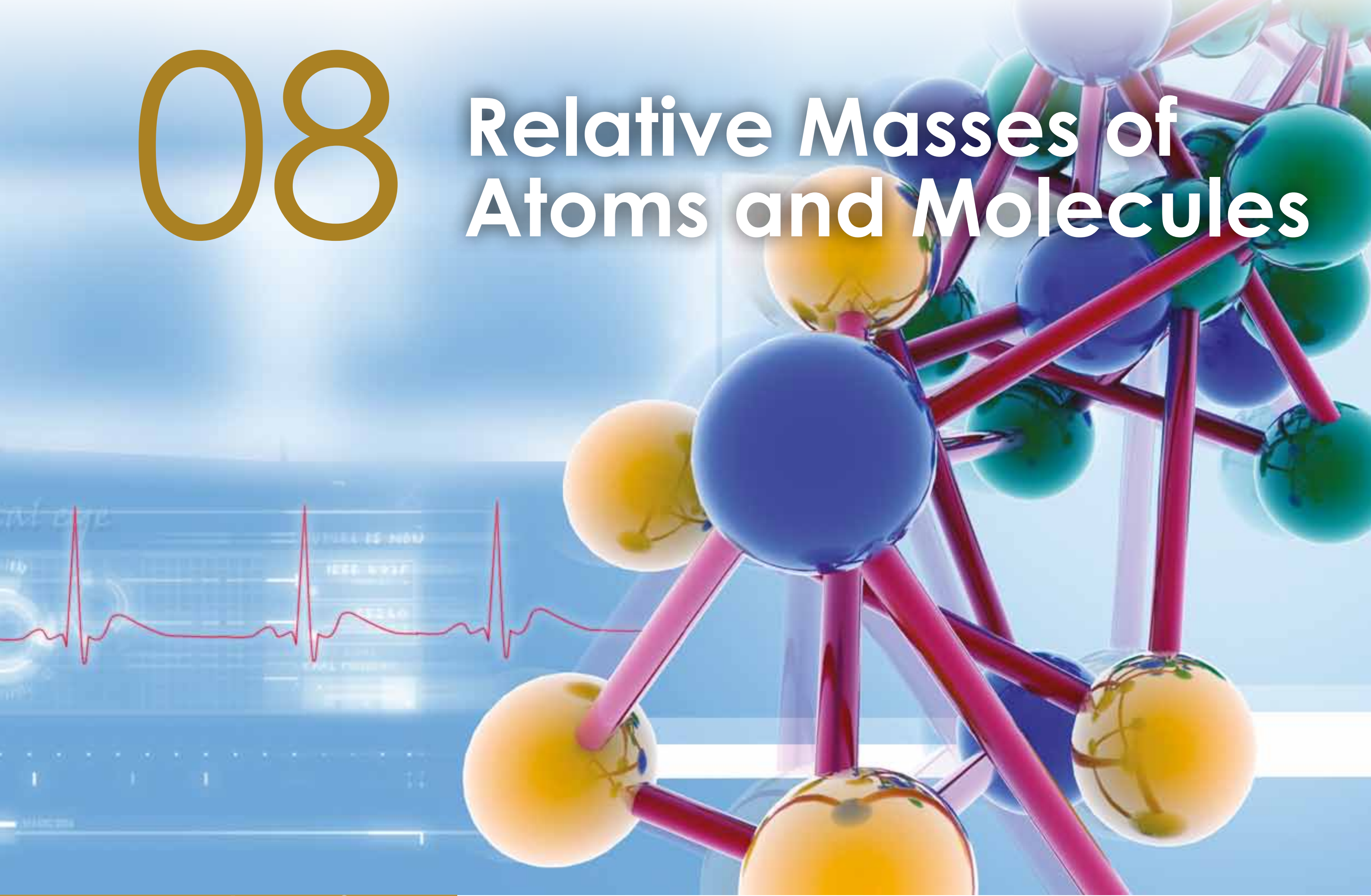
08 Relative Masses of Atoms and Molecules



Introduction

In Chapter 5, the masses of individual atoms were compared using nucleon numbers. Thus a carbon-12 atom with a nucleon number of 12 is 12 times the mass of a hydrogen-1 atom with a nucleon number of 1 (with masses of electrons neglected). In this chapter, the actual masses of atoms in elements are considered leading to the idea of relative atomic mass. This is extended to relative molecular mass and relative formula mass and to use of these to calculate the percentage composition of elements in compounds.

