Oxford Resources for IB

Chemistry – 2023 Edition

Answers

Structure 1.1 – Introduction to the particulate nature of matter

Data-based questions (page 7)

1. A +0.50 ± 0.02 g (increase)

   B –1.29 ± 0.02 g (decrease)
2. A colour change from red to black

   B colour change from green to black
3. Both changes are chemical as the colour and mass change, suggesting the formation of a new substance.
4. As substance A increases in mass, this suggests that the new substances formed is a compound. Therefore, substance A could be an element or a compound of lower mass than the substance formed. Substance B decreases in mass, and therefore must be a compound, as pure elemental substances cannot be broken down into smaller stable constituents by chemical means.
5. No. Different substances may have similar colours and form. Further analysis is required to ascertain the identity of the two substances formed.

Skills questions (page 8)

Answers will vary. Guidance:

1. Relevant qualitative data include appearance of the solid and liquid substances. Relevant quantitative data include temperature at which each substance starts to melt and the temperature at which it finishes melting.
2. Compare the melting points of the pure substances (pure A and pure B) to that of the impure substance (mixture of A and B).
3. The structural formula can be used to deduce the molar mass and the functional groups present, which can in turn suggest the nature and strength of the intermolecular forces present.
4. The melting point of the solid product of an organic synthesis can be obtained. Information about the product's purity can be inferred from the range and accuracy of the melting point. However, the identity of the product cannot be confirmed without further analytical tools (e.g. spectroscopy).

Data-based questions (page 10)

1. Purple. It moved the furthest with the first solvent as well as with the second solvent.
2. The yellow dot substance moved quite a lot with solvent 1, indicating a strong affinity for the solvent, but did not rise much with solvent 2. Similarly, the orange dot substance moved quite a lot with solvent 1 but not so far with solvent 2.
3. The pink dot substance, which is second from the bottom in figure 9b, did not move much with solvent 1. This indicates that the intermolecular forces of attraction towards the water in the chromatography paper were stronger than those for solvent 1. However, when placed in solvent 2, the pink dot substance rose quite a bit with this solvent so the intermolecular force of attraction to this solvent must be greater than those to the water in the paper.

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Skills questions (page 14)

Answers will vary. Guidance:

1. Properties such as the colour, texture, and state of matter of the three substances can be described and organized in a suitable table.
2. Possible independent variables include the ratio of cornstarch to water, brand of cornstarch, temperature of the mixture, dissolved impurities in the water, etc. Possible dependent variables include depth of a crater left by a marble falling into the fluid, flow rate, etc.
3. Other non-Newtonian fluids include tomato sauce, cream, slime, etc.
4. Answers will vary.

End of topic questions (pages 18–19)

1. Answers will depend on the student, but a possible answer might be: All matter consists of atoms, which can be modelled in many ways, from hard indestructible balls to fuzzy clouds of various sizes and shapes. The ideal gas theory (IGT) assumes that gases consist of moving particles of negligible volume that collide elastically and experience no intermolecular forces. The kinetic molecular theory (KMT) introduces intermolecular forces to explain physical properties of matter and changes of state. The collision theory expands the IGT and KMT to allow non-elastic collisions and chemical changes. The quantum theory explains the interaction of matter with light, including discrete atomic spectra and ionization of atoms, in terms of quantum numbers and energy levels.

2. D

3. C

4. C

5. C

6. B

7. A

8. B

9. The zero on Celsius temperature scale does not correspond to zero kinetic energy of particles. Doubling the Celsius temperature from 20 °C to 40 °C, for example, is not doubling the kelvin temperature, but is an increase from 293 K to 313 K. To double the kinetic energy, the temperature would need to be raised from 293 K to 586 K. This rise is the equivalent of raising the temperature from 20 °C to 313 °C. When temperature is raised by 20 °C from 20 °C to 40 °C, the kinetic energy increases by a factor of 313 ÷ 293, or 1.068, whereas doubling the kelvin temperature will double the average kinetic energy of molecules.

10. a. Br_2

b. $Pb^{2+} + 2Br^{-} \rightarrow Pb + Br_2$

c. $Pb^{2+} + 2Br^{-} \rightarrow Pb(l) + Br_2(g)$

Notice that we normally omit states of ions in molten electrolytes, as $Pb^{2+}(l)$ and $Br^{-}(l)$ cannot exist as individual phases.

