A Graphite contains ions that can move and diamond contains none.

   B In graphite each carbon atom has one electron that is free to move.

   C Graphite is a metal.

   Answer at the back of the book.

5. Why is graphite soft and slippery?

   A Its layers are held by weak forces, so they slide over each other.

   B The carbon atoms in each layer are weakly bonded.

   C Graphite has fewer carbon atoms than diamond.

   Answer at the back of the book.

6. A nitrogen atom has 5 outer electrons. How many hydrogen atoms bond to one nitrogen atom in ammonia, NH_3?

   A 5 hydrogen atoms

   B 4 hydrogen atoms

   C 3 hydrogen atoms

   Answer at the back of the book.

7. **From an earlier chapter**

   What kind of particles carry the current when molten sodium chloride conducts?

   A Ions

   B Electrons

   C Molecules

   Answer at the back of the book.

8. A hydrogen atom bonds with an atom of sulfur. Sulfur has 6 outer electrons. How many hydrogen atoms bond to one sulfur atom?

   Answer at the back of the book.

9. A molecule of O_2 has 2 shared pairs of electrons. How many electrons are shared in all?

   Answer at the back of the book.

KEEP IT

Copy this into your exercise book.

A covalent bond is a shared pair of electrons. Simple molecules: strong bonds inside, weak forces between, low melting points, no conduction. Diamond: four bonds each, hard. Graphite: layers that slide, and it conducts.

Draw: A dot and cross diagram of water, with the shared pairs in the overlaps and two lone pairs on oxygen.

S4.6.8 CHAPTER 8

Metals and alloys

Why can a metal wire be bent, when a lump of salt shatters?

YOUR GUESS

Pick one before you read on. It is fine to be wrong.

- ☐ **A** The layers of a metal can slide over each other, and the bonding still holds.
- ☐ **B** The bonds in a metal are very weak.
- ☐ **C** Metal atoms are not joined to one another.

IF THIS FEELS HARD, READ THIS FIRST

- Level 3, Elements, mixtures, reactions and acids, S3.6.1. It names common metal elements, such as iron and gold.
- Level 3, Electricity and magnetism, S3.10.1. It says that a current is a flow of charge, which we explain here.
- Level 3, Elements, mixtures, reactions and acids, S3.6.2. It tells a pure substance from a mixture, which helps with alloys.

BY THE END YOU CAN

- Explain how metallic bonding lets metals conduct and bend
- Explain why alloys are harder than pure metals

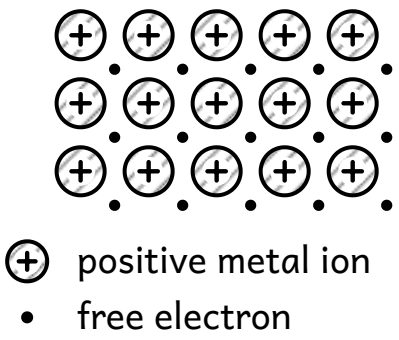
Think of copper wire, an iron nail and a gold ring. Most metals share some properties. They are shiny when polished and strong. They conduct heat and electricity. They bend and can be hammered into shape.

A metal that can be hammered or bent into shape is **malleable**. Most metals also have high melting points. A few are exceptions, such as mercury, which is a liquid at

room temperature.

In Chapter 6 a metal atom lost its outer electrons to become a positive ion. In a lump of metal this happens to all the atoms. Their outer electrons come free. They no longer belong to one atom. We say they are **delocalised**.

The positive ions sit in a regular pattern, in layers. The delocalised electrons move freely through all the spaces between them, like a sea. The attraction between the ions and the sea of electrons is the **metallic bond**.



A metal. The ions are in layers. The free electrons move between them.

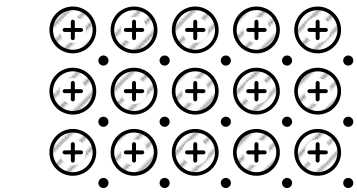
The metal as a whole has no charge. There are as many free electrons as there are charges on the ions. The sea of negative electrons balances the positive ions.

Metals conduct electricity because the free electrons can move. When a metal is part of a circuit, the electrons are pushed along it and carry charge. Salt in the solid state cannot do this, because its ions are fixed.

Metals conduct heat well for the same reason. The free electrons carry energy quickly from the hot end of a metal to the cold end. This is why a metal spoon in a hot drink soon feels hot.

DRAW IT FIRST

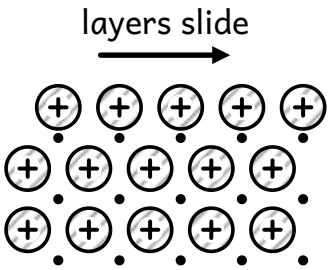
Why a metal bends



positive metal ion

free electron

1 Layers of positive ions are held in place by the sea of free electrons.



positive metal ion

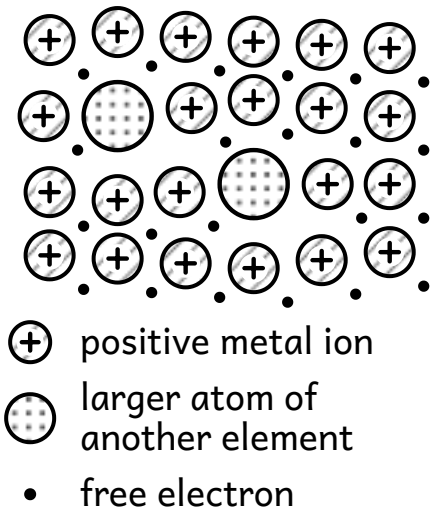
free electron

2 A push slides one layer over the next. The ions are still surrounded by the sea of electrons, so the metal holds together and just changes shape.

