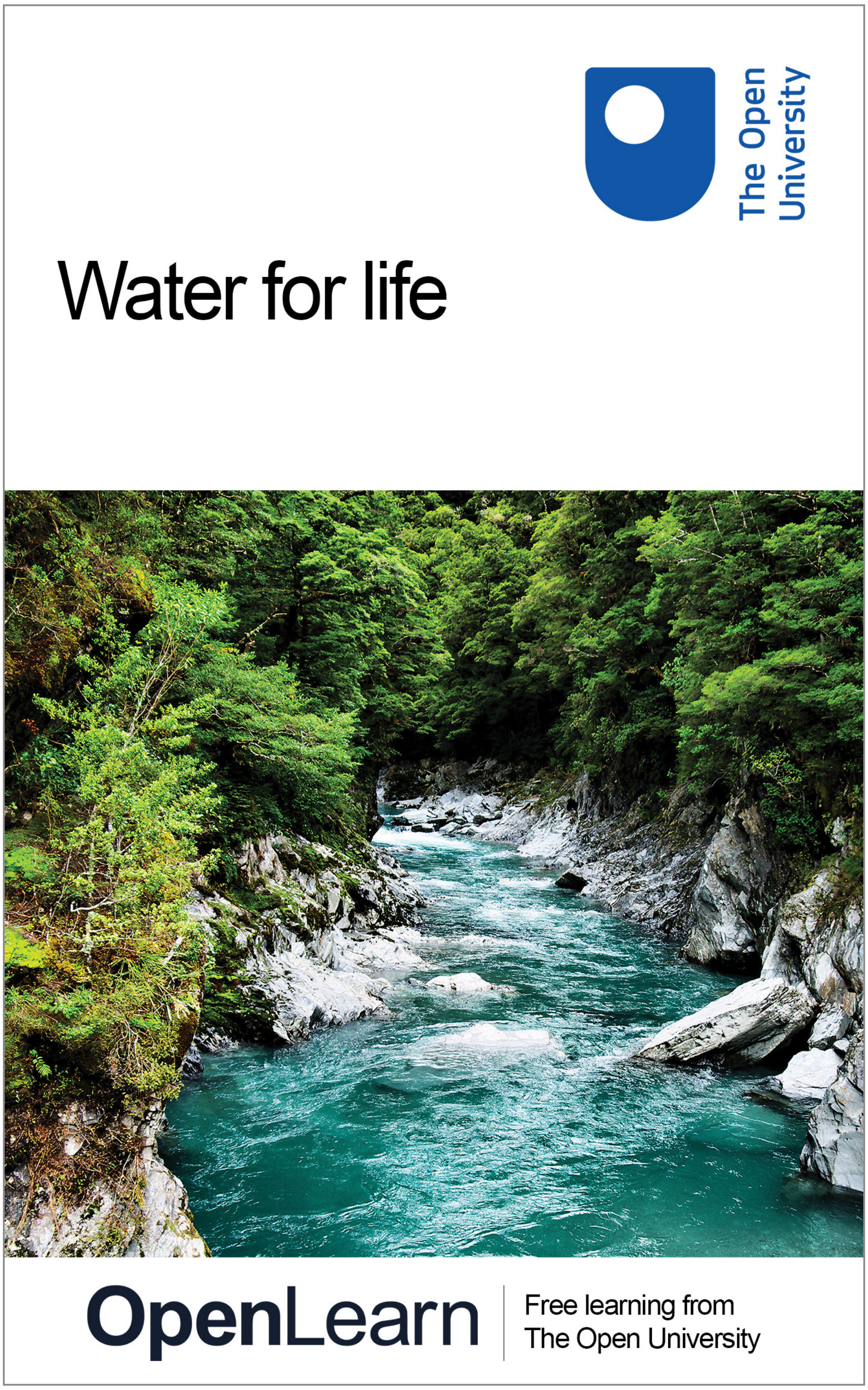
Water for life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Introduction

This course is an introduction to chemistry concepts, using water as the main illustration. Much of the course is devoted to exploring the smallest water particle - a water molecule - what it is and how it gives rise to the particular properties of water. The course also explains powers of ten and scientific notation, which are a convenient way of expressing both very large and very small numbers. It is a good introduction to science.

This OpenLearn course provides a sample of level 1 study in Environment & Development

Learning Outcomes

After studying this course, you should be able to:

- read data presented in tables
- use scientific notation to express both large and small quantities
- appreciate why chemists use different models to represent molecules
- identify the number and type(s) of atom present in a molecule from its chemical formula
- identify the reactants and products of a reaction in a chemical equation.

1 The power of water

The ways in which human activities interact with the water cycle can have devastating consequences for all forms of life. These range from the very large scale - for example, the effects of the movement of large volumes of water in a tsunami - to the molecular scale and the ability of water to dissolve solids, such as agricultural fertilisers (Figure 1).

Figure 1 (a) A tsunami wave; (b) a bag of agricultural fertiliser; (c) white crystals of the fertiliser sodium nitrate dissolving in a beaker of water. The image in (b) is a still taken from the video sequence *Elements and Compounds* which you will watch in Activity 1. It shows a bag of Chilean nitrate of soda which is sodium nitrate

Much of this course is devoted to exploring the smallest water particle - a water molecule - what it is and how it gives rise to the particular properties of water. You will be introduced to the use of powers of ten and scientific notation, which give a convenient way of expressing both very large and very small numbers. There is a video sequence to watch during your study of this course.

2 Earth's store of water

2.1 Where water occurs and how we measure it

When astronauts first ventured to the Moon in the late 1960s, they were captivated by a vision of the Earth in colour as it had never been seen before (Figure 2). It is not surprising that, after pictures like this were published, the Earth became known as the 'blue planet'.

Figure 2 A view of the Earth from space. The brown areas are Africa and Arabia, the larger blue areas are the oceans, and the white areas are cloud

It is astonishing how much of the Earth's surface is covered by water. The oceans occupy about 71% of the Earth's surface. Altogether, the total volume of water on Earth, including the oceans, lakes, rivers and what is stored in rocks underground, is estimated to be roughly 1460 000 000 000 000 000 000 (1460 billion billion) litres.

Question 1

What is the average daily intake of water for a person in the UK (from food as well as drinks)?

Answer

It's about 2.5 litres.

Even allowing 5 litres per person to ensure the most basic standard of domestic use (i.e. the minimum for cooking and washing), in addition to what humans take into their bodies, it would be reasonable to imagine that there is enough water around to sustain not only the Earth's 6000 000 000 (6 billion) human inhabitants, but all the other species of animals and plants as well - with an awful lot to spare.

However, there are frequent news bulletins that illustrate the appalling consequences of droughts in some parts of the world. Even countries such as the UK suffer water shortages: for example, in southeast England during the summer of 2006. It seems that the planet is well endowed with life-giving water but, from a human perspective, it is often in the wrong place, in the wrong form (for example, seawater is plentiful in coastal towns but fresh drinking water could be in short supply), or available at the wrong time.

To find out why there are water shortages and droughts on a planet endowed with 1460 billion billion litres of water, it is necessary to look at where the water occurs. First, the numbers need to be made more manageable by introducing a larger unit to measure the volumes. The unit most commonly used for this purpose is the **cubic kilometre**, abbreviated to km^3, which is the volume of a cube with sides 1 km long. One cubic kilometre is equivalent to 1000 000 000 000 litres, or one million million litres, which can be demonstrated as follows.

To discover how many litres (each of which is equivalent to a 10 cm cube) can be stacked up in a 1 km cube: there are 10 lots of 10 centimetres in one metre (since 10 × 10 cm = 100 cm = 1 m), and there are 1000 metres in 1 kilometre, and so there are 10 × 1000 lots, or 10 000 lots, of 10 centimetres in 1 kilometre. This means that 10 000 one-litre cubes could be placed side-by-side along one edge of a one-kilometre cube. So the total number of one litre cubes that could be stacked within a one-kilometre cube is 10 000 × 10 000 × 10 000, which is 1000 000 000 000. The relationship between litres and km^3, m^3 and cm^3 is summarised below.

Units of volume

1 km^3 = 1000 000 000 000 litres

1 m^3 = 1000 litres

1 cm^3 = 1/1000 litre, so

1000 cm^3 = 1 litre

A cubic kilometre is 1000 000 000 000 times **larger** than a litre, so the number of cubic kilometres of water on the Earth is 1000 000 000 000 times **smaller** than the number of litres. This means that the number of cubic kilometres of water on Earth is:

$$\frac{1460\ 000\ 000\ \cancel{000}\ \cancel{000}\ \cancel{000}\ \cancel{000}}{1\cancel{000}\ \cancel{000}\ \cancel{000}\ \cancel{000}} = 1460\ 000\ 000$$

Note how 12 zeros have been cancelled out. This makes the number representing the total water volume a little more manageable, and this volume is shown as the bottom line in Table 1, together with the volumes (in km^3) stored in each of the Earth's various natural reservoirs. (Don't confuse this use of the term 'reservoir' with the reservoirs that are built to store water for human use.) The volumes listed in Table 1 for ice and snow and for the atmosphere are the volumes of liquid water that would be produced by melting the solid ice and snow and by condensing the water vapour from the atmosphere. It is important to note that all of the volumes shown in Table 1 are estimates; clearly, no one has been able to measure the volume of water in the oceans accurately.

Table 1 Estimated volumes of water stored in the Earth's natural reservoirs. To be completed as part of Question 1.

Reservoir	Volume/km^3	Volume/% total water
oceans	1400 000 000	96
ice and snow	43 000 000	
underground water	15 000 000	1.0
lakes and rivers	360 000	0.025
atmosphere	15 000	0.001
plants and animals	2 000	0.000 14
total	1460 000 000*	100*

*The numbers in the middle column add up to 1458 377 000, but they have been rounded to 1460 000 000 to reflect the limited accuracy of the larger numbers. Similarly, when you have filled in the gap in the third column (Question 1), you will find that the numbers do not add up to exactly 100.

Even though the 12 zeros have been removed by expressing the volumes in km^3 rather than litres, the numbers in the middle column of Table 1 are still too large to be handled easily. They still have too many zeros. It is much easier to work with percentages of the total water volume in the Earth's natural reservoirs, which are displayed in the right-hand column of the table. You can see that about 96% of the water is stored in the oceans, which means that there is only a small percentage available for human use on the land. To put it another way, if all the Earth's water was represented by the contents of a 4.5 litre (1 gallon) can, all but the contents of a tea cup would be seawater.

Question 1

There is a gap in the right-hand column of Table 1. Calculate the proportion of water that is stored in ice and snow as a percentage of the total volume of water stored on Earth.

(*Hint:* to do this, first write down the proportion as a fraction. If the numbers involved are too large to enter on your calculator, you will need to reduce the fraction to an equivalent fraction with smaller numbers on the top and the bottom by cancelling out some zeros. Then use your calculator to work out the required percentage.)

Answer

From Table 1, the volume of water stored in ice and snow is 43 000 000 km^3. Expressing this as a fraction of the total volume gives $\frac{43\ 000\ 000\ \text{km}^3}{1460\ 000\ 000\ \text{km}^3}$

Six zeros (and the unit) can be cancelled from the top and the bottom of this fraction, so the percentage is

$$\frac{43}{1460} \times 100\% = 2.9\%.$$

(Note that 43 is exactly the same percentage of 1460 as 43 000 000 is of 1460 000 000.)

Percentages are one way to avoid having to work with cumbersome numbers such as those in Table 1, but an alternative is to use a mathematical notation for expressing the numbers in a more convenient form. This notation is called scientific notation and it is based on the observation that every time a number is multiplied by 10, a zero is added to the end of the number. The use of powers of ten and scientific notation is explained in Section 2.2.

2.2 Going up: using scientific notation for large numbers

Think again about the value for the total volume of water stored on Earth: 1460 000 000 km^3.

When dealing with large numbers such as one thousand four hundred and sixty million (1460 000 000), it is tedious to write the number in words or to keep writing all of those zeros. Worse still, it is very easy to lose some of the zeros or add extra ones by mistake. Fortunately, large numbers can be referred to without having to write out all of the zeros. The **powers of ten** notation is less prone to errors and tedium because it removes the zeros. However, the powers of ten notation will be introduced with some numbers more manageable than 1460 000 000.

One thousand is ten times ten times ten, i.e.:

$$10 \times 10 \times 10 = 1000$$

Powers notation can be used to write 1000 = 10^3.

Two tens are multiplied together to give one hundred (10 × 10 = 100) so the superscript after the 10 must be 2, i.e. 10^2.

When expressing 100 and 1000 in powers of ten, there are no great savings on writing zeros, but what about one million (1000 000)? One million is the product of multiplying together six tens:

$$10 \times 10 \times 10 \times 10 \times 10 \times 10 = 1000\,000$$

so it is written as 10^6. Now you can begin to see the benefit of the powers of ten notation. One thousand is often written not just as 10^3 but as 1×10^3. Spoken aloud, this is 'one times ten to the power three' or just 'one times ten to the three'. Likewise, one million is either 1×10^6 or simply 10^6. Now two alternative explanations can be given that may help you to grasp powers of ten. The power of ten shows how many times 1 has been multiplied by 10. Taking 1×10^3 as an example, 1000 is seen to be 1 × 10 × 10 × 10. In a second view, the power of ten shows how many places the decimal point has to move to the right to give the actual number. If 1 is written as 1.0 to remind you where the decimal point is, one move to the right would turn 1.0 into 10.0, a second move would give 100.0 and a third move would give 1000.0, i.e. one thousand.

You do not have to recall both of these ways of understanding powers of ten; just use the one that suits you best, or develop your own way of fixing the idea in your armoury of mathematical techniques.

Using the powers of ten notation, the total amount of water on Earth - 1460 000 000 cubic kilometres - could be written as 1.46×10^9 km^3. A significant saving on zeros! The complete number would be spoken as 'one point four six times ten to the power nine' or just 'one point four six times ten to the nine'. The '9' in 10^9 tells you how many times 1.46 has been multiplied by 10 to give the final number of 1460 000 000. It is nine times, i.e. the number comprises:

$$1.46 \times 10 \times 10 \times 10 \times 10 \times 10 \times 10 \times 10 \times 10 \times 10$$

To see clearly that this expression is still one thousand four hundred and sixty million, it helps to begin with 1.46 and to then multiply each time by ten to get the number you want:

1.46

$1.46 \times 10 = 14.6 = 1.46 \times 10^1$

$1.46 \times 10 \times 10 = 146 = 1.46 \times 10^2$

$1.46 \times 10 \times 10 \times 10 = 1460 = 1.46 \times 10^3$

If you carry on doing this, you will end up with:

$$\begin{aligned} &1.46 \times 10 \times 10 \times 10 \times 10 \times 10 \times 10 \times 10 \times 10 \times 10 \\ &= 1460\,000\,000 \\ &= 1.46 \times 10^9 \end{aligned}$$

Alternatively, you can think of each increase by one in the power of ten as moving the decimal point one place to the right. That is, if you multiply 1.46 by 10 the decimal point moves one place to the right, giving 14.6.