11. By a factor of $\sqrt{2}$

12. a. 508 K

b. **i.** mean = 0.234 g, range = 0.286 g

ii. 23.9%, 24% to 2 significant figures

One mark for the correct answer, one mark for correct sf and rounding

iii. Method 2 because its caffeine product has the smallest melting point range, and the melting point was closest to the theoretical value.

c. (one of) Repeat trials and calculate a mean. Employ more precise equipment

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13. a. $H_2SO_4(aq) + CuO(s) \rightarrow CuSO_4(aq) + H_2O(l)$

One mark for correct formulas and balancing

One mark for correct state symbols

b. Filtration will selectively remove the CuO; (because) copper(II) oxide does not dissolve in water AND copper(II) sulfate does

c. Three out of the following:

- place the filtrate/solution in an evaporating dish and heat;
- until crystals appear when a drop of solution is put on a cold tile/glass stirring rod;
- leave to cool for crystals to form slowly;
- filter supernatant off and pat crystals dry with a clean piece of filter paper

14. a. Temperature remains constant during a phase change such as melting;

The energy input is used to overcome the attractive forces between molecules rather than to increase the kinetic energy of the molecules

b. A heating curve like the one in figure 16, but with plateaus at –3 °C and 101 °C (rather than at 0 °C and 100 °C)

15. a. Gentle heating: $I_2(s) \rightarrow I_2(g)$

Cooling: $I_2(g) \rightarrow I_2(s)$

Heating under pressure: $I_2(s) \rightarrow I_2(l)$

b. $114 + 273.15 \approx 387$ K

c. Gaseous iodine can be pressurized at a temperature above 114 °C. When the pressure becomes high enough, iodine gas will condense into a liquid:
$I_2(g) \rightarrow I_2(l)$

Structure 1.2 – The nuclear atom

Activity (page 21)

Nearly all the alpha particles went straight through the gold foil: The nucleus is very small in comparison to the size of the atom.

Occasionally, some of the alpha particles bounced straight back: The nucleus is very dense, containing virtually all the mass of the atom.

The alpha particles are repelled when closely approaching the nucleus: The nucleus has a positive charge.

Skills questions (page 24)

1. Answers will vary.

2.

Item	Length / m	Length / m
proton	0.84×10^{-15}	8.4×10^{-16}
sheet of paper, thickness	0.10×10^{-3}	1.0×10^{-4}
onion cell, diameter	250×10^{-6}	2.5×10^{-4}
iodine-iodine bond, length	267×10^{-12}	2.67×10^{-10}
printed full stop, diameter	0.30×10^{-3}	3.0×10^{-4}
carbon atom, diameter	150×10^{-12}	1.5×10^{-10}
C_{60} fullerene, diameter	0.71×10^{-9}	7.1×10^{-10}

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3. From smallest to largest:

Item	Length / m
Proton	8.4×10^{-16}
Carbon atom, diameter	1.5×10^{-10}
Iodine-iodine bond, length	2.67×10^{-10}
C60 fullerene, diameter	7.1×10^{-10}
Sheet of paper, thickness	1.0×10^{-4}
Onion cell, diameter	2.5×10^{-4}
Printed full stop, diameter	3.0×10^{-4}

4. Answers will vary. For example, the mass (note not the diameter!) of an electron is roughly $\frac{1}{2000}$ that of a proton. An example of an intermediate value is the wavelength of X-rays and a larger value could be the length of a hyphen: -

5. Answers will vary but all must be presented according to an accepted citing and referencing system.

Activity (page 25)

Atomic symbol	Atomic number	Mass number	Protons	Neutrons	Electrons
O	8	16	8	8	8
Al	13	27	13	14	13
Rb	37	85	37	48	37
Br	35	80	35	45	35
Co	27	59	27	32	27
Hg	80	200	80	120	80
Pb	82	207	82	125	82
Tm	69	169	69	100	69

Activity (page 26)

$^{52}_{24}Cr^{3+}$

Activity (page 26)

Isotope	Nuclear symbol	Z	N	A
hydrogen-1 (protium)	$^{1}_{1}H$	1	0	1
hydrogen-2 (deuterium)	$^{2}_{1}H$	1	1	2
hydrogen-3 (tritium)	$^{3}_{1}H$	1	2	3

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Practice questions (page 29)

1. $^{39}_{19}K$, 19 protons, 20 neutrons; $^{65}_{29}Cu$, 29 protons, 36 neutrons.
2. $A_r(S) = 32 \times 0.9502 + 33 \times 0.0075 + 34 \times 0.0421 + 36 \times 0.0002 = 32.09$.
3. The relative abundances of isotopes in a particular sample of sulfur can differ from the natural abundances of these isotopes.

Data-based questions (page 31)

1. m/z peak at 204, relative intensity = 2%

   m/z peak at 206, relative intensity = 24%

   m/z peak at 207, relative intensity = 22%

   m/z peak at 208, relative intensity = 52%

   $$\frac{(204\times2)+(206\times24)+(207\times22)+(208\times52)}{100}=207$$

   Closest matching element on the periodic table is lead, Pb.