In salt the layers cannot slide in the same way. A slide puts like charges side by side, and they repel. The crystal splits. In a metal the electrons hold the layers whatever the position, so a metal bends instead of breaking.

Pure metals are often soft. In a pure metal all the atoms are the same size, so the layers slide easily. Pure gold and pure iron are examples. A soft metal is no use for a bridge or a tool.

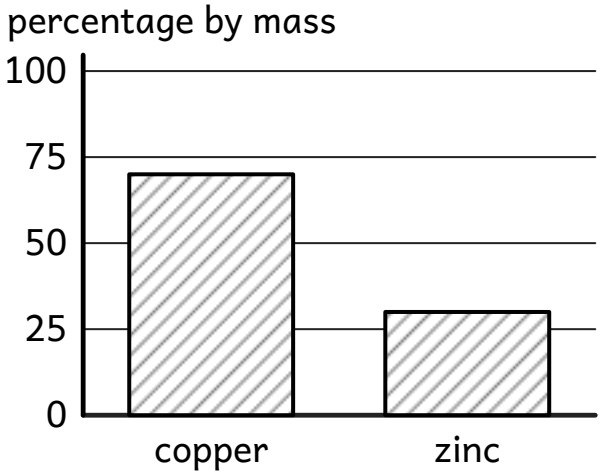
An **alloy** is a mixture of a metal with one or more other elements. Brass is copper with zinc. Bronze is copper with tin. Steel is iron with a small amount of carbon. The other atoms are a different size.



An alloy. The larger atoms disturb the layers, so they cannot slide easily.

The odd sized atoms get in the way when a layer tries to slide. The layers slide less, so an alloy is harder and stronger than the pure metal. Alloys are still held by metallic bonding, so they still conduct.

The mass of each part of an alloy is often given as a percentage by mass. A percentage tells us how many parts out of 100.



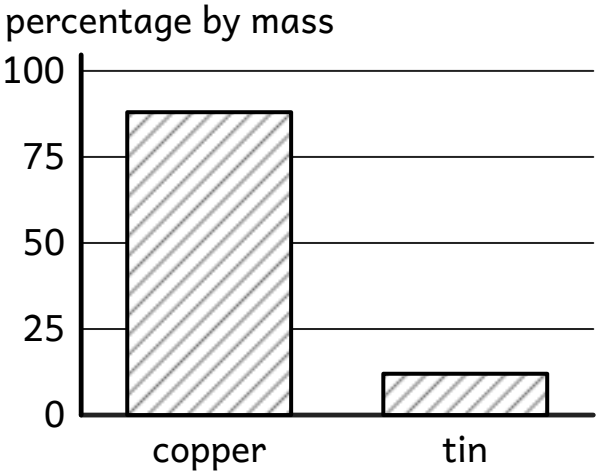
A common kind of brass is 70% copper and 30% zinc.

WORKED EXAMPLE

A common kind of brass is 70% copper by mass. How many grams of copper are in a brass piece of mass 250 g?

1. 70% means 70 parts in every 100.
2. Find 70% of 250 g: 70 ÷ 100 × 250 g.
3. 70 ÷ 100 × 250 g = 175 g.

Answer: 175 g



A common kind of bronze is 88% copper and 12% tin.

WORKED EXAMPLE

A small statue is made of bronze with a mass of 500 g. This bronze is 88% copper by mass and the rest is tin. How many grams of tin are in the statue?

1. The tin is the rest: 100% − 88% = 12%.
2. Find 12% of 500 g: 12 ÷ 100 × 500 g.
3. 12 ÷ 100 × 500 g = 60 g.

Answer: 60 g

TRY IT

Make layers slide, then stop them

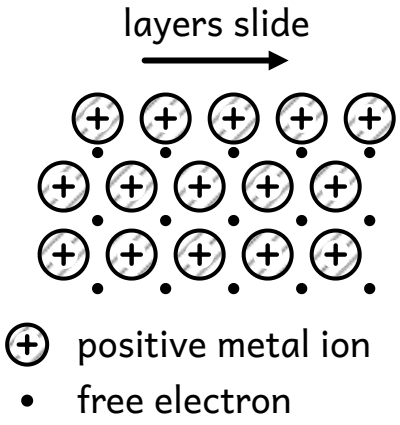
You need: a shallow tray or box lid with a rim, about 30 round things of one size: dried peas, marbles or small round stones, a few bigger things, such as large beans or bigger stones.

Be safe: Marbles and small stones can be swallowed by small children, and they roll. Do the activity on a table, and pick up every piece when you finish.