1.4 6

Likewise, to multiply 1.46 by one thousand, the decimal point moves three places to the right, giving 1460.0. In the powers of ten notation, this is written as 1.46×10^3.

1.4 6 0 0

The convention called **scientific notation** is used when writing a number with a power of ten. Scientific notation requires the number accompanying the power of ten to be less than 10 but equal to or greater than 1. Take the example of one million. It could be correctly expressed as 1×10^6, 10×10^5, 100×10^4, 1000×10^3, and so on, or even as 0.1×10^7 but only the first of these obeys the convention of scientific notation and this is the one that should be used. As a second example, it is mathematically correct to write 85 000 as 85×10^3 or 0.85×10^5 but correct scientific notation would demand 8.5×10^4.

> Scientific notation requires the number accompanying the power of ten to be less than 10 but equal to or greater than 1.

Question 2

Express the following numbers in scientific notation.

(a) 100 000 000

(b) 35 000

(c) 95×10^5

(d) 0.51×10^3

Answer

(a) 100 000 000 = 1×10^8

(b) 35 000 = 3.5×10^4

(c) $95 \times 10^5 = 9.5 \times 10^6$

(d) $0.51 \times 10^3 = 5.1 \times 10^2$

Question 3

Write out in full the numbers corresponding to:

(a) 7.3×10^4

(b) 4.44×10^5

(c) 6.05×10^3

Answer

(a) 7.3×10^4 = 73 000

(b) 4.44×10^5 = 444 000

(c) 6.05×10^3= 6050

2.2.1 Using a calculator for scientific notation

You are likely to be doing many calculations with numbers in scientific notation, so it is important that you know how to input them on your calculator efficiently and how to interpret the results.

First, make sure that you can input numbers in scientific notation on your calculator. There are a couple of ways to do this, but the most straightforward is to use the special button provided for entering scientific notation. This might be labelled as EXP, EE, E or EX, but there is considerable variation between calculators. Make sure that you can find the appropriate button on your calculator. Using this sort of button is equivalent to typing the whole of '× 10 to the power'. So, on a particular calculator, keying 2.5 EXP 12 enters all of 2.5×10^{12}.

To enter a number such as 10^9 on your calculator using the scientific notation button, it is helpful to remember that 10^9 is written as 1×10^9 in scientific notation, so you will need to key in for example 1 EXP 9.

In addition to being able to enter numbers in scientific notation on your calculator, it is important that you can understand your calculator display when it gives an answer in scientific notation. Enter the number 2.5×10^{12} on your calculator and look at the display. Again there is considerable variation among calculators, but the display will probably be similar to one of those shown in Figure 3. The 12 at the right of the display is the power of ten, but note that *the ten itself is frequently not displayed*. If your calculator displays 2.5×10^{12} as shown in Figure 3(e), you will need to take particular care; this *does not* mean 2.5^{12} on this occasion. You should be careful not to copy down a number displayed in this way on your calculator as an answer to a question; this could cause confusion at a later stage. No matter how scientific notation is entered and displayed on your calculator or computer, when writing it on paper you should always use the form exemplified by 2.5×10^{12}.

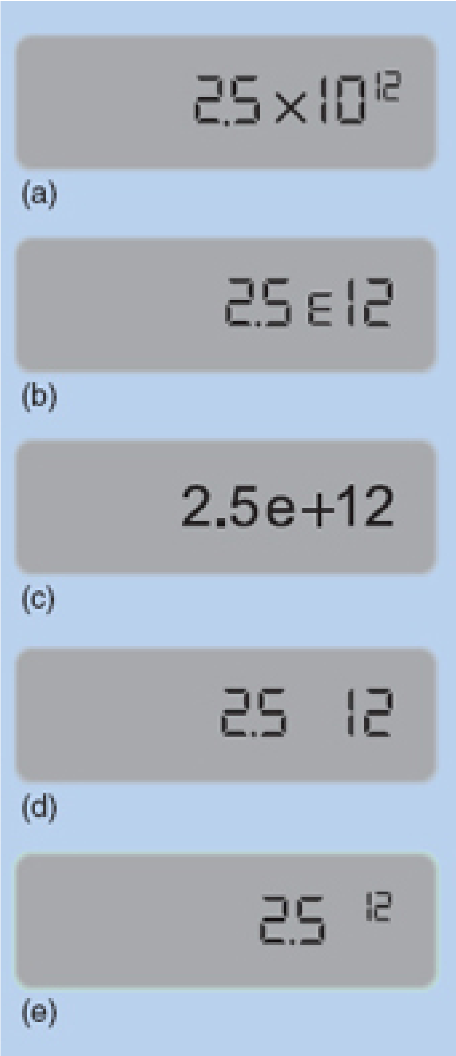


Figure 3 Examples of how various calculators display the number 2.5×10^{12}

Question 4

To check that you can use your calculator for scientific notation, do the following calculations.

(a) $(4.5 \times 10^4) \times (4.0 \times 10^{11})$

(b) $10^{12} - (5.66 \times 10^{11})$

Answer

(a) $(4.5 \times 10^4) \times (4.0 \times 10^{11}) = 1.8 \times 10^{16}$

(b) $10^{12} - (5.66 \times 10^{11}) = 4.34 \times 10^{11}$

(*Note:* if you got the incorrect answer 9.434×10^{12} you probably entered 10 EXP 12 instead of 1 EXP 12 on your calculator. Remember that 10^{12} can be written as 1×10^{12}.)

Question 5

The numbers in Table 1 can be presented in a different way. In Figure 4 (below) they are given more visual interest by being displayed in a diagram that shows the locations of the reservoirs as well. The amounts of water stored in the various natural reservoirs are shown in the boxes.

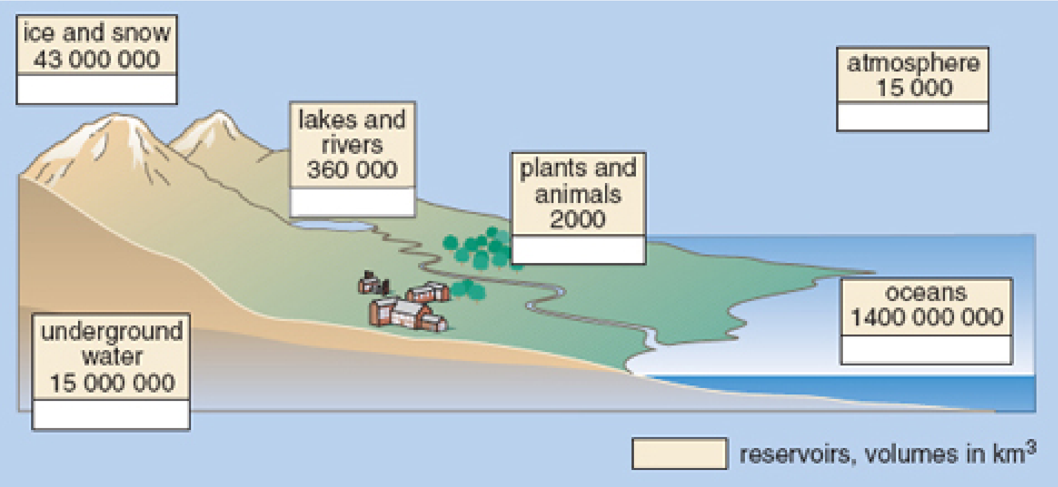


Figure 4 The amounts of water (in km^3) stored within the Earth's natural reservoirs

Convert each number in Figure 4 into correct scientific notation, and note down your answers.

Answer

Your answers should be as follows: ice and snow, 4.3×10^7; underground water, 1.5×10^7; lakes and rivers, 3.6×10^5; plants and animals, 2.0×10^3; atmosphere, 1.5×10^4; oceans, 1.4×10^9.

2.3 The study of a raindrop

Most of the usable water is derived from the 1.1×10^5 km^3 that falls over the land surface each year as rain, snow, sleet or hail. The collective term for all of these sources of water is **precipitation**. At this point, you will consider the size of the drops of water that make up clouds or rain (Figure 5).

Figure 5 A water droplet

The typical distance across a water droplet in a cloud is one hundred-thousandth of a metre, that is, $\frac{1}{100\,000}$ m or 0.000 01m. This corresponds to $\frac{1}{100}$ mm or 0.01 mm, which is very small. Imagine dividing the gap between adjacent millimetre marks on a ruler into 100 parts! Many of these droplets coalesce to give a raindrop that is about two-thousandths of a metre wide ($\frac{2}{1000}$ m, 0.002 m or 2 mm). Even these drops are small, but clearly they are water.

It is interesting to contemplate whether there is such a thing as a smallest particle that is still recognisably water and from which all larger volumes of water are made. In other words, if you start with a raindrop and keep halving its volume, is there a point when a further reduction gives something that stops being water? It is often useful in science, when dealing with complex ideas, to think of an **analogy**. One analogy for this 'halving' of a drop of water is to define a single living cow starting from a small herd of eight cows. If you halve the herd, you get four cows. Repeating the process gives two cows and repeating it again leaves one living cow. If this remaining cow were halved, you would agree that what remains is certainly not a living, whole cow. The cow would have been destroyed. You can conclude that one whole living cow is the smallest item from which herds of any size can be composed. Unfortunately, once a drop of water is halved several times, it becomes extremely small. It is a process that cannot be studied with the naked eye - or even with a conventional microscope.

In principle, a typical raindrop - say, 2 mm across - could be halved in volume 67 times before a single particle that is still recognisably water emerges. The 68th division by two, like the halving of a single cow, would destroy the water. This smallest particle that is still water is called a water **molecule** and its dimensions are almost inconceivably small. Molecules are the basic particles of many solids, liquids and gases.

It is not easy to describe the size of a water molecule because its shape is not regular. However, if its shape were likened to a tiny sphere, it would be about 0.000 000 0002 m across. It is difficult to comprehend a number this small, but you can probably imagine why it is impossible to do the halving experiment with a molecule. Roughly 10^{20} of these molecules would be needed to make a single raindrop.

As when writing very large numbers, there is an inherent danger in writing very small numbers such as 0.000 000 0002. Once again, the zeros are the problem. There are just too many of them! However, there is a notation that minimises the risk of making mistakes when working with such numbers. As before, it relies on the powers of ten idea to reduce many of the zeros. It is explained in Section 2.4.

2.4 Going down: using scientific notation for small numbers

You saw in Section 2.2 how the powers of ten notation provides a concise method of expressing very large numbers and reduces the chances of errors when, otherwise, many zeros would have to be written out. You will now see how the powers of ten notation can be extended to cover small numbers, such as 0.000 000 0002 m.

Write down the next two numbers in each of the following two sequences.

10 000	1000	100	....	....
1×10^4	1×10^3	1×10^2	....	....

In the first sequence, each successive number is *divided* by 10 (i.e. one zero is taken off the end) so the number that follows 100 is $\frac{100}{10} = 10$. The next number in that sequence must result from another division by 10. That is, you must divide 10 by 10 and $\frac{10}{10} = 1$. Therefore, the second answer is 1. In the second sequence of numbers, each successive number has 1 *subtracted* from its power, so the first answer is 1×10^1 because 2 - 1 = 1. For the second answer, you must subtract 1 from the power 1. Because 1 - 1 = 0, the next answer is 1 × 10°.

In fact, both sequences are the same because 10 000 is 1×10^4, 1000 is 1×10^3, 100 is 1×10^2, and 10 is 1×10^1. The implication is that $1 = 1 \times 10^0$ and hence $10^0 = 1$. This makes perfectly good sense if you recall that, in the second sequence given above, the power is the number of times that 1 is multiplied by 10 (e.g. $10^2 = 1 \times 10 \times 10$). For 1×10^0, 1 is multiplied by 10 no times at all, leaving it as 1.

Why stop at 1 or 10^0? Using the same rules, write down the next number in each of the following sequences.

100	10	1	…………	…………
1×10^2	1×10^1	1×10^0	…………	…………

In the first sequence, dividing 1 by 10 gives $\frac{1}{10}$ or 0.1 as the next number. Here, decimals are being used, so the answer you want is 0.1. But what about the second sequence? The answer is more straightforward than it may seem. You continue to subtract 1 from the powers of ten so that the next number in the sequence has a negative power of ten (1×10^{-1}) because 0 − 1 = −1. Remembering that the two sequences are equivalent, it seems that $1 \times 10^{-1} = 0.1$. This is exactly right! You could equally write $10^{-1} = 0.1$.

Just as a positive power often denotes how many times a number is *multiplied* by 10, so a negative power of ten denotes how many times a number is *divided* by 10. For 10^{-1}' you must divide 1 by 10 once and you get 0.1.

Question 2

What is the meaning of 10^{-2}?

Answer

The power is now −2, so you must divide 1 by 10 *twice*. That is, 1 ÷ 10 ÷ 10 = 0.01.

Another way to think about powers of ten for very small numbers involves shifting the decimal point. A negative power of ten denotes the number of places that the decimal point moves to the left. For example, think of 1×10^{-2}, which is written as 1.0×10^{-2} to remind you of the position of the decimal point. Starting with the number 1.0, the power of −2 requires the decimal point to be moved two places to the left. One place to the left gives 0.1 and two places 0.01.

You therefore have $10^{-2} = 0.01$.

Try an example. Suppose a raindrop has a breadth of about 0.002 m. This distance could be given in scientific notation as 2×10^{-3} m. This is clear from the following series.

Start with: 2

Divide by ten: $2 \div 10 = 0.2 = 2 \times 10^{-1}$

Divide by ten again: $2 \div 10 \div 10 = 0.02 = 2 \times 10^{-2}$

And again: $2 \div 10 \div 10 \div 10 = 0.002 = 2 \times 10^{-3}$

Alternatively, in considering the meaning of 'two times ten to the power minus three,' you could start with the number 2.0 and move the decimal point three places to the left to give 0.002.

You know from Section 2.2 that when expressing large numbers in scientific notation, the power of ten (which is positive) denotes the number of places that the decimal point moves to the right. Similarly, when expressing small numbers in scientific notation, a negative power of ten denotes the number of places that the decimal point moves to the *left*.