2. m/z peak at 58, relative intensity = 1.00, relative abundance 69%

   m/z peak at 60, relative intensity = 0.37, relative abundance 26%

   m/z peak at 61, relative intensity = 0.03, relative abundance 2%

   m/z peak at 62, relative intensity = 0.05, relative abundance 3%

   $$A_r(\mathrm{Ni})=\frac{58\times1.00+60\times0.37+61\times0.03+62\times0.05}{1.00+0.37+0.03+0.05}\approx58.7$$

   According to figure 13, cobalt has a larger A_r (59.0) than nickel (58.7). However, both the accuracy and precision of A_r values obtained from figure 13 are limited, so the difference of 0.3 atomic units is close to the experimental error.

3. The difference is caused by several factors. First, we used mass numbers, which are rounded values for the actual masses of nickel isotopes. Second, isotopic composition of an element can vary slightly between samples, especially if these samples are extraterrestrial (e.g., meteorites). Third, our estimation of the relative intensities of peaks in figure 13 has limited accuracy and precision.

End of topic questions (page 33)

1. Answers will depend on the student, but a possible answer might be: Atomic nuclei consist of positively charged protons and uncharged neutrons, collectively known as nucleons. The different nuclei of the same element, known as isotopes, differ by the number of neutrons only. The nuclei of different elements always differ by the number of protons and may also differ by the number of neutrons.

2. A

3. C

4. D

5. B

6. B

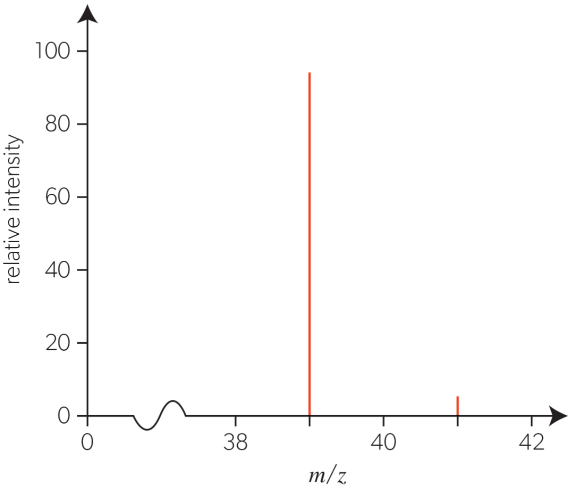
7. **a.** $^{4}_{2}He^{2+}$

Note that the symbol for alpha particles usually omits the charge, for example when discussing nuclear equations in physics.

b. **i.** The alpha particles would all have been deflected significantly or repelled.

ii. The alpha particles would have been attracted to the gold nuclei. This attraction would have caused them to be absorbed, or deflected, or emerge as neutral atoms.

8. Let $NA(^{39}K) = x$, then $NA(^{41}K) = 1 - x$
   $39x + 41(1 - x) = 39.10$
   $x = 0.95$
   Therefore, $NA(^{39}K) = 0.95$, or 95%, and $NA(^{41}K) = 1 - 0.95 = 0.05$, or 5%.
   Mass spectrum of potassium:



   Note: for a sketched graph, the scales on both axes are optional.

9. A sample of the analysed metal can be dissolved in a suitable acid mixture (such as a mixture of concentrated nitric and hydrochloric acids), and the solution injected into the mass spectrometer. The Dutch metal will produce several peaks with m/z values between 60 and 70 (according to the isotopic composition of copper and zinc). In contrast, gold will produce only one peak with m/z 197 (as gold has only one stable isotope, Au-197).

Structure 1.3 – Electron configurations

Skills questions (page 36)

1. Answers will vary. Guidance: Indicate the lower energy and higher energy ends of the spectrum. All emissions should be shown as thin lines, and their colour, indicated.
2. The emission spectra are emission spectra because they contain bright lines at discrete wavelengths.
3. Answers will vary. Guidance: Theoretical emission spectra will contain more emission lines, more colours and slightly different wavelengths than the observed emission lines.
4. Answers will vary depending on the source and gas observed. Guidance: The graph should follow the guidance given in *Tool 3: Technology*.
5. Answers will vary. Refer to the guidance on graphs given in *Tool 3: Technology*.
6. Answers will vary.

Skills questions (pages 37)

Answers will vary. Guidance:

1. The emission spectra are likely to contain more lines and possibly more colours than the observed spectra.
2. The flame colours are caused by excited electrons moving back down to lower energy levels. Since the difference between energy levels varies from one element to another, the energy (and therefore, wavelength and colour) of the photons released will also vary.

Activity (page 39)

a. highest wavelength – red

b. highest frequency – green

c. highest energy – green

Data-based question (page 39)

The emission spectrum of hydrogen shows the same lines as four of the lines in the absorption spectrum of the Sun. Hydrogen must be present to absorb the radiation and create these dark lines.

