2024 AUSTRALIAN SCIENCE OLYMPIAD EXAM

CHEMISTRY

TO BE COMPLETED BY THE STUDENT. USE CAPITAL LETTERS.

Student Name: ……………………………………………………………………………….

Home Address: ………………………………………………………………………………..

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Telephone: (……….) ………………………… **Mobile:** ……………………

E-Mail: ……………………………………………… **Date of Birth:** ……/……/……

☐ **Male** ☐ **Female** ☐ **Unspecified** **Year 10** ☐ **Year 11** ☐ **Other:** …….

Name of School: ………………………………………………………… **State:** ……...

Examiners Use Only:

2024 AUSTRALIAN SCIENCE OLYMPIAD EXAM

CHEMISTRY

Time Allowed

Reading Time: 10 minutes
Examination Time: 120 minutes

INSTRUCTIONS

- *Attempt all questions in ALL sections of this paper*.
- Permitted materials: non-programmable, non-graphical calculator, pens, pencils, erasers and a ruler.
- Marks will not be deducted for incorrect answers.

MARKS

▪ SECTION A	15 multiple choice questions	30 marks
▪ SECTION B	3 short answer questions	30 marks each
	Total marks for the paper	120 marks

Integrity of Competition

If there is evidence of collusion or other academic dishonesty, students will be disqualified. Markers' decisions are final.

DATA

Avogadro constant (N) = 6.022×10^{23} mol^{-1}	Velocity of light (c) = 2.998×10^{8} m s^{-1}
1 Faraday = 96 485 coulombs	Density of water at 25 °C = 0.9971 g cm^{-3}
1 A = 1 C s^{-1}	Acceleration due to gravity = 9.81 m s^{-2}
Universal gas constant (R) 8.314 J K^{-1} mol^{-1} 8.206×10^{-2} L atm K^{-1} mol^{-1}	1 newton (N) = 1 kg m s^{-2}
Planck's constant (h) = 6.626×10^{-34} J s	1 pascal (Pa) = 1 N m^{-2}
Molar volume of ideal gas • at 0 °C and 100 kPa = 22.71 L • at 25 °C and 100 kPa = 24.79 L • at 0 °C and 101.3 kPa = 22.41 L • at 25 °C and 101.3 kPa = 24.47 L	$pH = -\log_{10}[H^+]$ $pH + pOH = 14.00$ at 25°C $K_a = \{[H^+][A^-]\} / [HA]$ $pH = pK_a + \log_{10}\{[A^-] / [HA]\}$ PV = nRT E = hν
Surface area of sphere $A = 4\pi r^2$	c = νλ

Periodic Table of Elements

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H 1.008		atomic number Symbol atomic weight															2 He 4.003
3 Li 6.94	4 Be 9.01											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
11 Na 22.99	12 Mg 24.31											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.07	17 Cl 35.45	18 Ar 39.95
19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.87	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.69	29 Cu 63.55	30 Zn 65.38	31 Ga 69.72	32 Ge 72.63	33 As 74.92	34 Se 78.97	35 Br 79.90	36 Kr 83.80
37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.95	43 Tc -	44 Ru 101.1	45 Rh 102.9	46 Pd 106.4	47 Ag 107.9	48 Cd 112.4	49 In 114.8	50 Sn 118.7	51 Sb 121.8	52 Te 127.6	53 I 126.9	54 Xe 131.3
55 Cs 132.9	56 Ba 137.3	57-71	72 Hf 178.5	73 Ta 180.9	74 W 183.8	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.1	79 Au 197.0	80 Hg 200.6	81 Tl 204.4	82 Pb 207.2	83 Bi 209.0	84 Po -	85 At -	86 Rn -
87 Fr -	88 Ra -	89-103	104 Rf -	105 Db -	106 Sg -	107 Bh -	108 Hs -	109 Mt -	110 Ds -	111 Rg -	112 Cn -	113 Nh -	114 Fl -	115 Mc -	116 Lv -	117 Ts -	118 Og -