1. Fill the tray with rows of the small round things, touching, in neat rows.
2. Push the top row sideways with a finger. Watch how easily it slides over the row below.
3. Take out about six of the small ones, spread through the rows. Put the bigger things in their places.
4. Push the top row again. Does it slide as freely?

What you will see: With rows of one size the top row slides easily. With bigger pieces mixed in, the rows catch on them and slide much less. This is how an alloy is harder than a pure metal.

If you cannot try it, this is what happens.



A WRONG IDEA MANY PEOPLE HAVE

~~**A metal has a negative charge, because it has a sea of electrons.**~~

Why it feels right: The electrons are negative, and there are very many of them.

The test that breaks it: Count the charges. Every free electron came from an atom that became a positive ion. Each ion has a charge that one electron balances.

What is true: A metal is neutral. The negative sea of electrons exactly balances the positive ions.

KEY WORDS

malleable
able to be hammered or bent into shape without breaking.

delocalised
not attached to one atom, and free to move.

metallic bond
the attraction between the positive ions of a metal and its sea of free electrons.

alloy
a mixture of a metal with one or more other elements.

percentage by mass
how many grams out of every 100 g of a mixture are one part of it.

BACK TO YOUR GUESS

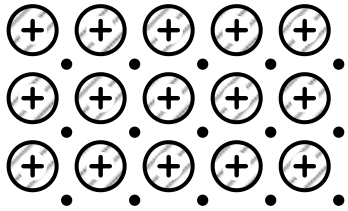
The answer is A: The layers of a metal can slide over each other, and the bonding still holds.

A metal is positive ions in a sea of free electrons. The layers of ions slide, and the electrons still hold them together. In salt a slide puts like charges side by side, and the crystal splits.

CHECK YOURSELF

Try each one before you look. A wrong answer tells you where to go next.

1. This is a model of a metal. What holds the metal together?



⊕ positive metal ion

• free electron

   A The attraction between positive ions and a sea of free electrons

   B Shared pairs of electrons between pairs of atoms

   C Electrons passing from metal atoms to non-metal atoms

   Answer at the back of the book.

2. Why do metals conduct electricity?

   A The positive ions flow through the metal.

   B Metal atoms contain more electrons than other atoms.

   C Free electrons move through the metal and carry charge.

   Answer at the back of the book.

3. Why can a metal be bent without breaking?

   A The layers of ions slide over each other, and the sea of electrons keeps them together.

   B The metal bonds are weak.

   C A slide puts like charges side by side, so the metal bends.

   Answer at the back of the book.

4. Why is an alloy harder than the pure metal?

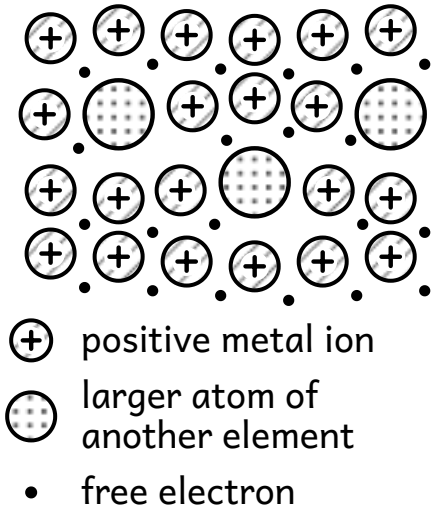
   A The alloy has stronger metallic bonds.

   B Atoms of a different size disturb the layers, so they slide less easily.

   C All the atoms in an alloy are the same size.

   Answer at the back of the book.

5. This picture shows rows of metal atoms with a few larger atoms of another element in them. What is this material?



   A A compound of two elements

   B A giant ionic lattice

   C An alloy

   Answer at the back of the book.

6. A brass key has a mass of 200 g. Brass is 70% copper by mass. How many grams of copper are in the key?

   A 70 g

   B 140 g

   C 60 g

   Answer at the back of the book.

7. **From an earlier chapter**

   Graphite and a metal both conduct electricity. What do they have in common?

   A Free electrons that carry the charge

   B Ions that are free to move

   C Shared pairs that carry the current

   Answer at the back of the book.

8. A brass piece has a mass of 250 g. Brass is 70% copper by mass. How many grams of copper are in it?

   Answer at the back of the book.

9. A bronze piece has a mass of 400 g. It is 88% copper by mass, and the rest is tin. How many grams of tin are in it?

   Answer at the back of the book.

KEEP IT

Copy this into your exercise book.

A metal is positive ions in a sea of free electrons. The electrons carry charge and heat. Layers slide, so metals bend. In an alloy, atoms of other sizes block the layers, so it is harder.

Draw: Rows of positive ions with dots between them for electrons, and a second picture with two larger atoms in the rows.