Activity (page 48)

a. s, p, d, f and g

b. s has 1, p has 3, d has 5, f has 7 and g has 9

c. Total number of orbitals = 1 + 3 + 5 + 7 + 9 = 25

d. Maximum number of electrons = 25 × 2 = 50

Practice questions (page 50)

1. The 1s and 2s orbitals are lower in energy than the 2p orbitals, so they are filled first, as this produces the most stable electron configuration.

2. E is the correct diagram

A Electrons in singly occupied p orbitals do not all have the same spin

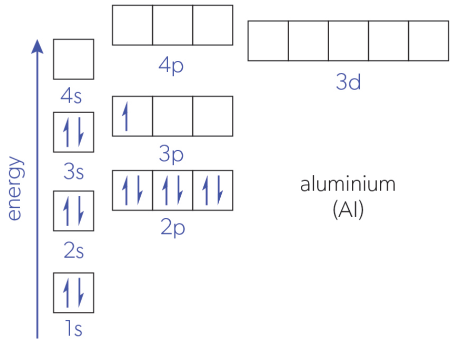
B Both electrons are in the doubly occupied p orbital rather than in two singly occupied p orbitals

C Electrons in singly occupied p orbitals do not all have the same spin

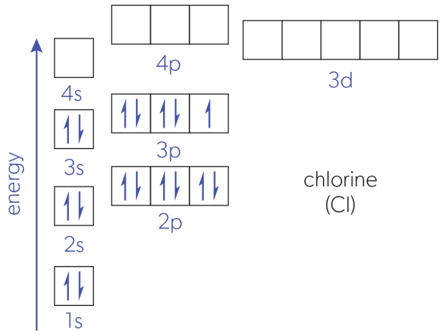
D The two electrons in the second p orbital do not have opposite spins

Activity (page 51)

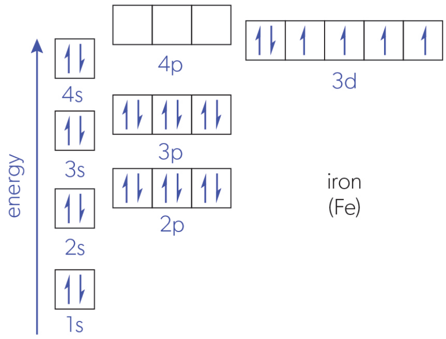
a.



b.



c.



Practice question (page 52)

3. $1s^2\,2s^2\,2p^6\,3s^2\,3p^3$

Practice question (page 53)

4. $[Ne]\,3s^2\,3p^3$

Activity (page 54)

$[Ar]\,3d^9$

Practice question (page 58)

5. 2370 kJ mol^{-1}

6. 2030 Å

Practice question (page 59)

7. Group 13, because the largest increase in energy occurs from the third ionization to the fourth.

Data-based question (page 59)

For Na, the electron configuration is $1s^2\,2s^2\,2p^6\,3s^1$. The large jump in energy between $n = 1$ and $n = 2$ signifies the breaking of the stable inner core [Ne] configuration and between $n = 9$ and $n = 10$ the breaking of the [He] configuration.

Skills questions (page 60)

5b. As electrons are removed from an atom or ion, the electron–electron repulsion decreases. The ionic radius decreases with each successive ionization and the electrostatic attraction between the electrons and nucleus increases. Hence, the ionization energy increases.

5c. Large increases in ionization energy indicate a change in energy levels because the electron is being removed from a noble gas configuration. For example, the removal of an electron from $n = 2$ requires greater energy than removing an $n = 3$ electron.

9b. Log scales allow us to plot data that covers a very large range. It is useful for identifying unusually large increases, such as those observed in graphs of successive ionization energies.

11. In a given energy level, s electrons require a greater energy to be ionized than p electrons do. For example, the energy required to ionize a 2s electron will be higher than that of a 2p electron. Therefore, when a slightly larger increase is observed on the graph, between 2p and 2s electrons.

End of topic questions (page 61–62)

1. Answers will depend on the student, but a possible answer might be: Electrons in atoms occupy discrete energy levels, which converge at higher energies. Each main energy level is split into s, p, d and f sublevels of successively higher energies. Each sublevel contains a fixed number of atomic orbitals, and each orbital can accommodate up to two electrons with opposite spins. When an electron jumps to a higher level or sublevel, a quantum of energy is absorbed. When an electron falls back to a lower level or sublevel, the same quantum of energy is emitted, typically in the form of visible, IR or UV light.

2. A

3. B

4. A

5. D

6. C

7. C

8. B

9. C

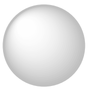
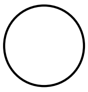
10. Electrons in atoms occupy discrete energy levels, so electron transitions between these levels consume or emit specific quanta of energy. Each quantum of energy corresponds to a photon of specific wavelength.