You have seen that a negative power of ten tells you how many times you need to divide by ten, so that

$$0.001 = 10^{-3} = 1 \div 10 \div 10 \div 10 = \frac{1}{1000}$$

Of course, $1000 = 10^3$, so

$$0.001 = 10^{-3} = \frac{1}{1000} = \frac{1}{10^3}$$

and so

$$10^{-3} = \frac{1}{10^3}$$

This relationship between positive and negative powers of ten is quite general, so

$$10^{-6} = \frac{1}{10^6}, 10^{-8} = \frac{1}{10^8}, 10^{-13} = \frac{1}{10^{13}}, \text{ and so on.}$$

Recall from Section 2.2 that, when writing large numbers in scientific notation, the power of ten should be accompanied by a number that is equal to or greater than 1 but less than 10. The same convention is used when dealing with small numbers and hence negative powers of ten. This is why 0.002 m, the width of the raindrop, is given in scientific notation as 2×10^{-3} m, and not as 0.2×10^{-2} m or 20×10^{-4} m.

To enter a number such as 5×10^{-16} on your calculator, you may need to use the button labelled something like +/− or ± in order to enter the negative power.

Question 6

Express the following measurements in scientific notation.

(a) A water molecule, about 0.000 000 0002 m across;

(b) An average-sized sand grain (on a gently sloping beach), about 0.000 25 m across;

(c) The size of one particle of clay, the main constituent of mud, about $\frac{1}{1000\,000}$ across

(d) The average size of a hailstone, 0.0035 m across

Answer

(a) The starting point for quoting 0.000 000 0002 in scientific notation is 2.0 (the number between 1.0 and 9.9). The decimal point has to be moved ten places to the left to reach 0.000 000 0002, so the power of ten must be −10 and the answer 2×10^{-10} m.

(b) 2.5×10^{-4} m.

(c) First, convert the fraction into a decimal. This is 0.000 001. In scientific notation, this is 1×10^{-6} m. Alternatively,

$$\frac{1\text{m}}{1000\ 000} = \frac{1\text{m}}{10^6} = 1 \times 10^{-6}\text{m}$$

(d) 0.0035 m = 3.5×10^{-3} m.

Question 7

Write out in full the decimal numbers corresponding to:

(a) 7.3×10^{-4}

(b) 2.9×10^{-7}

Answer

(a) To find the decimal number corresponding to 7.3×10^{-4}, the decimal point in 7.3 has to be moved four places to the left to give 0.000 73. The alternative approach is to think of, and work out,

7.3 ÷ 10 ÷ 10 ÷ 10 ÷ 10.

(b) 0.000 000 29

Question 8

To check that you can use your calculator for scientific notation, including negative powers of ten, do the following calculations.

(a) $(6.5 \times 10^{-27}) \times (2.0 \times 10^{-14})$

(b) $10^8 \div (2 \times 10^{-17})$

Answer

(a) 1.3×10^{-40}

(b) 5×10^{24}

2.5 What is water made of?

The size of a water droplet may seem very small but in terms of the scale of scientific measurement it is relatively large. You already know that water is made up of molecules so now consider a water droplet more closely to see what water molecules are made up of. If you could magnify a water droplet until it no longer has a smooth surface, you would see something similar to that shown in Figure 6. The spheres shown in the diagram are about 10^{-10} m in size and are called **atoms**.

One way of trying to visualise the size of an atom within a water droplet is to imagine a droplet magnified to the size of the Earth; an atom would be roughly the size of a tennis ball.

Figure 6 illustrates an important aspect of water, namely that it is made of water molecules, and that each molecule is made up of two types of atom: hydrogen atoms (shown as small white spheres) and oxygen atoms (shown as larger red spheres). Atoms are the basic building blocks of *all* material, whether the material is natural, such as rocks, plants and animals, or synthetic, such as plastic.

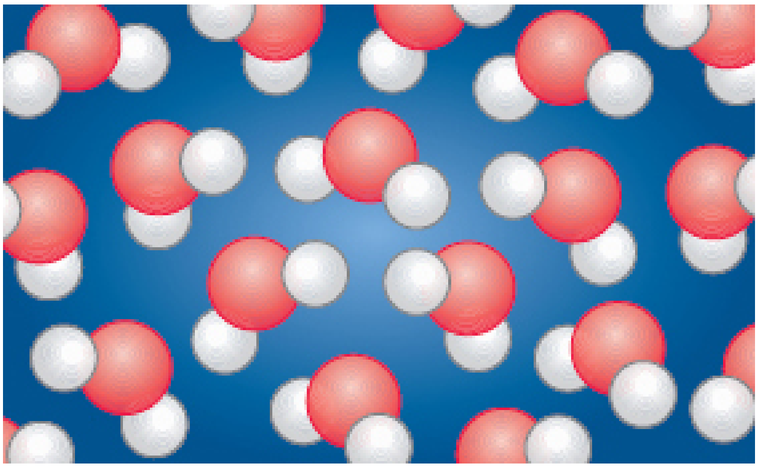


Figure 6 The individual atoms in water that could be seen if the drop was magnified 10^9 times. The white spheres represent hydrogen atoms, and the red ones represent oxygen atoms

Question 3

How many hydrogen atoms are there compared with oxygen atoms in Figure 6?

Answer

There are two hydrogen atoms to every oxygen atom.

Question 4

How many hydrogen atoms and how many oxygen atoms are there in one molecule of water?

Answer

Two hydrogen atoms are joined to one oxygen atom to make one molecule of water.

Atoms are extremely small - about 10^{-10} m in diameter. Because they are so small, a *model* is needed to represent them and, moreover, to show how they are linked together to form molecules. Scientists use the term 'model' to mean any method of representing some structure or idea, so you won't be surprised to learn that there is more than one way of representing a water molecule. Figure 6 is one version, but there are others. If you are familiar with the children's building blocks called Lego®, you may find that a model based on this is helpful (seeSection 2.6).

2.6 Models of a water molecule

2.6.1 (a) Using Lego as a model

In this kind of building set, there are a limited number of types of block and each block has a particular shape. Just as importantly, each one has a particular way in which it can link to other blocks because of the way the studs are arranged.

The blocks can help you see how the atoms link in a molecule of water. Look at Figure 7 where the red brick represents an oxygen atom and the white bricks represent hydrogen atoms. There are only two locations where the hydrogen atoms can join the oxygen atom - at the top and bottom - as shown in Figure 7.

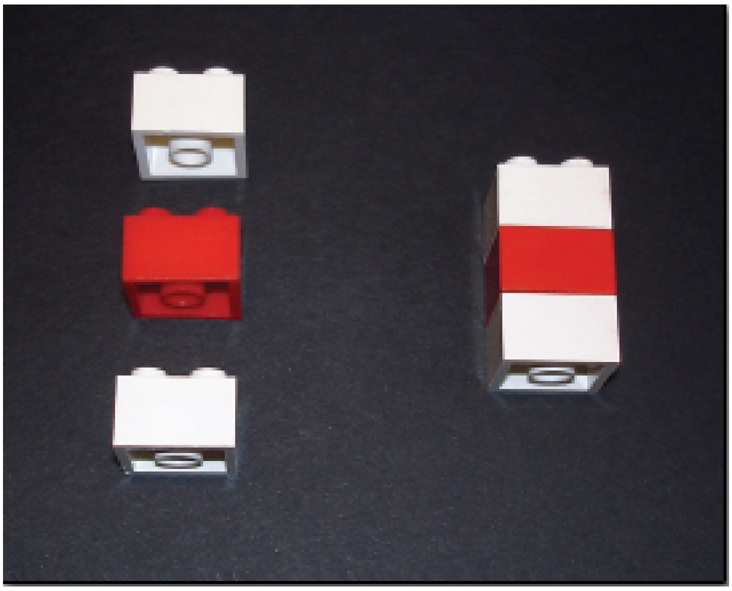


Figure 7 A Lego representation of a water molecule where the red brick represents an oxygen atom which is sandwiched between the two white bricks, each representing a hydrogen atom

2.6.2 (b) Using spheres

Chemists have their own convention for representing molecules and their constituent atoms. As in Figure 6, they often use circles (or spheres if they make a three-dimensional model) to represent atoms - and they often use *short, straight lines* between the circles to represent the **bonds** that join one atom to another in molecules such as water. For now, think of these bonds as a sort of 'glue' that holds the atoms together (much like the studs on Lego). Thus a chemist's drawing of water might look something like Figure 8a. Chemists sometimes make models using specially designed 'ball-and-stick' kits - an example is shown in Figure 8b. This enables the relative positions of the centres of the atoms to be seen more easily; water is a bent molecule with an angle of about 104° between the two hydrogen-oxygen bonds in each molecule. Figure 8c is a computer-drawn space-filling view. A note on colour: chemists traditionally use white spheres for hydrogen atoms and red ones for oxygen atoms. Later in this course you will see that black spheres are used for carbon atoms and blue ones for nitrogen atoms.

Models can be very helpful in showing how atoms fit together to make molecules.

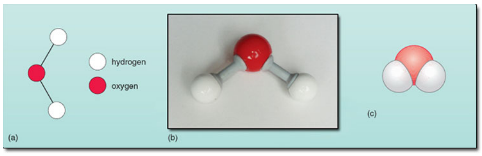


Figure 8 Models of a water molecule: (a) a chemist's representation of water; (b) a ball-and-stick model; (c) a space-filling model. *Note*: although the hydrogen and oxygen atoms are shown as the same size in (a), in fact they are different sizes as reflected in (b) and (c)

With Lego, an enormous range of structures can be built from a small number of different types of block. It is just the same for atoms: there are only about 100 different types of atom in the entire Universe! Yet everything is built from these atoms.

A substance containing only one type of atom is known as a **chemical element**, or just an **element**.

Question 5

Given that there are about 100 different kinds of atom in the Universe, how many different elements are there?

Answer

The same number as for the kinds of atoms - about 100.

The Ancient Greeks believed that there were four earthly elements - earth, air, fire and water. However, by the 18th century, the idea that these were fundamental substances was discredited. The scientist John Dalton was the first to propose (in 1808) that elements were composed of atoms, and that substances that were not elements were compounds, comprising a combination of atoms. (Compounds are considered in detail in Section 3.)

Examples of elements that you might have heard of include hydrogen, which has its own unique hydrogen atoms, oxygen which has its own unique oxygen atoms and, an example of an element that you can see, *gold* which has its own unique gold atoms. A piece of pure gold contains nothing but identical atoms of the element gold.

Question 6

Why is water not classified as a chemical element?

Answer

Water contains the elements hydrogen and oxygen combined together.

Table 2 lists the ten most common elements in the human body which together make up 99.8% of the total number of atoms present in the body. One important kind of atom in living systems, the third one down in Table 2, is the element *carbon*. It is possible to have some of the element itself - that is, some pure carbon containing nothing but carbon atoms - for example, a piece of charcoal of the type used in barbecues.

Table 2 The ten most common elements in the

human body and their approximate percentages (of the total number of atoms in the body)

Element	%
hydrogen	63.00
oxygen	25.20
carbon	9.50
nitrogen	1.40
calcium	0.31
phosphorus	0.22
potassium	0.06
sulfur	0.05
chlorine	0.03
sodium	0.03
all others	0.20

2.7 The 'salt' in seawater

The difficulty with having so much of the Earth's water locked up in the oceans is summed up poetically by Coleridge's 'Ancient Mariner', becalmed on board ship in the doldrums, beneath a blazing Sun.

Water, water, everywhere,
And all the boards did shrink;
Water, water, everywhere,
Nor any drop to drink.

(Samuel Taylor Coleridge, *The Rime of the Ancient Mariner*, 1797-8)

With so much Pacific Ocean around them, and dying of thirst, why didn't the ship's crew just lower a bucket and bring up some seawater to drink? As you know, there is a very important difference between seawater and fresh water. Seawater contains various salts. The most abundant of these salts is known as sodium chloride, the most common constituent of table salt. Other salts contain calcium and magnesium. If you were to put 100 g of seawater in a pan and boil it, you would find about 3.5 g of the different salts left behind as a residue after all the water had evaporated. Although some salts are required in the human diet, there is only a certain amount that can be tolerated. The excess is removed by the body.

Question 7

How are these excess salts removed from the body?

Answer

Some salts may be lost in sweat, but most of the excess is removed by the kidneys and excreted in urine.

The problem for the kidneys is that in order to remove the salts, they need water. The more salts, the more water they require. So, after drinking seawater, the 'Ancient Mariner' crew would have been even thirstier, because of the need to remove the excess salts. The problem is compounded by the fact that one of the constituents of the salts in seawater irritates the last section of the large intestine called the rectum. This causes diarrhoea, with a further loss of water. The end result would be that the crew members would be thirstier than before.

Seawater can be converted into fresh water by a process called **desalination** (which means, literally, salt removal). The easiest and cheapest way to do this is to use the natural energy of the Sun to evaporate seawater, but this is a slow process. Other methods of desalination use different energy sources - oil, for example. Either way, desalination is a costly business and so is generally used only in those countries wealthy enough to afford it (e.g. in the Arabian Peninsula, Iran and the USA - in Arizona and California), and only where there is no other source of fresh water. The salt residue left over from the evaporation of seawater may be used as a commercial source for the brands of table salt that are sold as 'sea salt' (Figure 9). One such brand boasts on its label: 'Obtained from the Mediterranean Sea, naturally evaporated by the hot sun'.

Both water and salts are described as chemical compounds. You will take a closer look at them in the next section.

Figure 9 At the Janubio saltpans on the west coast of Lanzarote, salt is produced as seawater evaporates in an extensive area of small, shallow ponds. These old saltpans are not used as much now as in earlier times

3 What are compounds?

Activity 1: Elements and compounds

0 hour(s) 10 minutes(s)

Click on the video clip to watch *Elements and Compounds*, which focuses on water and its constituent elements.

Click below to view video clip. (6 minutes)

Video content is not available in this format.
Video 1

Although there are about only 100 elements, there are many, many more than 100 substances in the world - not just thousands but millions of different substances. You could begin a list starting in your kitchen: water, salt, sugar, vinegar, bicarbonate of soda. None of the substances in this particular list are elements, so what are they? They are substances in which atoms of *different* elements are joined together. The proper chemical term for any such substance is **chemical compound** or just **compound**.

Question 8

Is water a compound or an element?

Answer

Water is a compound. It contains more than one element: hydrogen and oxygen atoms are joined together; as illustrated in the video clip *Elements and Compounds*, above.