Key words, A to Z

Every key word in this book, what it means, and the chapter that teaches it.

abundance
how much of an isotope there is, often as a percentage of all the atoms. S4.6.3

alkali metals
the metals of group 1. S4.6.5

alloy
a mixture of a metal with one or more other elements. S4.6.8

alpha particle
a small, fast, positive particle given out by some radioactive substances. S4.6.2

atomic number
the number of protons in an atom. S4.6.1

covalent bond
a shared pair of electrons between two atoms. S4.6.7

delocalised
not attached to one atom, and free to move. S4.6.8

dot and cross diagram
a drawing of outer electrons, with the electrons of one atom as crosses and of the other as dots. S4.6.6

double bond
two shared pairs of electrons between two atoms. S4.6.7

electron
a particle outside the nucleus with a charge of −1 and almost no mass. S4.6.1

electron arrangement
the number of electrons on each shell, from the inside, such as 2, 8, 1. S4.6.4

evidence
the results of careful experiments. S4.6.2

giant covalent structure
a huge network of atoms joined by covalent bonds. S4.6.7

giant ionic lattice
a regular pattern of ions that repeats in all directions. S4.6.6

group

a column of the periodic table. The number is the outer electrons. S4.6.4

group number
the number of electrons in the outer shell, with group 0 for a full outer shell. S4.6.4

halogens
the non-metals of group 7. S4.6.5

high melting points
melting points far above those of most things at home. S4.6.6

ion
an atom, or a group of atoms, with an electric charge. S4.6.6

ionic bond
the attraction between oppositely charged ions. S4.6.6

ionic compound
a compound held together by ionic bonds. S4.6.6

isotopes
atoms of one element with the same number of protons and different numbers of neutrons. S4.6.3

lone pair
a pair of outer electrons on one atom that is not shared. S4.6.7

malleable
able to be hammered or bent into shape without breaking. S4.6.8

mass number
the number of protons plus the number of neutrons. S4.6.1

metallic bond
the attraction between the positive ions of a metal and its sea of free electrons. S4.6.8

model
a picture or idea that explains what we measure. S4.6.2

molecule
a small group of atoms joined by covalent bonds. S4.6.7

molten
melted, as a liquid. S4.6.6

neutral
with no overall charge. S4.6.1

neutron
a particle in the nucleus with no charge and a mass of 1. S4.6.1

noble gases
the unreactive gases of group 0. S4.6.5

nuclear model
the atom as a tiny positive nucleus with electrons far outside it. S4.6.2

nucleus
the tiny centre of an atom, made of protons and neutrons. S4.6.1

outer shell
the outermost shell that holds electrons. S4.6.4

percentage by mass
how many grams out of every 100 g of a mixture are one part of it. S4.6.8

period
a row of the periodic table. The number is the number of shells. S4.6.4

period number
the number of shells in the atom. S4.6.4

periodic table
the elements in order of atomic number, in rows and columns so that similar elements are in one column. S4.6.5

plum pudding model
the atom as a positive ball with electrons spread through it. S4.6.2

predicted
said before it is found, from a pattern. S4.6.5

proton
a particle in the nucleus with a charge of +1 and a mass of 1. S4.6.1

reactivity
how readily an element takes part in reactions. S4.6.5

relative atomic mass
the mean mass of the atoms of an element, on a scale where a carbon 12 atom is exactly 12. S4.6.3

share
to use a pair of electrons that belongs to two atoms at once. S4.6.7

shell
a place at a set distance from the nucleus where electrons move. S4.6.4

simple molecule

a small molecule, with strong bonds inside it *a*nd weak forces between molecules. S4.6.7

trend

a change that goes step by step down *a* group or *a*long *a* period. S4.6.5

Answers

S4.6.1. Inside the atom

1. **3 electrons**

   The hatched circles are protons, and there are 3. A neutral atom has as many electrons as protons.

   - **If you chose B:** You may have counted the neutrons. Neutrons have no charge. The electrons must cancel the protons, which are the hatched circles.
   - **If you chose C:** You may have counted every particle in the nucleus. Only the protons need electrons to cancel their charge.

2. **The neutron**

   A neutron has a charge of 0. That is why it is called neutral.

   - **If you chose A:** A proton is in the nucleus, but it carries a positive charge of +1.
   - **If you chose C:** An electron is very light, but it carries a negative charge of −1.

3. **It has the opposite charge and much less mass.**

   A proton is +1 and an electron is −1. An electron has about $^{1}/_{1840}$ of the mass of a proton.

   - **If you chose A:** The charges are opposite, but an electron has only about $^{1}/_{1840}$ of the mass of a proton.
   - **If you chose B:** A proton is positive and an electron is negative. The charges are opposite.

4. **In the nucleus**

   Protons and neutrons each have a mass of 1. Electrons have almost none. Protons and neutrons are in the nucleus.

   - **If you chose B:** Electrons have almost no mass. The shells are mostly empty space.
   - **If you chose C:** That is the solid ball idea. The mass is packed into the tiny nucleus.

5. **10 neutrons**

   Neutrons = mass number − atomic number = 19 − 9 = 10.

   - **If you chose A:** The mass number counts protons and neutrons together. Take away the protons.
   - **If you chose B:** That is the number of protons. Neutrons = mass number − atomic number.
   - **If you chose C:** Adding gives too many. The mass number already includes the protons, so you take the protons away.

6. **It has as many electrons as protons, and their charges cancel.**

   Each proton is +1 and each electron is −1. With equal numbers the total is 0.

   - **If you chose A:** Neutrons have no charge, so they cannot cancel anything. The electrons do that.
   - **If you chose C:** It does. It has protons (+1) and electrons (−1). They cancel.