Chapter Opener (page 118)

1. To open the chapter, the following questions could be discussed. Precise answers are not needed at this stage.

In calculations, chemists do not use actual masses of atoms and molecules. Suggest a reason why?

Answer: This relates to the inconvenience of using the very small actual masses of atoms and molecules.

Chemists prefer to use relative masses of atoms. What do you think this means?

Answer: The mass of an atom compared with the mass of another (standard) atom.

An important idea in chemical calculations is that of 'percentage composition'? What do you think this means?

Answer: The percentage (by mass) of each atom in a compound.

2. Carry out an 'Inquiry Preview.'

Learning Outcomes

After completing this chapter, the students should be able to:

- Define relative atomic mass, relative molecular mass and relative formula mass
- Calculate relative molecular mass and relative formula mass
- Calculate the percentage mass of an element in a compound given appropriate information

Teaching Notes for

ChemMystery (page 119)

Producing iron — how does the chemist produce 30 000 tonnes of iron?

Initial Investigation

- A metal ore is a rock from which a (useful) metal is obtained.
- An equation in chemistry is the use of words (word equation) or symbols and formulae (chemical equation) to show the changes that occur in a chemical reaction.
- They are used to determine the amounts (masses or volumes) of products that can be obtained from known amounts of reactants and vice versa.

Teaching Notes for

8.1 Do Atoms have Mass? (page 120)

Stimulation

To compare masses of particles and to introduce the idea of relative masses, bring the heaviest (50-cent) and the lightest local coins (1-cent) to class. Get a student to hold one coin in each hand and to feel which coin is heavier. Next, ask the class how this comparison can be carried out more accurately. Use a balance to weigh each coin and then compare the mass of the larger coin to that of the small coin and obtain the relative masses. Lead the discussion to the idea of the use of *relative masses* of atoms and that because calculations in Chemistry can involve comparisons of masses, actual masses are not needed.

Notes on Singapore coins:

- Mass of 1-cent coin ~ 1.24 g. Take relative mass as 1.
- Mass of 50-cent coin ~ 7.28 g. The relative mass of this 50-cent coin compared to the 1-cent coin is 7.28 ÷ 1.24 = 5.87.

Skills Practice (page 120)

1. **(a)** CH_4.
   (b) Carbon. **Note:** Carbon appears to be the heavier because it is larger. But the mass of an atom is not directly related to its mass. Thus, while potassium is one of the largest atoms, it is not the heaviest.
2. E.g. The mass of one atom compared with the mass of another atom.
3. Subtract the mass of four hydrogen atoms from the mass of the methane. Divide the answer by four to get the mass of a carbon atom. Compare this mass with the mass of a hydrogen atom to get the relative mass of the carbon atom which should be exactly 12.

(page 90)
Mystery Clue

A_r: Relative atomic mass
M_r: Relative molecular mass

Notes for Teachers

The meaning of stoichiometry
Quantitative chemistry includes relative atomic and molecular masses, numbers of moles, the composition of substances and the quantitative changes that occur during chemical reactions. The study of quantitative chemistry is called **stoichiometry**. The word was coined in 1792 and is derived from two Greek words: *stocheion* meaning 'elementary constituents' and *metrein* meaning 'to measure'.