11. Ti: $1s^2\,2s^2\,2p^6\,3s^2\,3p^6\,4s^2\,3d^2$ or $[Ar]\,4s^2\,3d^2$
Se: $1s^2\,2s^2\,2p^6\,3s^2\,3p^6\,4s^2\,3d^{10}\,4p^4$ or $[Ar]\,4s^2\,3d^{10}\,4p^4$
Si: $1s^2\,2s^2\,2p^6\,3s^2\,3p^2$ or $[Ne]\,3s^2\,3p^2$
Ti^{3+}: $1s^2\,2s^2\,2p^6\,3s^2\,3p^6\,3d^1$ or $[Ar]\,3d^1$
S^{2-}: $1s^2\,2s^2\,2p^6\,3s^2\,3p^6$ or [Ar]

12. $1s^2\,2s^2\,2p^7\,3s^2\,3p^5$ is impossible; the 2p sublevel can only hold 6 electrons

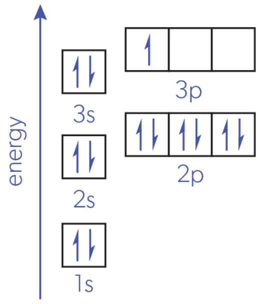
13. … $4p^6\,5s^1$; in the first instance (… $4p^5\,5s^1$) a 4p electron has been promoted to a 5s sublevel.

14.

 or  (any of the two would be acceptable).

15. The lines in visible emission spectrum of atomic hydrogen are produced by electron transitions from upper energy levels to the second energy level. Therefore, the arrow should originate at the level with n = 3 and end at the level with n = 2.

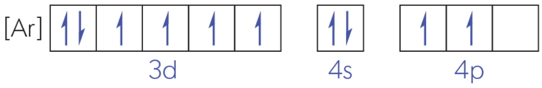
16.



One unpaired electron

17. 26

18.



8 occupied p orbitals. $2p^6$, $3p^6$, $4p^2$; three 2p orbitals (all full), three 3p orbitals (all full) and two 4p orbitals (each singly occupied)

19. The spectral lines in the emission spectrum converge at a certain wavelength, λ, which represents the ionization of the atom. This wavelength can be used to calculate the first ionization energy, IE_1, of the atom using the formula $IE_1 = \frac{hc}{\lambda}$, where c is the speed of light ($3.0 \times 10^8\ \mathrm{m\,s^{-1}}$).

20. The first ionization energy for the period 3 elements generally increases from Na to Ar (figure 25) because the number of protons in the nucleus increases and so the outermost electrons are held closer to the nucleus by the increasing nuclear charge. At the same time, the shielding effect remains nearly constant because new electrons are added to the outer energy level while the number of inner electrons does not change.

However, there are two discontinuities: there are drops in IE_1 from Mg to Al and from P to S.

The valence electron configuration of Mg is $3s^2$ while for Al it is $3s^2\,3p^1$. The paired $3s^2$ electrons in Al shield the single 3p electron from the nucleus, making this electron slightly easier to remove.

The valence electron configuration of P is $3s^2\,3p^3$ while for S it is $3s^2\,3p^4$. The electron configuration of P is more stable than that of S, as P has a half-filled outer p sublevel. The paired electrons in S occupy the same region of space, which increases their mutual repulsion. In contrast, the three 3p electrons in P do not come into close proximity. Therefore, more energy is required to remove an electron from P than from S.

21. The largest increase in ionization energy occurs between IE_2 and IE_3, which suggests that the third electron is removed from an inner energy level. Therefore, the element **X** is likely to belong to group 2.

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Structure 1.4 – Counting particles by mass: the mole

Activity (page 64)

a. 1.51×10^{24}

b. 1.51×10^{23}

c. 4.52×10^{23}

Activity (page 65)

a. 17.04;

b. 98.09

c. 322.25

Activity (page 67)

a. 98.09 g mol^{-1}

b. 0.0102 mol

c. 1.23×10^{22}

Practice question (page 69)

H 2.06%, S 32.69%, O 65.25%

Practice questions (page 70)

1. **a.** MnO_2
   b. CH_2
2. C_3H_6

Skills questions (page 71)

Answers will vary depending on the experimental data obtained. Guidance:

1. You should obtain the mass of magnesium (from step 2) and the mass of oxygen (by subtracting the mass of Mg from the mass of magnesium oxide). Then, calculate the number of moles of Mg and O. Divide these two numbers of moles by the smaller of the two to simplify the ratio.
2. The actual formula of magnesium oxide is MgO, thus the ratio of Mg to O is 1:1. How does your result compare to this?
3. You should find that the graph shows a constant rate of increase and is therefore linear.
4. Refer to the guidance given in *Tool 3* when drawing your graph.
5. The linear relationship shows that the Mg and O are present in a constant ratio, hence, the composition of magnesium oxide is constant.
6. This ensures the magnesium has all reacted.
7. Answers could include:
   - Formation of side products
   - Loss of magnesium oxide when the crucible lid was lifted
   - Presence of unreacted magnesium
   - Deposition of soot on the crucible, leading to an incorrect crucible mass
8. Answers could include:
   - Forming a loose Mg coil to allow plenty of air to come into contact with it
   - Lifting the crucible lid very slightly to minimise loss of MgO
   - Use of a roaring Bunsen flame to ensure no deposition of carbon soot due to incomplete combustion
   - Repeating trials