57 La 138.9	58 Ce 140.1	59 Pr 140.9	60 Nd 144.2	61 Pm -	62 Sm 150.4	63 Eu 152.0	64 Gd 157.3	65 Tb 158.9	66 Dy 162.5	67 Ho 164.9	68 Er 167.3	69 Tm 168.9	70 Yb 173.0	71 Lu 175.0
89 Ac -	90 Th 232.0	91 Pa 231.0	92 U 238.0	93 Np -	94 Pu -	95 Am -	96 Cm -	97 Bk -	98 Cf -	99 Es -	100 Fm -	101 Md -	102 No -	103 Lr -

SECTION A: MULTIPLE CHOICE
USE THE ANSWER SHEET PROVIDED

1. Which of the following formulas is both an empirical formula and a molecular formula? Select all that apply.

   A. SO_2

   B. KNO_3

   C. NH_3

   D. $C_5H_{10}O_5$

   E. CuF_2

2. Hydrogen gas is formed when aluminium foil reacts with sodium hydroxide solution according to the equation:

   $2Al(s) + 2NaOH(aq) + 6H_2O(l) \rightarrow 2NaAl(OH)_4(aq) + 3H_2(g)$

   Calculate the mass of hydrogen produced when 10.00 g of aluminium is placed in 100 mL of an aqueous solution containing 11.6 g of sodium hydroxide (molar mass 39.998 g mol^{-1}).

   A. 0.292 g

   B. 0.877 g

   C. 1.12 g

   D. 1.75 g

   E. 2.24 g

3. A substance does **not** conduct electricity well when solid, nor when liquid. Which of the following could this substance be? Select all that apply.

A. aluminium chloride

B. mercury

C. neon

D. nitrogen dioxide

E. calcium fluoride

4. 0.53 mol of aluminium sulfate is dissolved in water to produce a solution with a volume of 0.500 L. What is the concentration, in mol L^{-1}, of sulfate ions in this solution?

A. 0.177 mol L^{-1}

B. 0.353 mol L^{-1}

C. 1.06 mol L^{-1}

D. 2.12 mol L^{-1}

E. 3.18 mol L^{-1}

5. How many nitrogen atoms are there in 0.40 mol of copper(II) nitrate?

A. 1.5×10^{23}

B. 2.4×10^{23}

C. 4.8×10^{23}

D. 6.0×10^{23}

E. 3.0×10^{24}

6. What is the maximum mass of iron that can be extracted from 751 g of Fe_2O_3?

A. 168 g

B. 235 g

C. 263 g

D. 269 g

E. 525 g

7. Six consecutive elements in the periodic table have the following **second** ionisation energies (in kJ mol^{-1}): 2298, 2666, 3052, 1145, 1235, 1410.

Which of these **second** ionisation energies belongs to the element with the highest **third** ionisation energy (of these elements)?

A. 1145

B. 1235

C. 1410

D. 2298

E. 2666

8. Which of the following substances has the highest molar mass?

A. MgO

B. CaO

C. Na_2O

D. K_2O

E. Cl_2O

9. When 200.0 mL of 0.400 mol L^{-1} barium chloride solution is mixed with 125.0 mL of 1.644 mol L^{-1} lithium sulfate solution, a chemical reaction takes place, as follows:

$BaCl_2(aq) + Li_2SO_4(aq) \rightarrow BaSO_4(s) + 2\ KCl(aq)$

Calculate the concentration of sulfate ions in the resulting solution, assuming that there is no change in volume.

A. 0.386 mol L^{-1}

B. 0.622 mol L^{-1}

C. 0.822 mol L^{-1}

D. 1.244 mol L^{-1}

E. 1.644 mol L^{-1}

10. At a certain temperature and pressure, 22.84 g of oxygen gas has a volume of 23.72 L. Calculate the volume of 21.1 g of nitrogen gas under the same conditions of temperature and pressure.

A. 15.75 L

B. 23.72 L

C. 25.03 L

D. 31.50 L

E. 35.72 L

11. Which of the following molecules contain 4 bonding pairs of valence electrons? Select all that apply.

A. F_2O

B. N_2

C. CO_2

D. HF

E. CCl_4

12. 1.26 g of sodium iodide is dissolved in water and added to a solution containing excess lead(II) nitrate. What mass of lead(II) iodide is formed?