7. **12 neutrons**

   24 − 12 = 12.

8. **28**

   The mass number is protons plus neutrons: 14 + 14 = 28.

S4.6.2. How the model of the atom changed

1. **The nuclear model of Rutherford**

   It has a tiny nucleus and electrons far away in empty space, with no shells. That is the nuclear model.

   - **If you chose A:** The plum pudding model has electrons spread through a big positive ball. Here the positive part is a tiny nucleus.
   - **If you chose B:** Dalton drew a plain ball with nothing inside. This picture has a nucleus and separate electrons.
   - **If you chose D:** Bohr put the electrons on shells. Here they are scattered, and the circle is only the edge of the atom.

2. **The plum pudding model**

   A plum pudding atom has no tiny dense centre, so it could not make alpha particles bounce back.

   - **If you chose A:** Thomson had already replaced Dalton's ball when he found electrons, years before the gold foil experiment.
   - **If you chose C:** Bohr came after the gold foil results. He built on the nucleus that they showed.

3. **Most of an atom is empty space.**

   Particles pass freely only through empty space. The paths went straight, so there was nothing in the way.

   - **If you chose B:** If atoms were solid balls, alpha particles would be stopped or turned. Most went on as if nothing was there. Go to S4.6.1.
   - **If you chose C:** Atoms are neutral overall, but they hold charges. A few alpha particles were turned back, so something was repelling them. Go to S4.6.1.

4. **An atom has a tiny, heavy, positive nucleus.**

   A positive alpha particle is repelled by a positive nucleus. Only a heavy, tiny centre can turn it right round.

   - **If you chose A:** An electron is far too light to turn back a fast alpha particle, as a marble cannot turn back a lorry. The cause must be heavy. Go to S4.6.1.
   - **If you chose B:** A thick foil would stop particles, not send them back. The few that bounced came from a repelling positive centre.

5. **The electrons move on fixed shells.**

   Bohr put each electron at a set distance from the nucleus, on a shell. This fitted the light that hydrogen gives out.

   - **If you chose A:** That is the plum pudding model of Thomson. Bohr kept the nucleus and put the electrons on shells.
   - **If you chose C:** Neutrons were found in 1932, after Bohr's model. The new idea of 1913 was the shells.

6. **The nucleus had more mass than its protons could explain.**

   Helium has two protons but four times the mass of hydrogen. Neutral particles of the same mass as a proton fill the gap.

   - **If you chose A:** Electrons are held by the pull of the positive nucleus. The neutron has no charge and does not pull them. Go to S4.6.1.
   - **If you chose B:** A neutron has no charge at all. The extra particles added mass, not charge. Go to S4.6.1.

7. **Protons and neutrons**

   The nucleus holds protons (+1) and neutrons (0). The electrons (−1) are outside it.

   - **If you chose B:** Electrons are outside the nucleus. They move on the shells. Go to S4.6.1.
   - **If you chose C:** Most nuclei also hold neutrons. They add mass but no charge. Go to S4.6.1.

8. **About 3 bounce back**

   24 000 ÷ 8 000 = 3.

9. **300 m**

   3 mm × 100 000 = 300 000 mm. Divide by 1 000 to get metres: 300 m.

S4.6.3. Isotopes

1. **The number of protons**

   All carbon atoms have the same number of protons, and that is what makes them carbon. The neutrons can differ.

   - **If you chose A:** The neutrons are what differ. That is why the atoms are different isotopes.
   - **If you chose B:** The mass number is protons plus neutrons. With different neutrons, the mass number differs.

2. **They have the same number of electrons.**

   Reactions are about electrons. Isotopes have the same protons, so the same number of electrons, and so the same reactions.

   - **If you chose A:** Isotopes differ in mass, because they have different numbers of neutrons. Reactions depend on electrons.
   - **If you chose B:** Isotopes have different numbers of neutrons. The same electrons make the reactions the same.
   - **If you chose C:** They are different in mass, but they are still the same element. The sameness of the electrons is the reason.

3. **12 neutrons**

   Neutrons = mass number − atomic number = 22 − 10 = 12. Neon 20 has 10 neutrons, so this isotope has 2 more.

   - **If you chose B:** That is the mass number. It counts the protons too, so take the protons away. Go to S4.6.1.
   - **If you chose C:** That is the number of protons. Neutrons = mass number − atomic number. Go to S4.6.1.

4. **It is the mean mass of chlorine atoms, which are a mixture of isotopes.**

   Chlorine atoms have mass numbers of 35 and 37. The mean, weighted by how many there are of each, is 35.5.

   - **If you chose A:** No atom has half a particle. The 35.5 is a mean over a mixture of atoms.
   - **If you chose C:** Neutrons are whole particles. The half comes from averaging atoms of mass 35 and 37.

5. **10.8**

   (20 × 10 + 80 × 11) ÷ 100 = (200 + 880) ÷ 100 = 1 080 ÷ 100 = 10.8.

   - **If you chose A:** You found the plain mean of 10 and 11. Boron 11 is far more common, so it counts for more. Go to M4.7.2.
   - **If you chose B:** Boron 11 is the most common, but there is some boron 10, so the mean is a little lower.