Teaching pointers

8.2 What is Relative Atomic Mass? (page 121)

1. Teaching relative atomic mass: The scale based on ^{12}C = 12.00 is difficult for many students to grasp. The scale based on ^{1}H = 1 is easier and may be used for instructional purposes, e.g., one ^{16}O atom corresponds to 16 ^{1}H atoms (cf. Figure 8.3). Teachers may be able to construct and demonstrate a simple beam balance and balls with relative masses of 16 (oxygen) and 1 (hydrogen).

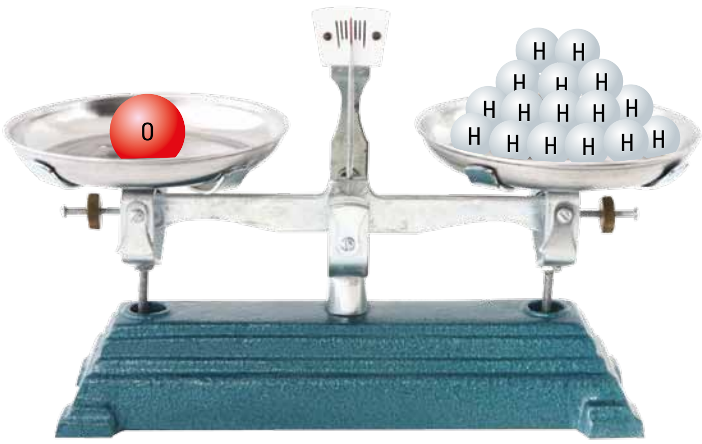


Figure 8.3 One oxygen atom has the same mass as 16 hydrogen atoms.

2. Emphasise the following points:
   (a) Relative atomic mass is a ratio and hence has no units.
   (b) The nucleon number of an atom is a whole number whereas the relative atomic mass may not be as it is an average value of the mass of all the atoms in an element.

3. Point out to students that at 'O' Level, only approximate relative atomic masses are used and that these values will be provided in questions that involve calculations. The Periodic Table on page 459 of the Textbook gives the approximate relative atomic masses of the atoms.

4. When discussing relative atomic masses that are not whole numbers, point out that as most elements consist of a mixture of isotopes, they have $\mathbf{A_r}$ values that are not whole numbers. Then get the class to refer to the accurate relative atomic masses for the elements in the Periodic Table on page 459 of the Textbook.

Skills Practice (page 122)

1. Refer to the textbook, page 121.

2. Relative atomic mass of an iron atom ÷ relative atomic mass of a nitrogen atom
   = 56 ÷ 14
   = 4
   Thus, 4 nitrogen atoms have the same mass as one iron atom.

3. Relative atomic mass of a bromine atom ÷ relative atomic mass of an oxygen atom
   = 80 ÷ 16
   = 5
   Thus, 5 oxygen atoms have the same mass as one bromine atom.

4. Relative atomic mass of a carbon atom ÷ relative atomic mass of a helium atom
   = 12 ÷ 4
   = 3
   Thus, 3 helium atoms have the same mass as one carbon atom.

5. Relative atomic mass of Cu = average mass of all the atoms in the isotopic mixture

$$= \frac{0.69 \times 63 + 0.31 \times 65}{100} \text{ (assuming 100 atoms in the mixture)}$$

$$= 63.62$$

Note: Some Periodic Tables may show the relative atomic mass of copper to be 63.5. This results from more accurate percentages than those that are used in this question.

Notes for Teachers

Calculating relative atomic mass

The relative atomic mass of an element is the average mass of all the atoms in the element. To calculate the relative atomic mass of an element, we need to know the relative abundance of the isotopes present in the element.

Consider the element, chlorine. The element consists of 75% of chlorine-35 atoms (^{35}Cl) and 25% of chlorine-37 atoms (^{37}Cl). Assume a sample of chlorine gas has 100 chlorine atoms.