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9. Numbers of moles that are derived from experimental data will rarely produce a whole number when simplifying the ratio. A decision therefore must be made on when to round, and when to scale up the ratio. This can lead to different empirical formulas. There are empirical formula calculators online that can demonstrate the effect of rounding at different points. When do you think it is advisable to round? Do you treat exam data and authentic experimental data differently?

Activity (page 74)

7.36 g

Activity (page 74)

1.53 mol dm^{-3}

Practice question (page 75)

3. 2.00×10^{-3} mol dm^{-3}

Data-based question (page 76)

0.38 mmol dm^{-3}

Skills questions (pages 77–78)

1. Answers will vary depending on the uncertainty of the glassware used.

   Example 1:

   volume = 100 cm^3 ± 0.08 cm^3

   mass = 0.499 g ± 0.001 g

   $$u(\text{concentration}1) = \frac{0.08}{100} + \frac{0.001}{0.499} = 0.002804$$

   u(concentration1) = 0.2804% ≈ 0.3% (1 sf)

   Example 2:

   volume = 100 cm^3 ± 0.5 cm^3

   mass = 0.50 g ± 0.01 g

   $$u(\text{concentration}2) = \frac{0.5}{100} + \frac{0.001}{0.5} = 0.025$$

   u(concentration2) = 2.5% ≈ 3% (1 sf)

2. Answers will vary depending on the absorbance values obtained for solutions 1 and 2.

3. The solution 1 concentration is more precise, because the uncertainty is smaller.

   Accuracy will depend on the answers to question 2. The solution concentration with the lowest percentage error is the more accurate one.

4. Answers will vary.

5. Advantages include: very low concentrations are possible, with a high level of precision. Disadvantages include: The accuracy of the concentrations of the dilutions depends on the concentration of the stock solution, as well as the correct use of volumetric glassware employed in the serial dilution.

Practice question (page 78)

2.50 dm^3

End of topic questions (page 79)

1. Answers will depend on the student, but a possible answer might be: Masses of atoms are compared on a scale relative to ^{12}C and are expressed as relative atomic mass (A_r) and relative formula mass (M_r). The amount of substance is expressed in moles. One mole contains 6.02×10^{23} atoms, molecules or other formula units. The ratio of atoms in a molecule or non-molecular formula unit is given by the empirical formula. The actual number of atoms of each element present in a molecule is given by the molecular formula.

2. C

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3. D
4. A
5. C
6. B
7. **a.** 474.46 g mol^{-1}
   b. 2.11×10^{-3} mol
   c. 6.09×10^{22}
   d. 0.0253 mol
   e. K 8.24%, Al 5.69%, S 13.52%, O 67.45%, H 5.11%
8. Approximately 100 billion (1×10^{11}) years.
9. **a.** SO_3 **b.** C_2H_6O
10. $\rho(K_2SO_4) = 34.86$ g dm^{-3}; $c(K_2SO_4) = 0.200$ mol dm^{-3}
11. **a.** Prepare a stock solution of potassium permanganate using volumetric glassware and a milligram balance. Typical concentration of the stock solution is 50.0 mmol dm^{-3}, although other concentrations could be used.
   b. Dilute the stock solution to 5.0 mmol dm^{-3}. Using a volumetric pipette, transfer 10.0 cm^3 of the solution into a clean 100 cm^3 volumetric flask, add deionized water to the graduation mark, stopper the flask and turn it over at least 10 times to ensure complete mixing.
   c. Dilute the 5.00 mmol dm^{-3} solution to 0.500 mmol dm^{-3} by repeating step (b).
   d. Dilute the 0.500 mmol dm^{-3} solution to 0.100 mmol dm^{-3} by repeating step (b) and using a 20 cm^3 volumetric pipette instead of the 10 cm^3 volumetric pipette.
   e. Other solutions (0.400, 0.300 and 0.200 mol dm^{-3}) can be prepared in the same way either from the 5.00 mmol dm^{-3} or 0.500 mmol dm^{-3} solution.
12. **a.** $2CO(g) + O_2(g) \rightarrow 2CO_2(g)$
   b. $V(CO) = 2.00\ dm^3$; $V(O_2) = 1.00\ dm^3$

Structure 1.5 – Ideal gases

Practice question (page 82)

1. 31.7 kPa

Activity (pages 83)

1. The ideal gas model assumes: negligible particle volume, absence of intermolecular forces attraction between gas particles, molecules of a gas are in constant random motion, elastic collisions between particles, particle kinetic energy is directly proportional to the kelvin temperature.
2. High pressure (or low volume): at higher pressures, there are more particles per unit volume, so the volume of the particles becomes significant.