An important feature of compounds is that they are very different from the elements from which they are made. For example, water is made from hydrogen and oxygen, which are both colourless gases, whereas water is the wet liquid you drink that makes up 65% of your body. So, it is important to realise that a water molecule is quite different from the two types of atom from which it is formed. Water is not simply a *mixture* of hydrogen and oxygen; it contains hydrogen and oxygen atoms linked together in an ordered way. (You can make a house from Lego but you would not look at a pile of the separate blocks and say that is a house! In scientific terminology, the house is the molecule and the blocks from which it is built are the atoms.)

Question 9

Look back at Table 2. From what you know about the composition of living organisms, why do you think the percentages of hydrogen and of oxygen atoms are so great?

Answer

If 65% of human bodies is water, you would expect to have a high percentage of the elements that make up water (hydrogen and oxygen) in your body.

The next most common element in human bodies, after hydrogen and oxygen, is carbon. This, when linked to other atoms, forms most of the compounds of which plants and animals are made (apart, that is, from water). One very important category of compounds found in plants and animals is the **proteins**. Part of a protein molecule is shown in Figure 10. This very large molecule (it contains thousands of atoms!) is made up of *only* four different types of atom; note the complex way in which the atoms are put together.

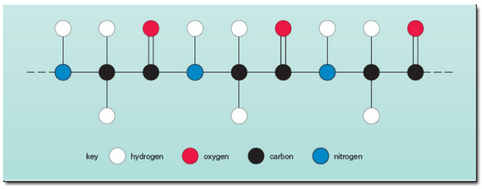


Figure 10 Part of the structure of a molecule of a protein. It is composed of four different types of atom

Question 10

Using the key in Figure 10, name the different kinds of atom (hence different kinds of element) found in a protein molecule.

Answer

Carbon, nitrogen, oxygen and hydrogen atoms are found in protein molecules.

Therefore, it is possible to have simple molecules such as water where only three atoms are bonded together to make a water molecule, and very complex molecules such as proteins where very large numbers of atoms are bonded.

Practise your understanding of elements and compounds by trying the following questions.

Question 9

Using the information about the types of atoms in water and protein (Figures 8 and 10), which of the following are elements and which are compounds?

hydrogen; water; nitrogen; carbon; protein

Answer

Water and protein are compounds because they consist of different types of atom bonded together. Hydrogen, nitrogen and carbon are elements because they each consist of only one type of atom.

Question 10

The gas methane is a major constituent of the gas used for cooking and heating. The only kinds of atom present in a molecule of methane are hydrogen and carbon. Use your understanding of the earlier parts of this course to complete the blanks in the following correct statement.

Methane contains the ……………… carbon and ……. Methane is not an element. It is a chemical ………………

Answer

Two answers are equally correct. Either fill in the blanks with elements/hydrogen/compound *or* with atoms/hydrogen/compound.

Question 11

The atmosphere contains several different kinds of gas: about 80% is nitrogen and about 20% is oxygen. There is a small amount of other gases, one of which is carbon dioxide. From the information given in statements (a) and (b), decide whether the gas named in each statement is an element or a compound.

(a) The bubbles of gas produced in beer and wine making are pure carbon dioxide. Analysis shows that the bubbles contain molecules in which there are two kinds of atom bonded together, namely carbon and oxygen.

(b) In nitrogen gas, nitrogen atoms are bonded together in pairs.

Answer

(a) Carbon dioxide is a compound; (b) nitrogen is an element.

4 Inside the atom

Before going on to see how atoms can link (bond) with each other, you need to look at atoms in a little more detail. Doubtless they are not like blocks of Lego! So what are they like?

In fact, every atom has a complex internal structure. Given the extremely small size of an atom, you may find it difficult to visualise any smaller bits inside it. However, you may already be familiar with some of the effects of one of these components - **electrons**. It is easy to do an experiment that shows the presence of electrons and, moreover, one of their important characteristics.

Activity 2: Detecting electrons

0 hour(s) 5 minutes(s)

The items you need for this small experiment are: a plastic comb (or plastic ruler or inflated balloon) and a small piece of tissue paper or newspaper.

Tear the tissue paper or newspaper into pieces about 1 cm square and leave them in a pile on a table. Rub the comb (plastic ruler or balloon) up and down several times on your clothes. (Some materials are better than others for doing this; wool and nylon are particularly good.) Now move the comb up to the paper and note what happens.

You should find that the paper is attracted to the comb. The explanation for this phenomenon is that the rubbing action transfers large numbers of the tiny electrons from the atoms of your clothes onto the plastic comb and vice versa. The plastic builds up *static electricity* which attracts the paper because the electrons have an electrical *charge*. You now need to look at the electrons in more detail.

Each electron carries a minute but standard amount of negative charge. Conventionally, chemists and physicists speak of an electron as having a charge of −1. The units do not matter in this case as the '−1' is a comparative amount such as a ratio: one electron has a charge of −1, two electrons a charge of −2 and ten electrons have a charge of −10.

Most objects - combs, people or atoms - do *not* usually have any net charge. They are described as electrically neutral. This is not a very hard concept to accept in the light of some intuitive ideas from mathematics or, indeed, bank balances! Something can be negative, positive or have a value of zero, which means no charge at all.

Question 11

Atoms are neutral particles: that is, they carry no net charge. If an atom can be shown to contain negative particles (that is, electrons), what else must there be in an atom?

Answer

There must be some particles carrying a positive charge to balance the negative charge of the electrons. Moreover, the total negative charge of the electrons must just be balanced by the total positive charge in these positive particles, so that the whole atom has a net charge of zero.

These positive particles are known as **protons** and each one carries the same amount of charge as an electron but has the opposite sign, +1.

Question 12

What is the relationship between the number of protons in an atom and the number of electrons in the same atom?

Answer

Since they have the same charge, but opposite signs, there must be the same number of protons as electrons.

Looking at a few atoms will put this important idea into perspective. The simplest element possible is hydrogen. It has just *one* proton and *one* electron. As +1 and −1 together give a charge of 0, it follows that the atom is neutral. Next there is helium, the light but non-flammable gas that is used to fill balloons at fairgrounds and for celebrations (Figure 11).

Figure 11 Helium-filled balloons

Each helium atom contains two protons and two electrons: together, +2 and −2 equal 0. Table 3 summarises this and gives three more examples of elements that you have already met. Note, in passing, two points: first, atoms with three, four and five protons are omitted from Table 3 for simplicity: they do exist! Indeed, the 100 different elements contain atoms with, progressively, 1 up to 100 protons.

Second, most atoms also contain electrically neutral particles called **neutrons**. These do not greatly affect the chemistry of elements and are not discussed further in this course. They are mentioned here in case you have already heard of them and wonder why they are omitted.

Table 3 The numbers of electrons and protons in five elements.

Element	No. of electrons	No. of protons
hydrogen	1	1
helium	2	2
carbon	6	6
nitrogen	7	7

oxygen	8	8

The number of protons determines the identity of each element. Thus, if an atom has six protons it *must* be an atom of the element carbon. If it has seven protons it *must* be nitrogen, and so on. As the number of protons increases so the mass of the atom increases. The number of protons in an atom also determines the number of electrons in that atom and it is the protons and electrons that give the atom its unique characteristics. Note that electrons have very little mass compared with protons.

Each element has a characteristic number of protons, e.g. hydrogen has one. In a neutral atom, the number of protons equals the number of electrons.

Chemists picture an atom as comprising a central **atomic nucleus**, which contains the protons, with electrons moving around it. In this picture (or model) the electrons are arranged in layers, like the layers in an onion. Figure 12 shows a simple representation of this for the element carbon.

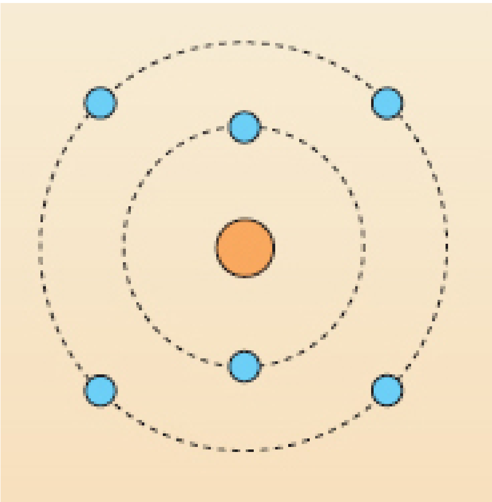


Figure 12 Chemists' simple representation of the carbon atom. The smaller dots represent electrons moving in concentric orbits around the central nucleus containing the protons

Question 13

Using Table 3 and the information in the last few paragraphs, label Figure 12 by making a note of the appropriate charge for each dot.

Answer

Figure 13 shows a labelled drawing of a carbon atom. The small blue dots represent electrons in layers around the central nucleus shown by a larger orange circle. There is a charge of +6 in the nucleus and 6 electrons each with a charge of −1.

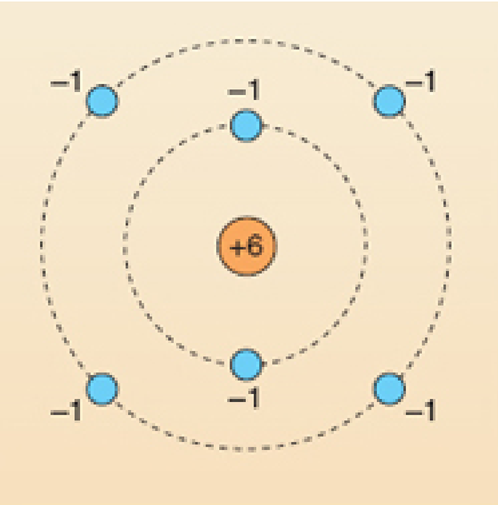


Figure 13 Labelled drawing of a carbon atom

The nature of atoms is described above. However, in Nature very few atoms ever exist entirely on their own: most atoms are joined to other atoms by some kind of *bonding*. In this course we consider two ways in which atoms can bond together. Both ways depend on 'interactions' between the outermost layer of electrons of each of the atoms that are bonding. One way is called **covalent bonding** (pronounced 'co-vay-lent') and the other is called **ionic bonding** (pronounced 'eye-on-ic'). They are discussed in Section 5 and Section 7 respectively.

Question 12

The nucleus of each atom of the element gold contains 79 protons. How many electrons are there moving around each atomic nucleus in this element?

Answer

A gold atom has 79 electrons. Atoms of gold, like atoms of all other elements, are electrically neutral. The charge carried by a proton is +1 so the charge on the nucleus of a gold atom is +79. To balance this, there must be 79 electrons each with a charge of −1.

Question 13

Totally dry air, from which all carbon dioxide has been removed, contains the following gases - in decreasing order of concentration:

Nitrogen (7), oxygen (8), argon (18), neon (10), helium (2), krypton (36) and xenon (54). (*Note*: krypton is pronounced 'krip-ton', and xenon is pronounced 'zen-on'.)

All these gases are elements. The figures in brackets are the number of electrons in each kind of atom. How many protons are there in the nucleus of each kind of atom? How did you deduce these values?

Answer

There are seven protons in the nucleus of a nitrogen atom. This can be deduced as follows: as there are seven electrons surrounding the nucleus in a nitrogen atom, the total negative charge is −7. Since the atom is electrically neutral, and the charge on a proton is +1, there must be seven protons altogether.

Similarly, the number of protons per atomic nucleus in each of the other elements is: oxygen, 8; argon, 18; neon, 10; helium, 2; krypton, 36; and xenon, 54.

Note, for interest, there is nearly 1% of argon in the air you breathe.

5 Molecules and covalent bonding

Covalent bonding is one kind of linking that joins atoms together. The group of atoms held together by covalent bonds is a molecule. The example you are most familiar with is the compound water: water consists of covalent molecules, i.e. it is a **covalent compound**. Recall what is in molecules of water from Section 2.5.

Question 14

Which atoms are in a water molecule? How are they bonded together?

Answer

A water molecule comprises two hydrogen atoms and one oxygen atom, and they are bonded covalently. (Look back at Figure 8.)

You have met three other compounds in the text so far: protein (Figure 10), methane (Question 10) and carbon dioxide (Question 11). These all involve covalent bonding and all exist as molecules. You have also met some gaseous elements that exist as covalent molecules. The oxygen gas in the air does not exist in the form of free individual oxygen atoms, but as pairs of oxygen atoms joined together by covalent bonds to give oxygen molecules. The same applies to the nitrogen in the air: here two nitrogen atoms join together to form a covalent molecule. (As noted earlier, very few elements exist as free, solitary atoms.)

Before going on, make sure that you are clear about three crucial points concerning molecules.

Key points about molecules

1. It is possible to have molecules that are elements (e.g. a molecule of oxygen) and molecules that are compounds (e.g. a molecule of water).
2. Molecules always consist of two or more atoms bonded together (e.g. two oxygen atoms bond together to make an oxygen molecule; two hydrogen atoms and one oxygen atom bond together to make a water molecule).
3. The kind of bonding in molecules is *always* covalent. If a compound or an element exists as *molecules*, the bonding *has to be* covalent.

Now consider the number of covalent bonds that different atoms like to form.

Question 15

The element nitrogen exists as a covalent molecule. From what you have read above, what is in a molecule of nitrogen?

Answer

Two nitrogen atoms joined together covalently.

Question 16

Nitrogen molecules and methane molecules are both covalent but one is an element and the other is a compound. Why is one described as an element and one as a compound?

Answer

Only one kind of atom is involved in the nitrogen molecule: nitrogen atoms. Two kinds of atom are involved in a methane molecule: carbon and hydrogen.

Look back at Figure 10. This is just *part* of a molecule of a protein. Recall that there are only four kinds of atom involved in a molecule of a protein: carbon, nitrogen, oxygen and hydrogen. The black lines in Figure 10 represent the covalent bonds. A protein molecule is always very large, and the dotted lines represent covalent bonds going to parts of the molecule not shown in the diagram. This may look very complex, but atoms obey fairly strict rules as to how they interconnect with other atoms. In particular, there is almost always a set *number* of covalent bonds that a given atom can form.

In the rest of this section, models of some of the more common atoms are used to show how more complex molecules, such as the protein in Figure 10, can be built up from simple atoms. This will show you how many different kinds of molecule can be built up from the same set of atoms; in short, from the chemists' Lego set!