Number of ^{35}Cl atoms in sample = 75
Number of ^{37}Cl atoms in sample = 25

$$\text{Average mass of a chlorine atom} = \frac{\text{total mass of } ^{35}Cl \text{ atoms} + \text{total mass of } ^{37}Cl \text{ atoms}}{100}$$

$$= \frac{(75 \times 35) + (25 \times 37)}{100}$$

$$= \frac{2625 + 925}{100}$$

$$= 35.5$$

Therefore, the relative atomic mass of chlorine is 35.5.

The carbon–12 scale

Using $\frac{1}{12}$ of the mass of one atom of carbon–12 in place of the mass of one atom of hydrogen hardly affects the values of the relative atomic masses.

There are two main reasons for comparing the masses of atoms to the mass of carbon rather than to that of hydrogen. The reasons are:

- Hydrogen is a gas and is difficult to handle compared to carbon, which is a solid.
- Most compounds contain carbon so it is more sensible to use carbon instead of hydrogen.

Note: Students do not have to know these reasons.

Teaching pointers

8.3 What are Relative Molecular Mass and Relative Formula Mass? (page 123)

1. Like relative atomic mass, relative molecular mass and relative formula mass do not have units.
2. An additional exercise is included at the end on this chapter to determine relative molecular mass using the speeds of gaseous molecules to find the relative molecular mass of unknown gases. Link the activity with diffusion of gases in Chapter 3. Ensure that students do not confuse the actual speeds of gas particles with the speed of diffusion of the gas. Individual gas molecules move at very high speeds in a straight line, but because of collisions with other molecules, the particles in a gas move in zigzag lines resulting in the speed of diffusion being much lower. For example, the average speed of hydrogen molecules is 1690 m/s whereas the speed of diffusion of hydrogen gas is much lower.

(page 92)

Mystery Clue

Fe_2O_3 – 160. Fe_3O_4 – 232.

Skills Practice (page 124)

1. Similarities: Both compare masses to $\frac{1}{12}$ of the mass of an atom of carbon–12. Differences: Relative molecular mass is the mass of molecules (e.g. water) whereas relative formula mass is the mass of ionic compounds (e.g. sodium chloride).
2. **(a)** H_2O : 18 **(b)** NH_3 : 17 **(c)** O_2 : 32
   (d) $CaCO_3$: 100 **(e)** H_2SO_4 : 98 **(f)** $Cu(NO_3)_2$: 187.5 (~188)
   (g) $(NH_4)_2SO_4$: 132 **(h)** $CuSO_4 \cdot 5H_2O$: 249.5 (~250)
3. **(a)** carbon dioxide: CO_2
   nitrogen dioxide: NO_2
   potassium chloride: KCl
   glucose: $C_6H_{12}O_6$
   methane: CH_4
   (b) Compounds consisting of molecules: CO_2, NO_2, $C_6H_{12}O_6$, CH_4
   Ionic compounds: KCl
   (c) relative molecular mass of CO_2: 44
   relative molecular mass of NO_2: 46
   relative molecular mass of $C_6H_{12}O_6$: 180
   relative molecular mass of CH_4: 16
   relative formula mass of KCl: 74.5
4. Relative molecular mass of B_nH_{11} = (n × relative atomic mass of B) + (11 × relative atomic mass of H)
   $66 = 11n + 11$
   $66 - 11 = 11n$
   $55 = 11n$
   $n = 5$

Teaching pointers

8.4 How Do We Calculate Percentage Composition? (page 124)

1. Percentage composition can be calculated using either (a) relative masses or (b) actual masses. In both methods, the ratio in the expression has no units. In this course, percentage composition is calculated using method (a).
2. For the calculations of the percentage of iron in iron(III) oxide and black iron oxide, it is the pure oxides that are considered and not the actual ores which will be impure. See the section 'Notes for Teachers' just before the Chapter Review .
3. **Note:** Do not confuse the ore magnetite (which contains iron(II, III) oxide) with the ore magnesite (which contains magnesium carbonate).
4. For copper(II) sulfate pentahydrate, get students to calculate the percentage of water in $CuSO_4 \cdot 5H_2O$. Calculation:

   The relative formula mass of $CuSO_4 \cdot 5H_2O = 250$
   There are 5 water molecules in the $CuSO_4 \cdot 5H_2O$ formula.