   Low temperature: lower particle kinetic energy leads to a greater significance of intermolecular forces, which affect the elasticity of the collisions between particles.
3. **a.** Strong intermolecular forces reduce the elasticity of the collisions between particles. Gases with stronger intermolecular forces deviate more from ideal gas behaviour.

   b. Large molecular volume increases the significance of the volume of molecules. Gases with larger molecular volume deviate more from ideal gas behaviour.
4. **a.** More likely to exhibit ideal behaviour: gas at low pressure because at low pressures, an inverse pressure–volume relationship is expected.

   b. More likely to exhibit ideal behaviour: gas at high temperature because the particles have higher kinetic energy, rendering any intermolecular forces insignificant.

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c. More likely to exhibit ideal behaviour: HBr because, unlike HF, hydrogen bonds are not present between HBr molecules. Strong intermolecular forces called hydrogen bonds exist between HF molecules (this is the reason behind the fact that the boiling point of HF is higher than that of HBr). See *Structure 2.2* for more information on intermolecular forces.

d. More likely to exhibit ideal behaviour: methane, because it is smaller molecule, with smaller molecular volume, and weaker London (dispersion) forces between its molecules (see *Structure 2.2* for more information on intermolecular forces).

e. More likely to exhibit ideal behaviour: butane, because of the weaker intermolecular forces between its molecules. Unlike butane, which is non-polar, propanone molecules are polar and therefore experience stronger dipole-dipole interactions. See Structure 2.2 for more information on intermolecular forces.

Skills questions (pages 85)

Answers will vary. Guidance:

1. Option 1: Select a number of molecules with similar molar masses, to ensure a similar degree of London (dispersion) forces. Collect boiling point data for the different substances to help you deduce the strengths of their intermolecular forces. Model the relationship between boiling point and the value of a for these substances, by plotting a graph (see Tool 3). Discuss any patterns you observe.

Option 2: Select a number of molecules with varying molar masses. Model the relationship between their molar mass and the value of b, by plotting a graph (see Tool 3). Discuss any patterns you observe.

Option 3: For a particular gas of your choice, plot a graph like the one in figure 4. Discuss how volume affects the deviation from ideal behaviour.

Practice question (page 85)

2. 70.9 g mol^{-1}; $Cl_2(g)$

Skills questions (pages 87)

Answers will vary. Guidance:

1. Refer to Tool 3 for guidance on drawing tables.

2. Work out the amount, in moles, of butane by using the ideal gas equation and entering your experimental values for pressure, volume and temperature.

Work out the mass of butane used by finding the change in mass of the lighter.

Molar mass can then be obtained by dividing the amount in moles, by the mass of gas used.

3, 4, 5 and 6. Refer to Tool 3 for guidance on propagating uncertainties, percentage error, accuracy, precision, systematic and random error.

7. The main source of error is the mass measurement, as the amount of water before and after releasing the butane is not the same. Other sources of error include incorrect pressure values (especially if not measured in the lab itself), the fact that the partial pressure of water in the air in the measuring cylinder has not been considered, difference in pressure inside and outside the measuring cylinder, temperature changes that could lead to volume variations (particularly if you held the measuring cylinder in your hand while measuring the volume), etc.

8. Answers will vary depending on the analysis in questions 3 to 7.

9. The pressure in the measuring cylinder is in fact the sum of the partial pressure of butane and that of water vapour. The partial pressure of water vapour at the temperature you carried the experiment out can be obtained. This can then be subtracted from the measured pressure to obtain the partial pressure of butane.

10. Alternative methods include the Dumas method (for the molar mass of volatile liquids), the determination of the molar mass of carbon dioxide through the reaction between an acid and a carbonate, the determination of the molar mass of hydrogen, by reacting an acid and a metal, etc.

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Skills questions (page 88)

1. Pressure vs temperature (at constant volume):

- Independent variable: temperature
- Dependent variable: pressure
- Control variables: volume, identity of gas, amount (in moles) of gas.

Volume vs temperature (at constant pressure):

- Independent variable: temperature
- Dependent variable: volume
- Control variables: pressure, identity of gas, amount (in moles) of gas.

Pressure vs volume (at constant temperature):

- Independent variable: volume
- Dependent variable: pressure
- Control variables: temperature, identity of gas, amount (in moles) of gas.

2. Pressure vs temperature (in K): direct proportion

Volume vs temperature (in K): direct proportion

Pressure vs volume: inverse proportion

3. Zero on the Kelvin scale corresponds to zero particle motion. Unlike Celsius (or other temperatures), kelvin temperatures are directly proportional to both pressure and volume of gases.