6. **Multiply each mass number by its percentage, add, and divide by the total of the percentages.**

   Each isotope counts as much as its share of the atoms. That is a weighted mean.

   - **If you chose B:** That is a plain mean. It ignores how common each isotope is. Go to M4.7.2.
   - **If you chose C:** That is close, but not exact. Every isotope counts in proportion to its share.

7. **The shell model of Bohr**

   Niels Bohr placed each electron on a shell at a set distance from the nucleus.

   - **If you chose A:** Rutherford showed a nucleus, but he did not put the electrons on shells. Go to S4.6.2.
   - **If you chose C:** Thomson spread his electrons through a positive ball. There were no shells. Go to S4.6.2.

8. **22 neutrons**

   41 − 19 = 22.

9. **20.5**

   (75 × 20 + 25 × 22) ÷ 100 = (1 500 + 550) ÷ 100 = 2 050 ÷ 100 = 20.5.

S4.6.4. Electron shells

1. **Group 6**

   Count the electrons on the outer shell. There are 6, so sulfur is in group 6.

   - **If you chose A:** Three is the number of shells, so it gives the period. The group is the number of outer electrons.
   - **If you chose C:** Eight is the electrons in shell 2. Count only the outer shell.

2. **Period 3**

   There are three numbers, so the atom has three shells. It is in period 3.

   - **If you chose A:** You may have added up the electrons. The period is the number of shells.
   - **If you chose B:** The first number is the electrons in shell 1, not the number of shells. Count the numbers in the arrangement.

3. **2, 7**

   Shell 1 takes 2. The other 7 go in shell 2. So the arrangement is 2, 7.

   - **If you chose A:** Shell 2 holds up to 8, but fluorine has only 9 electrons in all. 2 + 8 would be 10.
   - **If you chose B:** The numbers go from the inside out. Shell 1 is filled first, so it comes first.
   - **If you chose C:** All 9 cannot go on one shell. Shell 1 holds only 2, so the rest go on shell 2.

4. **Its outer shell is full.**

   Shell 1 holds at most 2 electrons. Helium has 2, so its outer shell is full. A full outer shell is a very steady arrangement.

   - **If you chose B:** Helium has only 2 electrons in all. Its outer shell is the first, which holds 2 when it is full.
   - **If you chose C:** It does. Its two electrons are on shell 1, which is its outer shell.

5. **Chlorine**

   Chlorine has the arrangement 2, 8, 7. It has 7 outer electrons and 3 shells, so it is in group 7 and period 3.

   - **If you chose A:** Sulfur is in period 3, but it is in group 6. It has 6 outer electrons.
   - **If you chose C:** Fluorine is in group 7, but it is in period 2. It has only 2 shells.

6. **8 electrons**

   For the first 20 elements the shells fill to 2, 8 and 8, then shell 4 starts. Argon has the arrangement 2, 8, 8.

   - **If you chose A:** In bigger atoms the third shell can hold up to 18. For the first 20 elements it fills to 8, and then shell 4 starts.
   - **If you chose B:** Two is what shell 1 holds. Shells 2 and 3 hold 8 each for these elements.

7. **2, 8, 7**

   Both isotopes have 17 protons, so 17 electrons. They fill 2, then 8, then 7 on the third shell.

   - **If you chose B:** That is argon, with 18 electrons. Chlorine has 17, so the last shell holds 7.
   - **If you chose C:** Chlorine 37 has more neutrons, not more electrons. Both isotopes have 17 electrons. Go to S4.6.3.

8. **2, 8, 3**

   Shell 1 takes 2 and shell 2 takes 8. The last 3 go in shell 3.

9. **Group 5, period 2**

   The arrangement is 2, 5. There are 5 outer electrons, so it is in group 5, and 2 shells, so period 2.

S4.6.5. The periodic table

1. **By atomic mass, in columns of similar elements**

   He put the elements in order of atomic mass and began a new row so that similar elements lined up. He swapped a pair where the properties demanded it.

   - **If you chose A:** That is how the modern table is arranged. Protons were not known in his day.
   - **If you chose B:** He did not use the date of discovery. He used atomic mass and behaviour.

2. **It would behave like silicon, the element above it.**

   Elements in a column have similar properties. The gap is in the silicon column, so the missing element should be like silicon.

   - **If you chose A:** Sodium is in group 1. The gap is in the same column as silicon, so it should be like silicon.
   - **If you chose C:** Argon is at the far right, in group 0. The gap is far from it, in the silicon column.

3. **It rises for the alkali metals and falls for the halogens.**

   A group 1 atom loses an electron, and that is easier further down. A group 7 atom gains an electron, and that is harder further down.

   - **If you chose B:** That is true of the alkali metals only. The halogens become less reactive going down.
   - **If you chose C:** It is the other way round. Potassium is more reactive than lithium, and fluorine is more reactive than iodine.

4. **Its outer electron is further from the nucleus, so it is lost more easily.**

   Potassium has four shells and lithium has two. The outer electron of potassium is held more loosely.

   - **If you chose A:** Both have one outer electron, as both are in group 1. The distance from the nucleus is what changes. Go to S4.6.4.
   - **If you chose B:** The pull is weaker in potassium, because the electron is further away and more inner shells shield it.