A. 0.97 g

B. 1.26 g

C. 1.94 g

D. 2.82 g

E. 3.88 g

13. Which of the following compounds contains 35.21% phosphorus by mass?

A. PH_3

B. PF_3

C. PCl_3

D. PBr_3

E. PI_3

14. Which of the following are species that have a shape that can be described as bent? Select all that apply.

   A. H_2Se

   B. NH_2^-

   C. CSe_2

   D. PH_3

   E. C_2F_2

15. Which of the following lists elements in order of increasing average distance from the nucleus to the innermost electrons?

   A. K, S, P, Cl

   B. K, P, S, Cl

   C. P, S, Cl, K

   D. K, S, Cl, P

   E. K, Cl, S, P

Question 16

$SnCl_2$ is a compound which is used for tin plating, silver mirror production, as an ingredient in toothpaste and as an industrial catalyst, amongst many other uses.

(a) Calculate the molar mass of $SnCl_2$ (in g mol^{-1}).

189.6 g mol^{-1}

(b) Calculate the amount (in mol) of $SnCl_2$ present in 4.397 g of $SnCl_2$.

n($SnCl_2$) = 4.397 g / 189.6 g mol^{-1} = 0.02319 mol

(c) Calculate the mass of chloride ions present in 4.397 g of $SnCl_2$.

n(Cl) = 2 × 0.02319 mol = 0.04638 mol **m(Cl) = 0.04638 mol × 35.45 g mol^{-1} = 1.644 g**

(d) An aqueous solution of $SnCl_2$ reacts with a small amount of NaOH to form a precipitate.

Which of the following substances are products of this reaction? Select all that apply.

- ☐ SnO_2
- ☐ HCl
- ☐ SnO
- ☐ $Sn(OH)_2$
- ☐ $Sn(OCl)_2$
- ☐ H_2
- ☐ NaCl
- ☐ Cl_2
- ☐ H_2O
- ☐ Na_2O

(e) What is the maximum mass of the precipitate mentioned above would be produced from 1.612 g of NaOH (molar mass 39.998 g mol^{-1})

n(NaOH) = 1.612 g / 39.998 g mol^{-1} = 0.04030 mol

n($Sn(OH)_2$ ppt) = 0.04030 mol / 2 = 0.02015 mol

m($Sn(OH)_2$ ppt) = 0.02015 mol × 152.716 g mol^{-1} = 3.077 g

$SnCl_2$ can be produced placing solid Sn into an aqueous solution of HCl, according to the equations:

- $Sn(s) + 2\ HCl(aq) \rightarrow SnCl_2(aq) + H_2(g)$, or
- $Sn(s) + 2\ H^+(aq) \rightarrow Sn^{2+}(aq) + H_2(g)$

(f) What happens to the concentration of Cl^- ions in the solution as the reaction proceeds? Select all that apply.

☐ Increases

☐ Stays the same

☐ Decreases

A piece of tin is placed into a flask containing 175 mL of 0.300 mol L^{-1} hydrochloric acid.

(g) What mass of Sn is required for complete reaction with the hydrochloric acid to form $SnCl_2$?

n(HCl) = 0.175 L × 0.300 mol L^{-1} = 0.0525 mol

n(Sn) = 0.0525 mol / 2 = 0.0263 mol

m(Sn) = 0.0263 mol × 118.7 g mol^{-1} = 3.12 g

(h) What mass of hydrogen gas (in g) is given off when the mass of tin above reacts completely with the hydrochloric acid?

n(H_2) = 0.0263 mol

m(H_2) = 0.0263 mol × 2.016 g mol^{-1} = 0.0523 g

In a separate flask, a piece of tin with a mass of 8.59 g is placed into 500 mL of 0.450 mol L^{-1} hydrochloric acid.