   The percentage of water in $CuSO_4 \cdot 5H_2O$

   $= \frac{\text{Relative molecular mass of 5 water molecules}}{\text{Relative formula mass of } CuSO_4 \cdot 5H_2O} \times 100$

   $= \frac{5 \times 18}{250} \times 100$

   $= 36\%$
5. Exercise 8.1 in the Theory Workbook involves calculating and comparing the percentage by mass of nitrogen in a variety of fertilisers containing nitrogen.

(page 125)

Mystery Clue

Percentage composition of iron (by mass) in Fe_3O_4 = 72.4%. Therefore, the percentage of iron in Fe_3O_4 is greater than in Fe_2O_3 (as calculated in Worked Example 3).

Skills Practice (page 126)

1. (a) The percentage of copper in CuO $= \frac{1 \times \text{Relative atomic mass of Cu}}{\text{Relative formula mass of CuO}} \times 100$

   $= \frac{1 \times 64}{80} \times 100$

   $= 80\%$

   (b) The percentage of magnesium in $MgSO_4 = \frac{1 \times \text{Relative atomic mass of Mg}}{\text{Relative formula mass of } MgSO_4} \times 100$

   $= \frac{1 \times 24}{120} \times 100$

   $= 20\%$

   (c) The percentage of sodium in NaOH $= \frac{1 \times \text{Relative atomic mass of Na}}{\text{Relative formula mass of NaOH}} \times 100$

   $= \frac{1 \times 23}{40} \times 100$

   $= 57.5\%$

   (d) The percentage of carbon in $C_2H_4O_2 = \frac{2 \times \text{Relative atomic mass of C}}{\text{Relative formula mass of } C_2H_4O_2} \times 100$

   $= \frac{2 \times 12}{60} \times 100$

   $= 40\%$

2. (a) The percentage of calcium in $CaCO_3 = \frac{1 \times \text{Relative atomic mass of Ca}}{\text{Relative formula mass of } CaCO_3} \times 100$

$= \frac{1 \times 40}{100} \times 100$

$= 40\%$

The percentage of oxygen in $CaCO_3 = \frac{3 \times \text{Relative atomic mass of O}}{\text{Relative formula mass of } CaCO_3} \times 100$

$= \frac{3 \times 16}{100} \times 100$

$= 48\%$

(b) The percentage of oxygen in $CuSO_4 \cdot 5H_2O = \frac{5 \times \text{Relative atomic mass of O}}{\text{Relative formula mass of } CuSO_4 \cdot 5H_2O} \times 100$

$= \frac{5 \times 16}{250} \times 100$

$= 32\%$

3. (a) There is one calcium atom in the $CaCO_3$ formula.
The relative formula mass of $CaCO_3 = 100$

Mass of calcium $= \frac{\text{Relative atomic mass of one calcium atom}}{\text{Relative formula mass of } CaCO_3} \times \text{mass of sample}$

$= \frac{40}{100} \times 25$

$= 10$ g

Thus, the mass of calcium in 25 g of $CaCO_3$ is 10 g.

(b) There are 2 chlorine atoms in the $CuCl_2$ formula.
The relative formula mass of $CuCl_2 = 135$

Mass of calcium $= \frac{\text{Relative atomic mass of two chlorine atoms}}{\text{Relative formula mass of } CuCl_2} \times \text{mass of sample}$

$= \frac{2(35.5)}{135} \times 27$

$= 14.2$ g

Thus, the mass of chlorine in 27 g of $CuCl_2$ is 14.2 g.