5. **Its outer shell is closer to the nucleus, so it pulls an extra electron in more strongly.**

   A halogen reacts by gaining one electron. The nearer the outer shell is to the nucleus, the more strongly the electron is pulled in.

   - **If you chose A:** Both are in group 7 and have seven outer electrons. Go to S4.6.4.
   - **If you chose C:** Bromine atoms are heavier. A reaction depends on how strongly the nucleus pulls an extra electron, not on mass.

6. **Its outer shell is full, so it has no need to gain, lose or share electrons.**

   A full outer shell is a steady arrangement. Argon has 2, 8, 8, so it keeps its electrons as they are.

   - **If you chose B:** Argon has a full outer shell of eight electrons. One outer electron is group 1. Go to S4.6.4.
   - **If you chose C:** Size is not the reason. Neon is smaller and argon is bigger, yet both are unreactive because their outer shells are full.

7. **Group 7**

   The outer shell holds 7 electrons, so the atom is in group 7. It is chlorine, a halogen.

   - **If you chose A:** Three is the number of shells, which gives the period. The group is the number of outer electrons. Go to S4.6.4.
   - **If you chose C:** Eight is the electrons in shell 2. Count only the outer shell. Go to S4.6.4.

8. **93 °C**

   −153 − (−246) = −153 + 246 = 93.

9. **218 °C**

   184 − (−34) = 184 + 34 = 218.

S4.6.6. Ionic bonding

1. **It moves to the chlorine atom.**

   Sodium loses its outer electron and ends with a full second shell. Chlorine gains it and fills its outer shell.

   - **If you chose A:** Sharing electrons is covalent bonding, which joins two non-metals. Sodium is a metal, so it gives its electron away.
   - **If you chose C:** Chlorine needs one more electron for a full shell. It gains one, it does not give one away. Go to S4.6.4.

2. **Mg^{2+}**

   Two electrons lost leaves 12 protons and 10 electrons. The charge is positive, 2+.

   - **If you chose B:** That is the ion after losing one electron. Magnesium has two outer electrons and loses both. Go to S4.6.4.
   - **If you chose C:** A minus charge means electrons were gained. This atom lost them, so the ion is positive.

3. **O^{2-}**

   Oxygen needs 2 more electrons for a full outer shell of 8. Gaining 2 makes the ion O^{2-}.

   - **If you chose A:** Losing all 6 outer electrons is far harder than gaining 2 to fill the shell.
   - **If you chose C:** A non-metal gains electrons and becomes negative. A plus sign means electrons were lost.

4. **Strong forces between oppositely charged ions act in every direction.**

   To melt salt you must pull the ions out of the lattice. The attraction is strong in every direction, so this takes a lot of energy.

   - **If you chose A:** There are no molecules in salt. It is a lattice of ions.
   - **If you chose B:** That is how simple molecules are made. Salt is a lattice of ions, and its strong forces act between all of them.

5. **Molten sodium chloride**

   When melted, the ions are free to move, and moving ions carry charge. Solid salt does not conduct.

   - **If you chose B:** The ions in a solid are fixed in the lattice, so they cannot carry a current.
   - **If you chose C:** It is a solid ionic compound. Its ions are fixed in place just as in salt.

6. **1 electron**

   Sodium has one outer electron, drawn as a cross. It is the only one that moves.

   - **If you chose A:** Seven is the number of outer electrons that chlorine already has. Count the crosses that move.
   - **If you chose B:** Eight is the full outer shell of the chloride ion. Only the crosses moved from sodium.

7. **Chlorine**

   Reactivity falls going down group 7. Chlorine is above bromine and iodine, so it is the most reactive of the three.

   - **If you chose A:** Iodine is at the bottom of group 7. The halogens become less reactive going down. Go to S4.6.5.
   - **If you chose C:** Bromine is below chlorine in group 7, so it is less reactive. Go to S4.6.5.

8. **10 electrons**

   Charge = protons − electrons, so electrons = protons − charge = 12 − 2 = 10.

9. **2 electrons**

   A full outer shell holds 8. Oxygen has 6, so it gains 8 − 6 = 2.

S4.6.7. Covalent bonding

1. **2 pairs**

   There are two overlaps, one with each hydrogen atom. Each holds a shared pair.

   - **If you chose B:** Six is the number of outer electrons of oxygen, not pairs. Look at the overlaps, where the pairs are shared.
   - **If you chose C:** One pair is shared with each hydrogen. There are two hydrogen atoms, so count both.

2. **A shared pair of electrons between two atoms**

   Two non-metal atoms share a pair, and it counts for both. Each atom then has a full outer shell.

   - **If you chose A:** That is an ionic bond, between a metal and a non-metal. Go to S4.6.6.
   - **If you chose C:** That is a weak force between molecules. A covalent bond is inside a molecule and is strong.

3. **Only the weak forces between the molecules must be overcome.**

   The atoms in each molecule stay joined. Only the weak forces between molecules are overcome, and this needs little energy.

   - **If you chose A:** They are strong, and they do not break when the substance melts.
   - **If you chose B:** Mass is not the reason. The forces between the molecules are weak.