Start by looking at the simplest atom. You have already seen that this is hydrogen and that it has one proton and one electron. Hydrogen likes to form just *one* bond with another atom. Visualising the bonding between atoms can be very difficult - unless, once again, a model is used. This time sketches of the different atoms somewhat similar to those used in the protein molecule in Figure 10 will be used, except that instead of straight lines hooks will be used. Thus, you might represent hydrogen as a sphere with one hook since it has one bond, as shown in Figure 14.

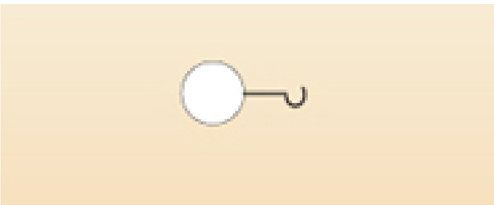


Figure 14 Representation of the hydrogen atom

When linking atoms together to make molecules, the 'golden rule' is that no atom must ever have any spare hooks. A hydrogen atom all by itself has got a spare hook and that is *not* allowed.

Question 17

What is the simplest molecule that hydrogen atoms alone can form? Use representations of the hydrogen atom, such as that in Figure 14, to sketch the molecule.

Answer

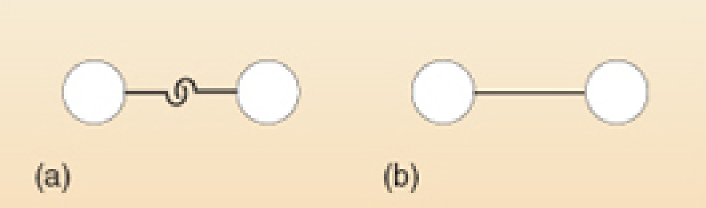


Figure 15 Two representations of the hydrogen molecule: (a) using hooks; (b) using bonds (with the two hooks redrawn as a line representing a single bond)

Hydrogen forms only one link with one other hydrogen atom, as shown in Figure 15(a).

Chemists usually draw the links between the different atoms that form molecules in the form of straight lines. This is shown for hydrogen in Figure 15(b). By comparing (a) and (b), you can see that 'two linked hooks' equals 'one covalent bond'.

Now apply the model-building idea to a molecule of water. Oxygen has two hooks, as shown in Figure 16.

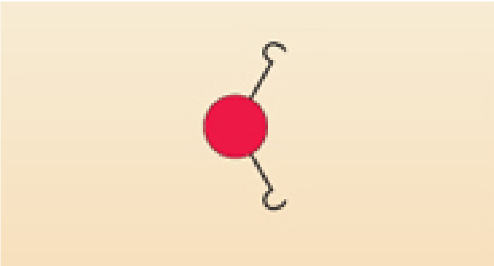


Figure 16 Representation of the oxygen atom

Question 18

Sketch a representation of the water molecule, but this time leave out the 'joined hooks' stage and write down the straight lines of the covalent bonds.

Answer

Your answer should look similar to that shown in Figure 8(a).

Now consider something slightly more complicated than a hydrogen molecule or water molecule. Methane, which is used in domestic heating and cooking, is a covalent compound that has been mentioned several times before. A molecule of methane contains only carbon and hydrogen. In fact, the molecule contains just one atom of carbon. Carbon atoms have four hooks as shown in Figure 17.

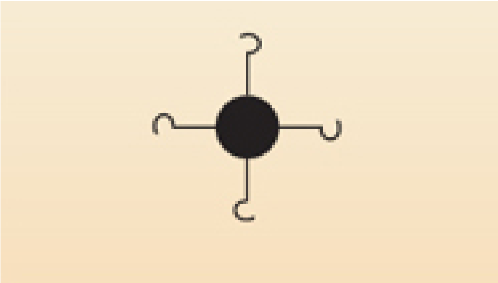


Figure 17 Representation of the carbon atom

Question 19

Use the model atoms of hydrogen (Figure 14) and carbon (Figure 17) to obtain a representation of the methane molecule. How many hydrogen atoms can be attached to the one carbon atom?

Answer

Your model should look similar to Figure 18(a). Each of the four carbon hooks attaches to a hydrogen hook to produce a methane molecule in which four hydrogen atoms form bonds to one carbon atom. Figure 18(b) shows the same molecule using bonds; as before, two joined hooks equals one covalent bond. Figure 18(c) illustrates a ball-and-stick model of methane.

Note that methane isn't a flat molecule - it is described as tetrahedral in shape, as shown in the ball-and-stick model (Figure 18(c)). (The four hydrogen atoms form the four corners of a tetrahedron with the carbon atom at the centre.) However, this is difficult to draw, hence chemists often don't accurately depict the three-dimensional shapes of molecules in written representations.

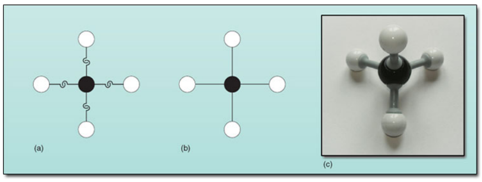


Figure 18 Models of the methane molecule: (a) using hooks; (b) using bonds; (c) using a ball-and-stick model

Try another example: carbon dioxide. This is the molecule produced when carbon (in coal, wood or oil) is burned and when humans or animals breathe out. The name of a compound sometimes gives useful information. In this instance, the 'di' in front of the oxide of *dioxide* tells you that the molecule has *two* oxygen atoms. The carbon dioxide molecule demonstrates another feature of bonding between atoms.

Question 20

How many bonds does carbon form? Look back at Figure 17 if necessary.

Answer

Carbon forms four bonds.

Question 21

How many bonds can oxygen form? Look back at Figure 16 if necessary.

Answer

Oxygen forms two bonds.

So, how does one carbon atom bond to two oxygen atoms in this instance? Imagine that all the hooks sticking out of the spheres of the atoms of carbon and oxygen are flexible. Try to fix them together so there are no unsatisfied hooks.

The only way for all the carbon hooks to be used is (i) for the *two hooks* of one oxygen atom to link to *two of the four hooks* of the carbon atom and (ii) the second oxygen atom to link in the same way to the remaining two hooks of the carbon atom. The molecule is represented in Figure 19(a) .

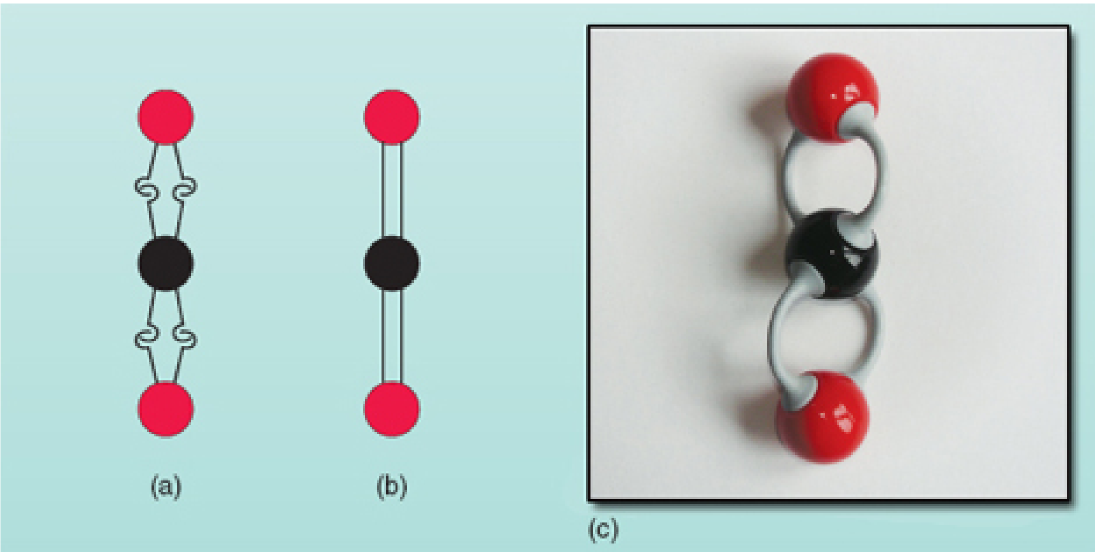


Figure 19 A carbon dioxide molecule: (a) using hooks; (b) using bonds; (c) using a ball-and-stick model

This type of sketch is quite clumsy and chemists prefer to represent the bonds as shown in Figure 19(b). When atoms bond in the way shown in this figure, the bonds formed are referred to as double bonds, as opposed to single bonds such as those formed in the methane and water molecules. Look back at Figure 10 - part of a protein molecule. The vertical 'double lines' between the carbon atoms and the oxygen atoms are carbon-to-oxygen double bonds.

It is entirely possible to have other molecules where carbon atoms are joined to carbon atoms by double bonds - as shown in the example in Figure 20. (*Note*: Chemists have a special name for compounds that contain carbon-to-carbon double bonds. They are described as *unsaturated* compounds or sometimes as *unsaturates*. If there are several such double bonds in a molecule, they are often called *polyunsaturates*, where 'poly' simply means 'many'. You may have heard the term in expressions such as 'high in polyunsaturates' used to describe certain margarines and spreads.)

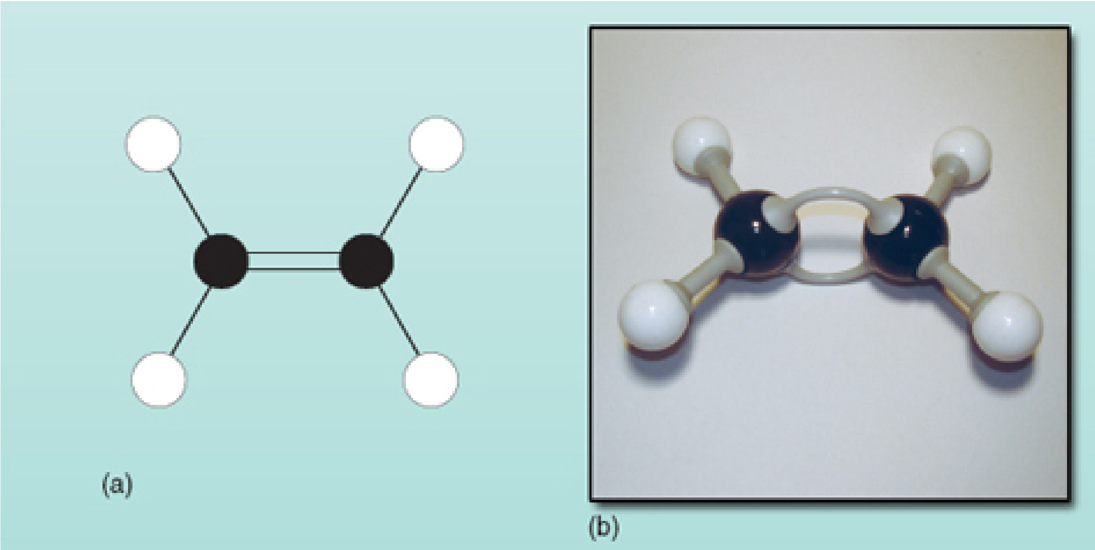


Figure 20 A carbon-to-carbon double bond in the ethene molecule: (a) using bonds; (b) using a ball-and-stick model

The number of covalent bonds that are normally formed by hydrogen, carbon, nitrogen and oxygen (the four atoms found in molecules of protein) are summarised in Table 4. To extend your 'chemistry Lego set' a little further, two other elements have been added to the table, namely sulfur and chlorine.

Table 4 Usual number of covalent bonds formed by six elements

Element	Usual number of bonds
hydrogen	1
carbon	4
nitrogen	3
oxygen	2
sulfur	2
chlorine	1

You may find it helpful to memorise this table.

In concluding this section on covalent bonds, it is important to remember that it is not really hooks that hold atoms together! You learned from Figure 12 that the nucleus of every atom is surrounded by electrons. When two atoms link covalently some of these electrons are *shared* between them. This idea of 'electron sharing' in covalent bonds is an important one in chemistry.

Question 14

Using the information in Table 4, which of the following are likely to exist as covalent molecules?

(a) One sulfur atom and two hydrogen atoms;

(b) One nitrogen atom and three hydrogen atoms;

(c) One carbon atom and five chlorine atoms.

Answer

(a) and (b) are likely to exist and in fact *do* exist as covalent compounds; (c) is most unlikely as carbon forms four and not five covalent bonds.

6 Chemical language

6.1 Introduction

The previous sections in this course include many terms which may have been unfamiliar to you: for example, atom, element, compound, molecule and bond. Chemistry has a language all of its own and grasping the terminology can be as much of a problem as understanding the chemistry itself. In Section 6, you will consider the language of chemistry before returning to the examination of bonding.

6.2 Chemical symbols

So far, atoms have been represented as labelled spheres or circles and the bonds that link atoms in molecules have been represented as lines. This is a rather cumbersome method of writing down molecules. Chemists have developed their own shorthand language for the names of the elements. It involves giving each element a **symbol** consisting of one or two letters. You can guess some of them, because they start with the *first letter* of the element's name. Thus oxygen is designated by the capital letter O and nitrogen by N.

Question 22

The symbols of the following elements are all formed in this way: hydrogen, carbon and sulfur. Write down their symbols.

Answer

The chemical symbols are H for hydrogen, C for carbon and S for sulfur.

However, there are about 100 elements and only 26 letters in the alphabet! So some elements such as calcium and aluminium are represented by the *first two* letters. Thus calcium is Ca and aluminium is Al. Note that the first letter is always a capital and the second is always written or printed as a small letter (lower case).

Question 23

The symbols of the following elements are all of the type just described: helium, nickel, bromine and silicon. Write down their symbols.

Answer

The chemical symbols are He for helium, Ni for nickel, Br for bromine and Si for silicon.

This may seem perfectly straightforward but, for historical reasons, some elements have unusual symbols. Sulfur had taken the symbol S and so an alternative was required for sodium.

Table 5 shows the symbols for a few of the more common elements, along with the origins of the element's name. As noted above, in any two-letter symbol, the second letter is *always* lower case.

Table 5 Name, origin and symbol* for 15 elements

Element name	Origin of name	Symbol
hydrogen	from the Greek, *hydro* (water) and *genes* (forming)	H
helium	from the Greek, *Helios* (the Sun)	He
carbon	from the Latin, *carbo* (charcoal)	C
nitrogen	from the Greek, *nitron* and *genes* (soda forming)	N
oxygen	from the Greek, *oxys* and *genes* (acid forming)	O
sodium	from the English, *soda* (*natrium* in Latin)	Na
magnesium	from Magnesia, a district of Thessaly in Greece	Mg
aluminium	from the Latin, *alumen* (alum)	Al
silicon	from the Latin, *silex* (flint)	Si
sulfur	from the Latin name *sulphur* for the element	S
chlorine	from the Greek, *chloros* (yellowish green)	Cl
potassium	from the English, *potash* (symbol from *kalium* - Latin for alkali)	K
calcium	from the Latin, *calyx* (lime)	Ca
iron	Anglo-Saxon name for the metal; the Romans called it ferrum	Fe
bromine	from the Greek, *bromos* (stench)	Br

*It is recommended that you memorise the chemical symbols for the 15 elements in Table 5. This will help you read and write the chemical shorthand used in chemical formulas (Section 6.3), and in chemical equations used to describe chemical reactions (Section 6.4).