Notes for Teachers

Amounts of iron in ores
The percentage by mass of iron in *pure* Fe_3O_4 (72.4%) is slightly higher than that in *pure* Fe_2O_3 (70%). But the actual haematite and magnetite *ores* are impure and contain other substances besides the iron oxides (usually quartz, limestone and clay). The impurities will lower the amount of iron that can be obtained from an ore.
In low grade magnetite ore (i.e., containing only a very small percentage of Fe_3O_4), the amount of iron that can be extracted is lower than that from haematite (which is rich in Fe_2O_3). In fact, haematite is the more important ore for extracting iron because of its high iron content and its high abundance.

08 Chapter Review

Self-Management

Misconception Analysis (page 127)

1. **False** Historically, hydrogen was used, but today, the mass of an atom is compared with the mass of an atom of carbon–12.

2. **False** As the mass of an atom is compared with the mass of an atom of carbon–12, it is a ratio and therefore has no units.

3. **True** This is because ionic compounds do not consist of molecules.

4. **False** The relative atomic masses of carbon and hydrogen are 12 and 1 respectively. Therefore in CH_4, the mass of carbon is 3 times the mass of all the hydrogen atoms.

Practice

Structured Questions (page 127–128)

1. Relative molecular mass of P_nO_{10}
$= (n \times \text{relative atomic mass of P})$
$+ (10 \times \text{relative atomic mass of O})$
$284 = 31n + 160$
$284 - 160 = 31n$
$124 = 31n$
$n = 4$

2. Relative molecular mass of $Ni(CO)_x$
$= (\text{relative atomic mass of Ni})$
$+ (x \times \text{relative atomic mass of CO})$
$171 = 59 + 28x$
$171 - 59 = 28x$
$112 = 28x$
$x = 4$

3. (a) (i) Methane gas
(ii) It has the smallest molecular mass.
(b) 396 seconds because it has the same relative molecular mass as CO_2.
(c) (i) Hydrogen
(ii) Bromine gas

4. (a) They contain different elements; their molecules contain different numbers of atoms.
(b) They both consist of two elements; they both have the same relative molecular mass of 30.

5. (a) $C_2H_4Cl_2$
(b) $M_r = (2 \times 12) + (4 \times 1) + (2 \times 35.5) = 99$
(c) The percentage by mass of carbon in $C_2H_4Cl_2$
$= \frac{2(12)}{99} \times 100$
$= 24.2\%$

Free Response Question (page 128)

The percentage by mass of iron in $Fe_2O_3 = \frac{2(56)}{160} \times 100$
$= 70\%$

The percentage by mass of iron in $FeS_2 = \frac{1(56)}{120} \times 100$
$= 46.7\%$

The percentage by mass of iron in $FeS = \frac{1(56)}{88} \times 100$
$= 63.6\%$

The percentage by mass of iron in $FeCO_3 = \frac{1(56)}{116} \times 100$
$= 48.3\%$

Descending order of the percentage by mass of iron each compound contains:

haematite (70.0%), pyrrhotite (63.6%), siderite (48.3%), marcasite (46.7%)

Extension (page 128)

(a) Typical results are given in the table below. (If you do not have a very accurate electronic balance, it is better to weigh a large number of similar coins and then calculate the average mass.)

Coin	Actual mass in grams	Relative coin masses (relative to a 1-cent coin)
1-cent	1.24	1
5-cent	1.57	1.27
10-cent	2.62	2.11
20-cent	4.5	3.63
50-cent	7.28	5.87
1-dollar	6.34	5.11

Note: The mass of the 1-cent coin varies slightly from year to year so the values given in the table above are the average masses of 10 coins. This is the same idea as relative atomic mass, which is also the average mass of atoms of an element.