4. **In graphite each carbon atom has one electron that is free to move.**

   Graphite uses three of its four outer electrons in bonds. The fourth is free and carries charge. In diamond all four are in bonds.

   - **If you chose A:** Neither is made of ions. Both are pure carbon. The difference is a free electron in graphite.
   - **If you chose C:** Graphite is carbon, a non-metal. It conducts because each carbon has one free electron.

5. **Its layers are held by weak forces, so they slide over each other.**

   Each layer is strong, but the forces between layers are weak. A little push makes the layers slide.

   - **If you chose B:** The bonds inside a layer are strong. The weak forces are between the layers.
   - **If you chose C:** Both are made of carbon atoms. What differs is how they are joined.

6. **3 hydrogen atoms**

   Nitrogen needs 8 − 5 = 3 more electrons. Each hydrogen shares one, so three hydrogen atoms bond.

   - **If you chose A:** Five is the number of outer electrons nitrogen already has. It needs 8 − 5 more, not 5.
   - **If you chose B:** Four is what carbon needs. Nitrogen has one more outer electron than carbon, so it needs one fewer.

7. **Ions**

   When salt melts, its Na^+ and Cl^- ions are free to move. Moving ions carry charge.

   - **If you chose B:** Free electrons carry current in metals and in graphite. In molten salt it is the ions that move. Go to S4.6.6.
   - **If you chose C:** Salt has no molecules. It is a lattice of ions, and the ions are free to move when it melts. Go to S4.6.6.

8. **2 hydrogen atoms**

   Sulfur needs 8 − 6 = 2 more electrons. Each hydrogen shares one, so 2 hydrogen atoms bond. The molecule is H_2S.

9. **4 electrons**

   Each pair is 2 electrons. 2 × 2 = 4.

S4.6.8. Metals and alloys

1. **The attraction between positive ions and a sea of free electrons**

   The free electrons are negative and the ions are positive. The attraction between them is the metallic bond.

   - **If you chose B:** That describes a covalent bond. In a metal the electrons are not shared by one pair. They move through the whole metal. Go to S4.6.7.
   - **If you chose C:** That describes an ionic compound. A pure metal has no non-metal atoms to receive the electrons. Go to S4.6.6.

2. **Free electrons move through the metal and carry charge.**

   A current is a flow of charge. The free electrons of a metal carry it.

   - **If you chose A:** The ions stay in their places. The free electrons are the ones that move.
   - **If you chose B:** It is not the number of electrons but that some are free to move. In salt the electrons are held on ions.

3. **The layers of ions slide over each other, and the sea of electrons keeps them together.**

   The attraction to the sea of electrons works in any position. The layers move, but the metal does not come apart.

   - **If you chose B:** Metallic bonding is strong. The metal bends because the layers can slide, and the electrons keep holding them.
   - **If you chose C:** That happens in salt, where it makes the crystal split. A metal has a sea of electrons, so nothing repels. Go to S4.6.6.

4. **Atoms of a different size disturb the layers, so they slide less easily.**

   The odd sized atoms get in the way. The layers cannot slide as easily as in a pure metal.

   - **If you chose A:** The bonding is much the same. The difference is that atoms of another size block the layers.
   - **If you chose C:** It is the other way round. In a pure metal the atoms are the same size, and the layers slide easily.

5. **An alloy**

   An alloy is a mixture of a metal with atoms of another element. The larger atoms disturb the layers.

   - **If you chose A:** A compound has its atoms joined in a fixed ratio by bonds of one kind. This is a mixture of a metal with atoms of another element.
   - **If you chose B:** An ionic lattice has positive and negative ions that attract. Here the other atoms are not ions, and a sea of free electrons holds the ions. Go to S4.6.6.

6. **140 g**

   70 ÷ 100 × 200 g = 140 g.

   - **If you chose A:** That uses the percentage as grams. 70% of 200 g is 70 ÷ 100 × 200. Go to M3.3.8.
   - **If you chose C:** That is the zinc, 30% of 200 g. The question asks for the copper.

7. **Free electrons that carry the charge**

   In graphite each carbon has one electron that is free. In a metal there is a sea of free electrons. Free electrons carry the current.

   - **If you chose B:** Neither is made of ions. Moving ions carry current in molten salt, not in graphite or a metal. Go to S4.6.6.
   - **If you chose C:** Shared pairs hold the atoms of a covalent substance together and stay in place. In graphite it is a spare electron that moves. Go to S4.6.7.

8. **175 g**

   70 ÷ 100 × 250 g = 175 g.

9. **48 g**

   The tin is 100% − 88% = 12%. 12 ÷ 100 × 400 g = 48 g.

About this book

For learners who can follow a written argument and have met elements, compounds and particles. In many schools this fits learners of about 14 to 16, and older learners can use it as a reference. Each chapter takes two or three short sessions. A learner can work alone: every exercise has its answer and the reason for it. The Try it activities use paper, seeds, stones and salt. Nothing is tasted and nothing is heated. Experiments that need a flame, a strong chemical or mains electricity are described as things scientists do, and the book says why they are not done at home. Keep small seeds and stones away from young children.

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