6.3 Chemical formulas

By using symbols, elements can be represented much more conveniently and much more briefly. This method of using symbols can be extended to compounds. You will now look further into this idea using a very familiar compound: water. Recall which atoms there are in a water molecule.

Question 24

What symbols would you use to represent the water molecule?

Answer

Since the water molecule has two hydrogen atoms and one oxygen atom, you might have written down HHO, HOH or OHH.

It is conventional to add up all the atoms of one type in a molecule, so it is written H_2O where the subscript 2 after the H indicates that there are two hydrogen atoms and the absence of a subscript after O indicates that there is only one oxygen atom. Such a representation is known as a **chemical formula**. Arguably, you should write H_2O_1 but for convenience and simplicity the subscript 1 is always omitted. Unfortunately, there is no obvious rule to indicate which element should be written down first in a chemical formula. Do you write H_2O or OH_2? You probably know the answer, of course; from saying 'aitch-two-oh': you would write H_2O. The reason is, essentially, a matter of convention: that's the way chemists do it. At first, you may find this system of writing formulas slightly awkward. Concentrate on remembering that the subscript refers to the symbol that *directly precedes it*. (There are two possible plurals for formula: we will use 'formulas' but you may also see 'formulae' in some textbooks.)

Question 25

Write down the chemical formulas for carbon dioxide and methane. You may need to refer back to previous sections to remind yourself which atoms are present and in what proportions.

Answer

The chemical formula for carbon dioxide is CO_2 (pronounced 'see-oh-two') and for methane is CH_4 (pronounced 'see-aitch-four').

The chemical formula of a covalent compound shows the number of each type of atom in one molecule of the compound. It is written using the symbols for the elements.

Having examined the naming of elements, their symbols and the formulas of compounds, what about the names of compounds? As with elements, the everyday names of some compounds have their origins in history. For example, words that *sound* like 'water' have been used for this liquid for thousands of years. The old English term was 'waeter', in old Saxon 'watar', in old German 'wazzar' and ancient Greek 'hudor'. For common compounds these old names linger on: water, ammonia, salt and alcohol are just some examples. However, there are millions of different compounds - if they all had common names you would never be able to remember them. A more simple, logical naming system is needed, which can be applied to any compound, so that everyone can understand which compound is being talked about.

The scientific name reflects the elements found in the compound. Where a compound contains just two elements, the name of the second element is usually modified slightly so that it ends in the letters '-ide' (pronounced as in 'side'). Thus, the compound HCl (pronounced 'aitch-see-ell') is hydrogen chloride not hydrogen chlorine. Similarly, CO_2 is carbon dioxide not carbon dioxygen. The 'di-' prefix indicates that there are two oxygen atoms and the '-ide' ending confirms that only two elements are involved in it.

Now try Questions 15 to 18, referring to Table 4 and Table 5 where necessary.

Question 15

Using chemical symbols to represent the atoms and the information in Section 5, write structures for (a) a molecule of oxygen and (b) a molecule of nitrogen. Draw covalent bonds as straight lines and not joined hooks. For example, the structure for water would be written as H—O—H.

Answer

$$O = O$$
$$N \equiv N$$

You may have gone through the stage of drawing linked hooks to get to these molecular structures showing double and triple covalent bonds, respectively. (*Note*: a triple covalent bond is the maximum allowed between two atoms; quadruple bonds between two atoms do not exist.)

Question 16

Which elements make up the following compounds? What is the ratio of the constituent atoms within each molecule?

(a) Ammonia, NH_3 (pronounced 'en-aitch-three')

(b) Hydrogen sulfide, H_2S (pronounced 'aitch-two-ess').

Answer

(a) Nitrogen and hydrogen: the atoms are in the ratio of 1 : 3 within the molecule of NH_3 (called ammonia).

(b) Hydrogen and sulfur: the atoms are in the ratio of 2 : 1, respectively, within the molecule of H_2S (called hydrogen sulfide).

Question 17

Write the chemical symbols for the elements that make up the following compounds.

(a) Hydrogen bromide

(b) Silicon dioxide

(c) Nitrogen trichloride ('tri-' is the prefix for three atoms).

Answer

The chemical symbol for: (a) hydrogen is H, bromine is Br; (b) silicon is Si, oxygen is O; (c) nitrogen is N, chlorine is Cl.

Question 18

Given that bromine, silicon and nitrogen normally form one, four and three covalent bonds respectively, and drawing on knowledge you already have about hydrogen and oxygen, write down the chemical formulas of the compounds named in Question 17. (You *can* write down the formulas from the names alone by using 'di', 'tri' and 'ide'. If you do this, use your understanding of covalent bonding to check your answers.)

Answer

The chemical symbol for hydrogen bromide is HBr, silicon dioxide is SiO_2, nitrogen trichloride is NCl_3.

(This ties in with their names, with the meaning of 'di-' and 'tri-', and with the idea of a 'preferred' number of covalent bonds.)

6.4 Chemical equations and chemical reactions

The previous section shows how different elements can either exist on their own or combine with other elements to make compounds. This section builds on these ideas by looking at chemical reactions in more detail. It also shows how chemical shorthand can be extended to describing chemical reactions.

First, consider some of the molecules described earlier: water, methane, carbon dioxide and ammonia.

Question 26

What are the formulas for each of these four molecules?

Answer

The formulas are H_2O, CH_4, CO_2 and NH_3, respectively.

Although you don't need to remember the chemical formulas of compounds introduced in this course, you'll probably find it useful to memorise a few such as those for the four molecules above, plus those for hydrogen (H_2), nitrogen (N_2) and oxygen (O_2) molecules. This will help you in reading and writing these chemical formulas without continually referring back to previous sections.

Now you will look at reactions involving the elements hydrogen, carbon and oxygen and the compounds methane, water and carbon dioxide.

Hydrogen will react with oxygen when it is ignited (it is quite explosive) to form water. To write such a reaction in terms of a **chemical equation**, the substances that undergo the reaction are put on the left and the substances that are produced in the reaction are put on the right. The **reactants** on the left are linked to the **products** on the right by an arrow.

The equation can be written as a word equation 'hydrogen and oxygen make water' or, using a little chemical shorthand, it can be written as:

$$\text{hydrogen} + \text{oxygen} \longrightarrow \text{water}$$

where the arrow means 'goes to'.

Now, try using chemical shorthand to write the equation. Substituting symbols in the word equation gives:

$$\text{hydrogen} + \text{oxygen} \longrightarrow \text{water}$$

$$\underbrace{H_2 + O_2}_{\textit{reactants}} \longrightarrow \underset{\textit{product}}{H_2O}$$

The equation shows the reactants on the left of the arrow being converted to the product on the right. However, there is something wrong with this equation. You can see what is wrong by looking at Figure 21 where the reactants and products are shown as a diagram.

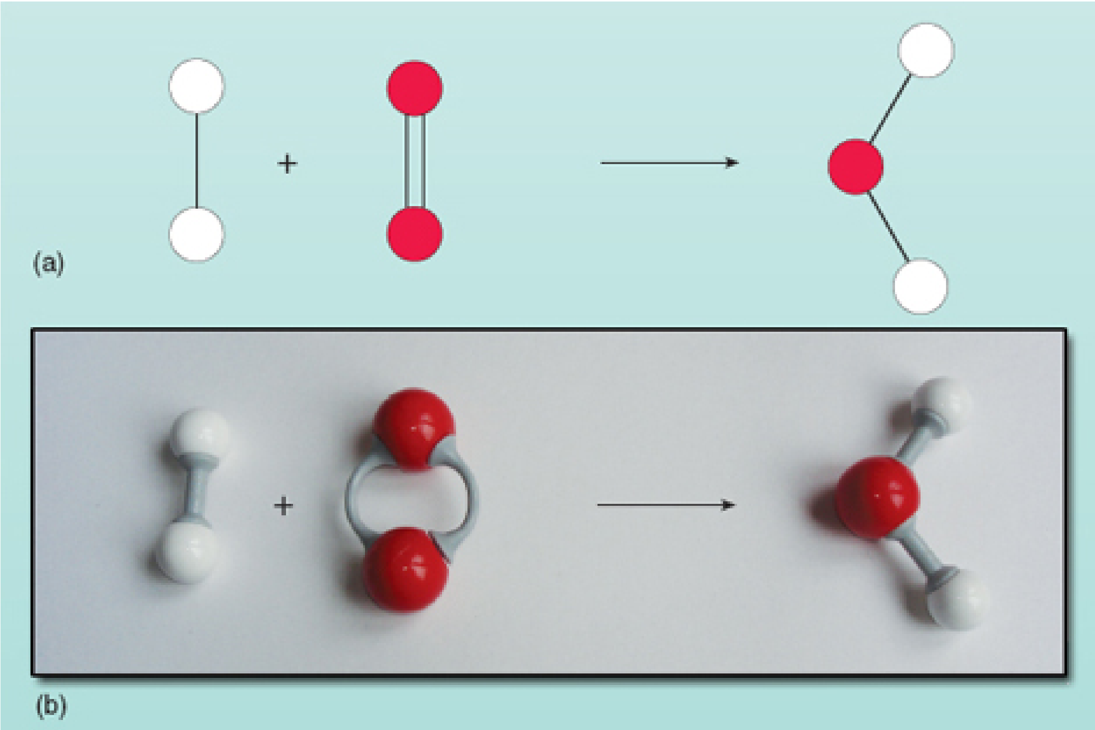


Figure 21 The unbalanced equation for the reaction between hydrogen and oxygen to give water: (a) diagrammatic representation; (b) ball-and-stick model. Note that the oxygen molecule comprises two oxygen atoms linked by a double bond. This is because each oxygen atom has two 'hooks' to link up

Counting the numbers of atoms on each side of the equation shows that there are two oxygen atoms on the left compared with one on the right. The number of oxygen atoms on both sides of the equation must be equal - they can't magically appear and disappear during a reaction. It is not possible to change the composition of the water molecule on the right of the equation as the water molecule exists as a group of two hydrogen atoms and one oxygen atom all bonded together. Each oxygen molecule supplies two oxygen atoms so will always form two water molecules, provided there are two hydrogen molecules (each being a unit of two atoms) to react with it. Thus two *molecules* of hydrogen and one molecule of oxygen are needed to make two molecules of water. The reaction is accurately expressed by:

$$H_2 + H_2 + O_2 = H_2O + H_2O$$

There are now the same numbers of each type of atom on both sides of the equation: the chemical equation is *balanced*, so we can now replace the arrow with an equals sign.

A final tidy-up to avoid repeating the hydrogen molecules on the left of the equation and the water molecules on the right is to represent them by $2H_2$ rather than $H_2 + H_2$. So the balanced chemical equation becomes:

$$2H_2 + O_2 = 2H_2O$$

This is shown diagrammatically in Figure 22.

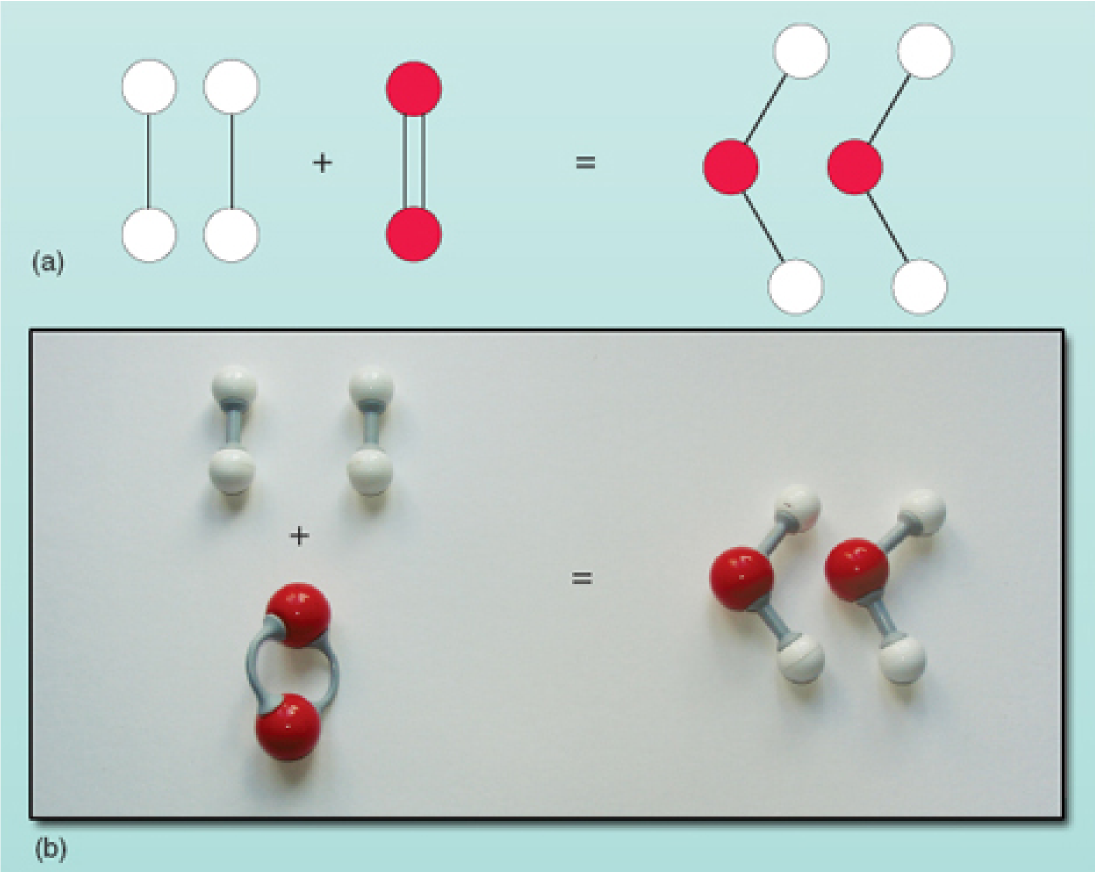


Figure 22 The balanced equation for the reaction between hydrogen and oxygen to give water: (a) diagrammatic representation; (b) ball-and-stick model

Chemical equations show in a very concise way not only which atoms and molecules react together to form the products but also how many of each sort of atom and molecule are involved. It is important to remember that the number before a molecule means the number of that particular molecule. For example $3H_2O$ means three molecules of water, giving a total of six hydrogen and three oxygen atoms.