Practice question (page 89)

3. 2.37 dm^3

End of topic questions (pages 92–93)

1. Answers will depend on the student, but a possible answer might be: The ideal gas model predicts very well the behaviour of real gases at low pressures and high temperatures. At high pressures and low temperatures, real gases show non-ideal behaviour, although the ideal gas model remains applicable for most practical purposes. The most important consequences of the ideal gas model are the constant molar volume of a gas at specified temperature and pressure and the relationship between pressure, temperature, volume and amount of a gas, which is shown by the ideal gas equation, $pV = nRT$.

2. A

3. D

4. C

5. B

6. D

7. B

8. C

9. C

10. At low temperatures, the molecules of gases move slowly, so the intermolecular forces in real gases cannot be neglected. If the temperature is low enough, a real gas will condense into a liquid while an ideal gas will not. At high pressures, the volume occupied by the molecules of a real gas becomes significant and thus cannot be neglected. The molecules themselves cannot be compressed, so the relationship between pressure and volume deviates from that predicted by the ideal gas model.

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11. Using the combined gas law, $\frac{p_1V_1}{T_1} = \frac{p_2V_2}{T_2}$, and converting the temperature to kelvins gives the following:

$$\frac{250 \times 12.0}{283} = \frac{261 \times V_2}{298}$$

Solving for the unknown volume gives $V_2 \approx 12.1\ \text{dm}^3$

Note that pressure and volume can be expressed in any consistent units, as these units cancel out.

12. $M((NH_4)_2CO_3) = 96.11\ \text{g mol}^{-1}$

$$n\left((NH_4)_2CO_3\right) = \frac{2.25\ \text{g}}{96.11\ \text{g mol}^{-1}} \approx 0.0234\ \text{mol}$$

According to the equation, $n(NH_3) = 0.0468$ mol and $n(CO_2) = 0.0234$ mol.

At STP, $V_m = 22.7\ \text{dm}^3\ \text{mol}^{-1}$, so $V(NH_3) = 1.06\ \text{dm}^3$ and $V(CO_2) = 0.531\ \text{dm}^3$.

13. The total amount of gases is 0.702 mol and $T = 473$ K. Solving the ideal gas equation for pressure gives $p = 184$ kPa.

14. **X**: empirical formula CF_4, $M_r = 88.1$, molecular formula CF_4.

Y: empirical formula CF_2, $M_r = 100$, molecular formula C_2F_4.

Z: empirical formula CF_3, $M_r = 138$, molecular formula C_2F_6.

15. a. $n(C) : n(H) : n(O)$

$$= \frac{54.5}{12.01} : \frac{9.1}{1.01} : \frac{36.4}{16.00}$$

$\approx 4.54 : 9.01 : 2.28 \approx 2 : 4 : 1$

Therefore, the empirical formula of **A** is C_2H_4O.

b. According to the ideal gas equation, $pV = nRT$, so:

$102\ \text{kPa} \times 0.0785\ \text{dm}^3 = n \times 8.31\ \text{J K}^{-1}\ \text{mol}^{-1} \times 368\ \text{K}$

Solving for n gives $n \approx 0.00262$ mol.

$$M(\mathbf{A}) = \frac{0.230\ \text{g}}{0.00262\ \text{mol}} \approx 87.8\ \text{g mol}^{-1}$$

c. $M(C_2H_4O) = 44.06\ \text{g mol}^{-1}$

$$\frac{M(A)}{M(C_2H_4O)} = \frac{87.8}{44.06} \approx 2$$

Therefore, the molecular formula of **A** is $C_4H_8O_2$.

16. a. According to the ideal gas equation, $pV = nRT$, so:

$p \times 25\ \text{dm}^3 = (0.32 + 0.16)\ \text{mol} \times 8.31\ \text{J K}^{-1}\ \text{mol}^{-1} \times 298\ \text{K}$

Solving for p gives $p \approx 48$ kPa.

Notice that the use of dm^3 instead of m^3 for volume gives pressure in kPa instead of Pa.

b. $2H_2(g) + O_2(g) \rightarrow 2H_2O(g)$

According to the equation, the reaction of 0.32 mol of $H_2(g)$ with 0.16 mol of $O_2(g)$ will produce 0.32 mol of $H_2O(g)$. Notice that water will be produced as steam, as the temperature is very high (800 °C).

Using the ideal gas equation gives the following:

$p \times 25\ \text{dm}^3 = 0.32\ \text{mol} \times 8.31\ \text{J K}^{-1}\ \text{mol}^{-1} \times 1073\ \text{K}$

Solving for p gives $p \approx 114$ kPa.

17. a. $64.04\ \text{g mol}^{-1}$

b. CHF

c. $C_2H_2F_2$

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