(b) The 1-ounce gold coin has a mass of 31.10 g. So on the relative mass scale for Singapore coins, its 'relative mass' is 25.08.
(c) Machines that accept coins need fixed masses, such as those that issue MRT tickets.
(d) 'Isotopes' of a coin are coins with the same value but different masses. An example is the 1-cent coin. Three 1-cent coins issued in different years, taken at random, have the following masses:

Date of 1-cent coin	Mass in grams
1982	1.78
1995	1.22
1998	1.27

Additional Teaching Material

Additional Exercise 1: Finding Relative Molecular Masses and Formulae

Objective

- To find the relative molecular masses of gaseous molecules

Key Competency

CIT: sound reasoning [*identifying patterns*]

The table gives the average speeds of different gas molecules at the same temperature. The table includes data on two unknown gases, X and Y.

Gas	Relative molecular mass	Average speed (m/s)
hydrogen	2	1690
helium	4	1200
gas X		600
neon	20	530
nitrogen	28	455
oxygen	32	425
carbon dioxide	44	360
gas Y		320

1. On a sheet of graph paper, draw a graph of average speed (y-axis) against relative molecular mass (x-axis) for the gases in the table. Make sure the graph extends to 80 on the x-axis.

Alternatively, you may use a computer program such as *Microsoft Excel* to draw the graph. To do this, first enter the data from the table into a simple spreadsheet, such as the following:

	A	B	C
1	gas	relative molecular mass	average speed
2	hydrogen	2	1690
3	helium	4	1200
4	gas X		600
⋮	⋮	⋮	⋮
⋮	⋮	⋮	⋮
⋮	⋮	⋮	⋮
9	gas Y		320
10		80	

Then choose the ‘scatter graph’ option and *Graph number 1* on the choice of graphs. This plots the points without drawing a line. Finally, add gridlines and insert a ‘power’ trendline through the points. Print your graph.

2. Paste your graph in the space below.

3. Use your graph to find estimates for the relative molecular masses of gases X and Y.

(a) M_r of X = ____________

(b) M_r of Y = ____________

4. Gases X and Y are hydrocarbons. This means their molecules contain only the elements carbon and hydrogen.

(a) Deduce the formula of gas X.

Formula of gas X = ____________

(b) Gas Y has the formula C_nH_{10}. Deduce the value of *n*.

n = ____________; formula of gas Y = ____________

Additional Teaching Material

Additional Exercise 2: What was the Question?

Objective

- To formulate questions for which the answers are given

Competencies

CIT: sound reasoning [*analysing*]; creativity [*generating questions*]

A. There is a chemistry problem. The final answer to this problem is **28**.

Think of as many questions as possible for which the answer is 28. You can do this by discussing with other students in groups of 2 or 4.

Write down the possible questions in the space below.

B. There is a chemistry problem. The final answer to this problem is **20**.

Think of as many questions as possible for which the answer is 20. You can do this by discussing this in groups of 2 or 4.

Write down the possible questions in the space below.

C. The answer to another chemistry problem is **40 g**.

Work back from this answer, think of as many possible questions for which this is the answer.

Write down the possible questions in the space below.

D. Relative masses of atom and molecules

(a) The answer to a Chemistry question related to relative masses of atoms and molecules is 4. Think of as many questions as possible to which this is the answer.

(b) The answer to a Chemistry question related to relative masses of atoms and molecules is 40. Think of as many questions as possible to which this is the answer.

(c) The answer to a Chemistry question related to relative masses of atoms and molecules is 32. Think of as many questions as possible to which this is the answer.