Chemical equations must balance; the number of atoms of each type of element on both sides of the equation must be equal.

You now know how to 'read' or interpret a chemical equation - and how it represents a chemical process. However, chemists are also very adept at writing chemical equations as a form of shorthand to describe various chemical processes or reactions. Writing chemical equations is like writing in any foreign language - it requires practice to become fluent. However, all budding scientists have to start somewhere and the section below shows you how to do this using a very familiar chemical reaction. If you wish to check whether you need to study this section, try Question 20 first.

6.4.1 Writing a chemical equation to describe a chemical process

Natural gas, which is largely methane, is burned to provide heat for cooking and domestic heating and as an industrial power source. This process of burning involves the reaction of methane with oxygen in air to produce carbon dioxide and water.

A chemical equation can be constructed for the reaction of methane with oxygen to give carbon dioxide and water as the products.

1. The first step is to write the formulas of the reactants on the left and the products on the right:

   $$CH_4 + O_2 \longrightarrow CO_2 + H_2O$$

2. At this point, all the products and reactants are featured, but the equation is not balanced; the numbers of hydrogen and oxygen atoms are not the same on both sides of the equation. Since oxygen atoms are in pairs in both carbon dioxide and oxygen, you know that you must have an even number of oxygens on the right-hand side of the equation too. To correct this 'odd oxygen' imbalance, add another water molecule to the right-hand side of the equation. Now count up the atoms on both sides of the equations.

   $$CH_4 + O_2 \longrightarrow CO_2 + 2H_2O$$

   There is now one carbon and four hydrogen atoms on each side of the equation. However, there are two oxygen atoms on the left-hand side and a total of 2 + 2 = 4 oxygen atoms on the right.
3. To correct this, add another oxygen molecule on the left-hand side to give the balanced chemical equation:

   $$CH_4 + 2O_2 = CO_2 + 2H_2O$$

   The total number of atoms is the same on each side of the equation.

Balancing chemical equations is not always easy but it does come with practice. Try practising by doing Questions 19 and 20 before moving on to the next section, which looks at ions and bonding.

Question 19

Balance the following equations. All the reactants and products are shown.

1. Magnesium is burned in oxygen to give magnesium oxide:

   $$Mg + O_2 \longrightarrow MgO$$

2. Carbon and chlorine gas react to form carbon tetrachloride:

   $$C + Cl_2 \longrightarrow CCl_4$$

3. Potassium oxide is formed by burning potassium in oxygen:

   $$K + O_2 \longrightarrow K_2O$$

4. Hydrogen reacts with chlorine gas to form hydrogen chloride:

   $$H_2 + Cl_2 \longrightarrow HCl$$

Answer

Remember that the number of atoms of each element must be the same on both sides of the 'balanced' equation.

$$2Mg + O_2 = 2MgO$$
$$C + 2Cl_2 = CCl_4$$
$$4K + O_2 = 2K_2O$$
$$H_2 + Cl_2 = 2HCl$$

Now try writing a balanced chemical equation yourself by doing Question 20.

Question 20

Write a balanced chemical equation for the chemical reaction in which nitrogen, N_2, and hydrogen, H_2, react together to give ammonia NH_3. These are the only reactants and product involved.

Answer

1. The first step is to put the formulas of the reactants on the left and the product on the right.

   $$N_2 + H_2 \longrightarrow NH_3$$

2. Now balance the number of atoms of nitrogen. With two atoms of nitrogen on the left, two ammonia molecules are needed on the right. (Remember, N_2 means two atoms of nitrogen joined as a molecule.)

   $$N_2 + H_2 \longrightarrow 2NH_3$$

3. The next problem is the number of hydrogen atoms: there is a total of six on the right (three in each of the two ammonia molecules) and only two hydrogen atoms in the single hydrogen molecule on the left. To correct this, three hydrogen molecules are needed on the left (to give a total of six atoms).

   $$N_2 + 3H_2 = 2NH_3$$

   The result is a balanced chemical equation for a process in which one molecule of nitrogen reacts with three molecules of hydrogen to give two molecules of ammonia.

7 Ions and ionic bonding

This section returns to bonding - the way in which atoms are joined to each other. You have already met one type of bonding involving covalent bonds, which is found in molecules. However, this is not the only bonding found in compounds. In this section you will look at ionic bonding and the **ionic compounds** that contain such bonding. What is the main *difference* between the covalent compounds you met in Section 5 and ionic compounds? Are there any *similarities* between these two enormous families of chemical compounds?

Glucose is a covalent compound and sodium chloride is an ionic compound. You meet glucose in solution in everyday life as it is the sugar in many sweet drinks (and is closely related to ordinary table sugar). You are certainly familiar with sodium chloride as it is the table salt used in kitchens. The formulas of both compounds tell you which atoms have combined together to make them. You can work this out for yourself in the following question.

Question 27

The formula of glucose is $C_6H_{12}O_6$ and the formula of salt is NaCl. Which elements are combined to make glucose? Which elements are combined to make salt? Use Table 5 to help you if necessary.

Answer

The covalent compound glucose is formed from the elements carbon, hydrogen and oxygen. The ionic compound sodium chloride is formed from the elements sodium and chlorine.

If you bought some glucose tablets from a pharmacy or a sports shop and crushed them, you would have a fine, white, sweet powder - certainly not like the elements that form it: black carbon, gaseous hydrogen and gaseous oxygen.

Equally, sodium chloride is vastly different from the elements that combine to make it (Figure 23). Sodium chloride is a white solid that is used in food. Yet chlorine is an enormously reactive green gas, deadly poisonous in concentrated form, and an excellent disinfectant when dissolved in water, such as in swimming pools. You probably haven't seen sodium as this silvery metal catches fire in air and almost explodes in water. Once again, the compound - an ionic compound in this case - is completely different from its constituent elements.

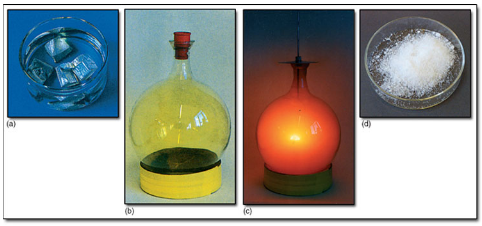


Figure 23 (a) Sodium metal (immersed in oil to prevent reaction with oxygen and moisture in the air); (b) chlorine gas; (c) the reaction between sodium and chlorine; (d) sodium chloride (common table salt)

If covalent and ionic compounds are similar in that they are unlike the elements that form them, in what key way do they differ? The answer is in the *nature of the bonding*. To understand ionic bonding, you need to recall what you learned in Section 4 about the internal structure of atoms.

Question 28

Which kind of charge does an electron carry? In which way is the overall electrical neutrality of atoms achieved?

Answer

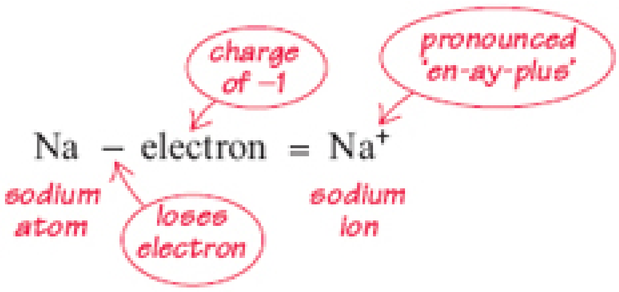
Each electron carries one negative charge that is represented as −1. An atom is neutral because the number of protons (each of which bears a positive or +1 charge) exactly equals the number of electrons.

Now apply this to the elements that are in common salt. Table 3 lists the number of electrons (and hence protons) in five elements. Table 6 shows the comparable information about sodium and chlorine.

Table 6 The number of electrons and protons in sodium and chlorine

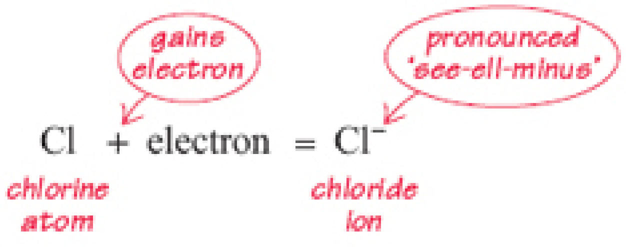
Element	No. of electrons	No. of protons
sodium	11	11
chlorine	17	17

How do these two elements bond together? Picture a sphere representing a sodium atom. The sphere isn't solid: it has a tiny central nucleus (with a charge of +11) and a cloud of electrons arranged in layers (with a total charge of −11). In many chemical reactions, an atom of sodium *very easily loses one electron* from the outer layer of this cloud of electrons. The loss of a single electron from a sodium atom makes it into a particle bearing a net *positive* charge of +1. This positive particle is termed an **ion** (pronounced 'eye-on'). By taking away one electron from a sodium atom, a sodium ion is formed:



This equation can be easily explained. The sodium atom is electrically neutral; it comprises 11 protons (+11) and 11 electrons (−11). When it loses one electron with a charge of −1, by arithmetic, the particle that is left must have a charge of +1. Note that this is represented by the symbol for sodium with a small superscript 'plus' sign.

Now picture a chlorine atom. This is electrically neutral: it has 17 electrons and 17 protons. In its reactions a chlorine atom *likes to gain one electron*. Following the same line of reasoning as before, adding one electron to this atom gives one extra negative charge. Thus a chlorine ion (usually called a chloride ion) is formed. Once again, the ion is represented by the symbol for the element followed by the charge written as a superscript. Thus:



The next question covers the same ground but looks at the change from atom to ion in overall terms.

Question 29

Look back at chlorine in Table 6. (a) What charge is in the nucleus after the electron is gained? (b) What total charge is there in the remaining set of electrons? (c) What, therefore, is the *net* charge on the ion as a whole?

Answer

(a) The protons are undisturbed; so the charge in the nucleus is still +17. (b) The electrons are one more than before; so their charge is −18. (c) The outcome of +17 and −18 is −1. So the *net* charge on the ion is −1.

The fact that a sodium atom likes to lose an electron and a chlorine atom likes to gain an electron means that they have a great potential for satisfying each other's 'needs'. This is what lies behind the violence of the reaction between shiny sodium metal and green poisonous chlorine gas (Figure 23(c)). If you dropped a lump of sodium into a container of chlorine gas (behind armoured glass as the reaction is very violent and involves flames) *electron transfer occurs*. Each sodium atom loses an electron (so forming Na^+) and each chlorine atom gains one (so forming Cl^-). On the bottom of the container of chlorine gas, there would be a trace of white powder: the compound sodium chloride, common table salt. The Na^+ ions and the Cl^- ions formed in the reaction attract each other in a similar way to a comb attracting paper. The positive ions are strongly attracted to the negative ions.

Question 30

Suppose one billion sodium atoms lost one electron each to one billion chlorine atoms. (a) How many electrons move from Na atoms to Cl atoms? (b) How many sodium ions (Na^+) are formed? (c) How many chloride ions (Cl^-) are formed? (d) What is the net charge on the resulting sodium chloride? (e) How many molecules are formed?

Answer

(a) one billion; (b) one billion; (c) one billion; (d) zero. The answer to (e) may surprise you: none!

The net charge on any ionic compound is always zero. The atoms, after all, start out neutral. All that happens is that some electrons move from one place to another. The total charge on the positive ions exactly equals the total charge on the negative ions.

The answer to (e) raises an important point. In ionic compounds such as salt, it is the attraction between the negatively charged chloride ions and the positively charged sodium ions which holds the substance together. This attraction *operates in all directions*, unlike the bonding in covalent compounds where the linking is directly between the atoms. Figure 24 shows this in a magnified piece of salt.

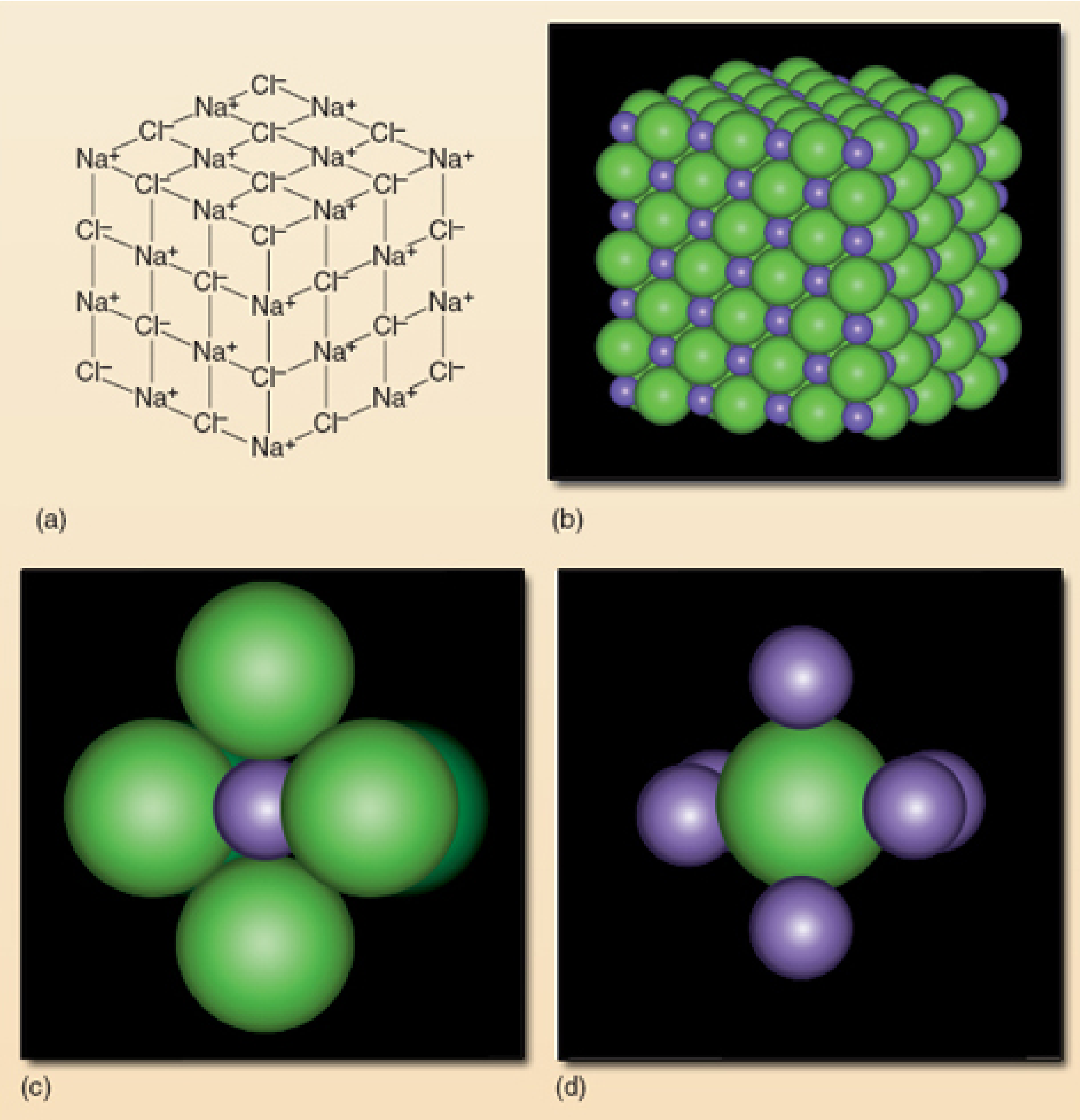


Figure 24 A magnified piece of salt. (a) Here the solid lines represent the electrical attraction between every Na^+ and each of its neighbouring Cl^- ions. In fact, this is a two-dimensional representation of a more complex three-dimensional structure. (b) The ions are shown in their space-filling representation. The larger spheres are chloride ions and the smaller ones sodium ions. (c) and (d) illustrate the 'ion packing' structure within sodium chloride - that each sodium ion is surrounded by 6 chloride ions, and that each chloride ion is surrounded by 6 sodium ions, respectively

A distinct *molecule* of sodium chloride *cannot* exist because each sodium ion is attracted to more than one chloride ion and vice versa. Thus drawing directional bonds between atoms, as you did for the covalent molecules in Section 5, would be meaningless.