Answers

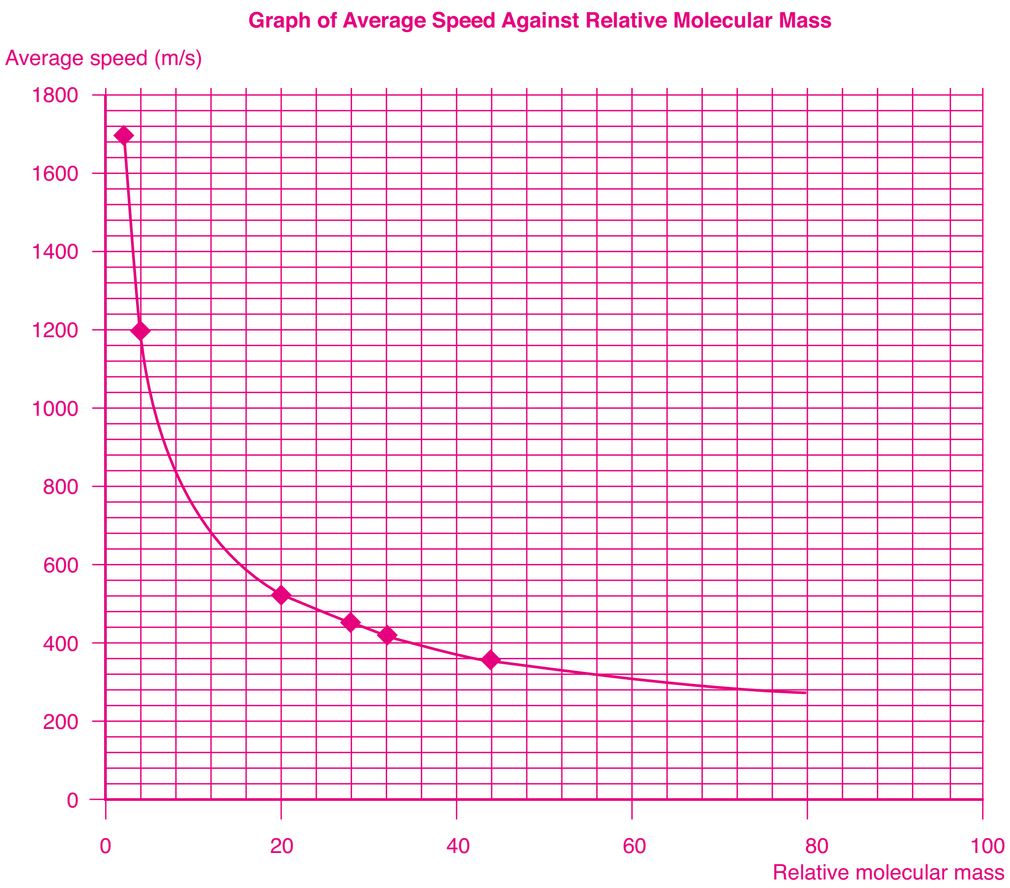
Additional Exercise 1:

3. **(a)** 16

(b) 58

4. **(a)** CH_4

(b) 4 ; C_4H_{10}



Additional Exercise 2:

A. 1. What is the relative atomic mass of silicon?

2. What is the relative molecular mass of nitrogen, N_2?

3. What is the relative molecular mass of carbon monoxide, CO?

4. What is the relative molecular mass of C_2H_4?

B. 1. What is the relative atomic mass of neon?

2. What is the relative molecular mass of HF?

3. What is the percentage of oxygen in copper(II) oxide, CuO?

4. What is the approximate percentage of oxygen in air? (This is an example of a question that can arise with a little lateral thinking.)

C. 1. What is the number of grams of calcium in 100 g of calcium carbonate, $CaCO_3$?

2. What is the mass of oxygen in 100 g of magnesium oxide, MgO?

(There are an infinite variety of possible similar questions.)

D. **(a)** Possible questions:

- What is the relative atomic mass of helium?
- How many hydrogen atoms have the same mass as one helium atom?
- How many helium atoms have the same mass as one oxygen atom?
- How many oxygen atoms have the same mass as one copper atom?

(b) Possible questions:

- What is the relative mass of calcium?
- What is the relative molecular mass of NaOH?
- What is the percentage of calcium in calcium carbonate, $CaCO_3$?
- How many grams of calcium are there in 100g of calcium carbonate, $CaCO_3$?
- What is the percentage of carbon in $C_2H_4O_2$?

(c) Possible questions:

- What is the relative mass of sulfur?
- What is the relative molecular mass of O_2?
- How many hydrogen atoms have the same mass as one sulfur atom?