So far, you have considered the Na^+ ion and the Cl^- ion which have lost and gained one electron, respectively. Some atoms like to lose more than one electron or gain more than one electron. For example, atoms of the element calcium (another very reactive metal) always lose *two* electrons, so the calcium ion is always Ca^{++} normally written as Ca^{2+} (pronounced 'see-ay-two-plus'). In this case, the superscript '2+' tells you that there are two plus charges on this ion.

Another example of a 'two electron change' is shown by atoms of the element oxygen. Recall that an oxygen atom forms two covalent bonds in some reactions (you saw this in Section 6 in H_2O and CO_2). However, in some other reactions it prefers to gain two electrons and thus forms ions. When this happens, the ion formed is O^{2-} (pronounced 'oh-two-minus'). This is called the *oxide ion*.

This preference for forming oxide ions is shown by oxygen in the many reactions where metals burn in oxygen. For example, calcium metal burns in oxygen to form the ionic compound *calcium oxide*. The formula for calcium oxide is CaO. This means that there is exactly one calcium ion (Ca^{2+}) to every oxide ion (O^{2-}) in a piece of calcium oxide. Thus the overall neutrality of the compound is maintained: (2+) + (2−) = 0.

Note that the formula of an ionic compound gives the ratio between the two kinds of ions. By convention, charges are not written in the formula. Thus it is NaCl and CaO and not $Na^{+}Cl^{-}$ and $Ca^{2+}O^{2-}$.

What happens in an ionic compound when an ion containing two charges is combined with ions bearing only one charge? The 'golden rule' is that electrical neutrality must be maintained.

Question 31

Calcium chloride has the formula $CaCl_2$. Which ions are in this compound and what is their ratio?

Answer

The subscript 2 in $CaCl_2$ means there are two Cl^{-} ions, each with a charge of 1−, i.e. 2− in total. The single Ca in $CaCl_2$ means one Ca^{2+} ion, i.e. a total charge of 2+. In the compound, the 2− charges and 2+ charges add up to zero. Thus neutrality is maintained.

So far, this section has described simple compounds containing only two types of element: one forms the positive ion and one forms the negative ion. However, there are several ionic compounds that are more complex than this because one or both of the ions contain more than one element. An example is the nitrate ion, the principal culprit in water pollution by agricultural fertilisers.

The nitrate ion contains a cluster of atoms: one nitrogen and three oxygen atoms covalently bonded together inside the nitrate ion. However, the cluster of atoms as a whole bears just one negative charge just like the simple Cl^{-} ion. So the chemical formula for the nitrate ions is NO_3^{-}. Another ion that contains a cluster of atoms is the sulfate ion. Table 7 summarises some common ions. You may find it useful to memorise the chemical formulas for these ions.

Table 7 Summary of ions in Section 7

Name	Formula
sodium ion	Na^{+}

potassium ion	K^+
calcium ion	Ca^{2+}
chloride ion	Cl^-
oxide ion	O^{2-}
nitrate ion	NO_3^-
sulfate ion	SO_4^{2-}
bicarbonate ion*	HCO_3^-

* Chemists prefer to call this ion hydrogen carbonate - but the 'old' name bicarbonate continues to be used in some areas such as food and household labelling.

Question 32

The chemical formula for the sulfate ion is given in Table 7. How many sulfur atoms and oxygen atoms are covalently bonded within each ion?

Answer

The sulfate ion contains one atom of sulfur and four of oxygen.

The negative nitrate ion pairs with a positive ion, of course. Sometimes this is a sodium ion (Na^+); alternatively, it could be potassium (K^+). Sodium nitrate ($NaNO_3$) and potassium nitrate (KNO_3) are, in fact, two of the commonest fertilisers containing the nitrate ion (Figure 1b). Sodium nitrate contains a vast number of sodium ions (Na^+) and nitrate ions (NO_3^-). As you can tell from the formula for sodium nitrate, these ions are present in equal numbers to give overall electrical neutrality.

The chemical formula of an ionic compound shows the ratio of ions (and atoms that form the ions) in that compound. It is written using the symbols for the elements.

The attraction of the positive and negative ions in sodium nitrate, in the solid form, holds the compound together in a similar way to that shown for NaCl in Figure 23. When sodium nitrate is added to water, the water molecules interpose themselves between the two types of ion reducing the attraction between them and allowing them to separate. The result is that the solid sodium nitrate dissolves in water (Figure 1(c)).

Question 33

Which ions are present in potassium nitrate and in what ratio are they?

Answer

Potassium nitrate contains the potassium ion (K^+) and the nitrate ion (NO_3^-). They are in the ratio 1 : 1.

A final point about the names of ionic compounds may be helpful. In some ionic compounds (e.g. sodium chloride and calcium oxide), the name of the negative ion ends in '-ide'. As you know from Section 5 on covalent compounds, this simply denotes 'two elements in the compound'. However, in ionic compounds where the positive ion is balanced by a negative ion containing oxygen and another element (such as in the ion NO_3^-), the ending usually changes to '-ate'. Thus the NO_3^- ion is called the *nitrate ion*; this tells you that the ion contains nitrogen and oxygen. Some general rules about the chemical names of different substances are summarised below.

Endings in chemical names

You may have noticed that endings such as '-ide' '-ate' and '-ium' are used in chemical names: for example, sodium chloride and calcium sulfate.

These endings give clues about the types of atom in a particular compound.

'-ide'	This usually means that there are only two elements in a compound. The convention applies to both covalent and ionic compounds, e.g. carbon dioxide and sodium chloride, respectively. In ionic compounds, the name of the negative ion ends in '-ide', e.g. oxide and chloride.
'-ium'	This usually signifies a part of a compound that comes from an element that is a metal, e.g. calcium and sodium. In ionic compounds, this part is the positive ion.
'-ate'	This ending applies only to ionic compounds. It usually means that the negative ion itself consists of two elements, one of which is oxygen, e.g. the sulfate and nitrate ions.

Try the following four questions to practise your understanding of chemical formulas.

Question 21

What are the names of the following ionic compounds?

(a) CaO; (b) KCl; (c) Na_2SO_4; (d) MgO.

Answer

(a) Calcium oxide, (b) potassium chloride, (c) sodium sulfate, (d) magnesium oxide.

Question 22

Which ions are present in a solid sample of compounds (a) to (d) in Question 21? In each case, what is the ratio of positive ions to negative ions? (You may need to refer to Table 7.)

Answer

Ca^{2+} and O^{2-} in the ratio 1 : 1; K^+ and Cl^- in the ratio 1 : 1; Na^+ and SO_4^{2-} in the ratio 2 : 1; Mg^{2+} and O^{2-} in the ratio 1 : 1.

Although Mg^{2+} is not in Table 7, you can deduce it from the formula MgO, knowing that the oxide ion is O^{2-}.

Make sure you have checked your answers to Questions 21 and 22 before trying Questions 23 and 24.

Question 23

Using your knowledge from this course so far (and your understanding of Questions 21 and 22), what are the chemical formulas of (a) calcium sulfate and (b) potassium sulfate?

Answer

The formula for calcium sulfate is $CaSO_4$ (one Ca^{2+} ion and one SO_4^{2-} ion).

The formula for potassium sulfate is K_2SO_4 (two K^+ ions and one SO_4^{2-} ion).

Question 24

Magnesium sulfate is very soluble in water. Which ions from magnesium sulfate would be present in the solution and in what ratio would they occur?

Answer

Mg^{2+} and SO_4^{2-} are in the ratio of 1 : 1. You know from Question 22 that the ion of magnesium is Mg^{2+}. Hence, magnesium sulfate is $MgSO_4$; the charge of 2+ on the magnesium ion balances the charge of 2− on the sulfate ion (SO_4^{2+}).

In the next section you will see why ions are an important feature of the water around you.

8 Water and its impurities

Water must be of a certain quality to be suitable for human consumption. No natural water found on Earth is pure; any sample of water contains more than just water molecules. Some materials, such as sodium nitrate, are very soluble and dissolve in water in large quantities, whereas other materials are much less soluble. This is just as well, otherwise rain would dissolve all the rocks and they would end up in the oceans!

Drinking water must not contain harmful materials, which means both harmful bacteria and dissolved material that could be dangerous. Water does not have to be absolutely pure to be drinkable and, indeed, not only would it be costly to make it so, but also water is an important source of many of the metal ions (such as Ca^{2+}) required in the human diet. Water must be processed to make it acceptable for consumption. However, water must have levels of impurities that are below a danger threshold. How such thresholds (recommended by the World Health Organization) are assessed can be contentious but, in order to make comparisons, some measure of the amount of a particular substance dissolved in water is needed. **Concentration** is the mass of a substance in a known volume of a liquid: for example, milligrams in a litre. The units of concentration are expressed as milligrams per litre (abbreviated to mg/l).

Question 34

What fraction of a gram is a milligram?

Answer

A milligram is one-thousandth of a gram:

$$1\,\text{mg} = \frac{1}{1000}\,\text{g} = 1 \times 10^{-3}\,\text{g}$$

As noted above, tap water is never pure in the sense that it contains only water molecules and no other chemicals. Even bottled waters are not 100% water. Which substances are dissolved in water and in what concentrations?

If you drink bottled mineral water, look at the label and note down the contents. You will find that it contains a wide range of ions. Table 8 gives the concentrations of some ions in various bottled waters and two tap waters. Note that tap waters can vary substantially. You are already familiar with most of the ions listed.

Table 8: Concentrations of ions in bottled and tap waters

Ion	Concentration/(mg/l)*					
	Volvic®	Vittel®	Buxton®	Evian®	Tap water	
					Area 1	Area 2
calcium	11.5	91.0	55.0	78.0	130.0	50.0
magnesium	8.0	19.9	19.0	24.0	9.4	6.6
sodium	11.6	7.3	24.0	5.0	51.0	128.0
potassium	6.2	-	1.0	1.0	9.4	1.6

chloride	13.5	-	37.0	4.5	82.0	27.1
nitrate	6.3	0.6	<0.1	3.5	26.0	17.6
sulfate	8.1	105.0	13.0	10.0	210.0	21.3
bicarbonate	71.0	258.0	248.0	357.0	?	?

< means 'less than'; - means too small to measure; ? means the values are not available.

*Note here that for clarity we have enclosed the units mg/l in brackets, i.e. the column heading is concentration divided by mg/l.

Question 35

What are the formulas for the following ions: calcium, sodium, potassium, chloride and nitrate?

Answer

In Section 7 you saw that calcium is Ca^{2+}, sodium is Na^{+}, potassium is K^{+}, chloride is Cl^{-} and nitrate is NO_3^{-}.

To interpret Table 8, above, a few points need to be clarified. For example, what do the values in Table 8 mean? They are given as concentrations in mg/l.

Question 36

From Table 8 what is the concentration of chloride ions in Buxton water?

Answer

The concentration is 37 mg/1, which means that in one litre of water there are 37 mg of dissolved chloride ions.

You may be wondering why ion concentrations in drinking water are deemed important enough to be measured by suppliers of both bottled drinking water and tap water. The following activity will help to clarify this.

Activity 3: Ions in drinking water

0 hour(s) 30 minutes(s)

The aim of this activity is to access information about ions in drinking water. Look at the information leaflets on the Drinking Water Inspectorate of England and Wales (DWI) website (accessed 12 February 2016) and answer the questions below. (You will need to access information on water hardness and nitrate.)

1. Which ions in Table 8 are responsible for the hardness of water?
2. What is the World Health Organization's guideline value for nitrate concentration in drinking water?
3. How does this concentration compare with the values for nitrate concentration in Table 8?

When you accessed the DWI web pages on drinking water you may have noticed that it isn't just ion concentrations that are monitored. Water companies are also required to monitor their treatment works for the presence of *Cryptosporidium* (a micro-organism that can cause diarrhoea) and pesticides.

Conclusion

You have learned about the following concepts in this course:

- Each type of atom contains a characteristic number of protons in a central nucleus and an equal number of electrons in layers surrounding the nucleus.
- Elements are substances that consist of only one type of atom. Compounds contain two or more elements combined together. There are two kinds of bond between atoms: covalent and ionic.
- Molecules are the smallest units in which elements and/or compounds can exist covalently bonded together.
- Ions are formed by atoms or groups of atoms gaining or losing electrons.
- Chemical formulas describe the number of atoms present in elements, ions and compounds.
- Balanced chemical equations describe, using chemical formulas, the reactants and products in a chemical reaction.
- Concentration is the mass of a substance dissolved in a given volume (usually 1 litre) of a liquid.

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