(i) Compare the mass of the flask **before** the tin is added to the mass of the flask when the reaction has finished. What is the change in mass of the contents of the flask?

n(Sn) = 8.59 g / 118.7 g mol^{-1} = 0.0724 mol

n(HCl) = 0.500 L × 0.450 mol L^{-1} = 0.225 mol

So HCl is in excess, and Sn is the limiting reagent.

n(H_2) = 0.0724 mol

m(H_2 lost) = 0.0724 mol × 2.016 g mol^{-1} = 0.146 g

m(Sn added) = 8.59 g

Δ mass = 8.59 g – 0.146 g = 8.44 g

Elemental tin can be produced from tin(II) chloride by reaction with aluminium.

(j) Write a balanced chemical equation for this reaction:

2 $Al(s)$ + **3** $SnCl_2(aq) \longrightarrow$ **2** $AlCl_3(aq)$ + **3** $Sn(s)$

In this reaction, electrons are transferred from aluminium atoms to tin(II) ions. Each tin(II) ion consumes two electrons and becomes solid tin, whereas each aluminium atom loses three electrons and becomes an aluminium ion:

$Sn^{2+}(aq) + 2\ e^{-} \longrightarrow Sn(s)$

$Al(s) \longrightarrow Al^{3+}(aq) + 3\ e^{-}$

(k) When 10.1 mol of electrons are transferred from aluminium to tin(II) ions, calculate the mass (in g) of tin produced.

n(Sn) = 10.1 mol / 2 = 5.05 mol

m(Sn) = 5.05 mol × 118.7 g mol^{-1} = 599 g

The amount of electrons (in mol) transferred in a reaction can be calculated if we know both the current flowing and the time for which the current is flowing. The relationship is as follows:

$$n(e^-) = \frac{I \times t}{F}$$

where:

- $n(e^-)$ = amount of electrons (in mol)
- I = current (in A)
- t = time (in s)
- F = Faraday constant = 96 485 C mol^{-1}

(l) If a constant current of 0.541 A flows for 5 hours when aluminium metal reacts with tin(II) ions, calculate the mass of aluminium consumed.

$$\boldsymbol{n(e^-) = \frac{0.541\ \mathrm{A} \times 18000\ \mathrm{s}}{96485\ \mathrm{C\ mol^{-1}}} = 0.101\ \mathrm{mol}}$$

n(Al consumed) = 0.101 mol / 3 = 0.0336 mol

m(Al consumed) = 0.0336 mol × 26.98 g mol^{-1} = 0.908 g

As we have seen, some chemical reactions involve a transfer of electrons and hence can cause an electric current to flow. If an electric current is passed through the same system in reverse, we can cause the chemical reaction to take place in reverse.

A current of 0.3865 A is passed through a mixture of Sn^{2+} ions and Pb^{2+} ions for 525 s, resulting in the deposition of both Sn and Pb on the same electrode.

(m) Calculate the total amount (in mol or mmol) of Sn and Pb deposited.

$$\boldsymbol{n(e^-) = \frac{0.3865\ \mathrm{A} \times 525\ \mathrm{s}}{96485\ \mathrm{C\ mol^{-1}}} = 2.10 \times 10^{-3}\ \mathrm{mol}}$$

$$\boldsymbol{n\left(\mathrm{Pb^{2+}\ and\ Sn^{2+}}\right) = \frac{2.10 \times 10^{-3}\ \mathrm{mol}}{2} = 1.05 \times 10^{-3}\ \mathrm{mol}}$$

The deposited mixture of Sn and Pb was removed by dissolving the metals in concentrated nitric acid and heating. The Sn forms an insoluble compound and is filtered off.

When a current of 0.3838 A is passed through the filtrate for 220.0 s, 0.1051 g of a lead-containing deposit formed, but on the opposite electrode from the previous electrolysis.

(n) The lead-containing deposit has a molar mass of under 350 g mol^{-1}. What is its molar mass?

$$n(e^-) = \frac{0.3838\ \mathrm{A} \times 220.0\ \mathrm{s}}{96485\ \mathrm{C\ mol^{-1}}} = 8.751 \times 10^{-4}\ \mathrm{mol}$$

If this is a one electron process, $n(Pb^{3+}) = 8.751 \times 10^{-4}\ \mathrm{mol}$

and molar mass $= \frac{0.1051\ \mathrm{g}}{8.751 \times 10^{-4}\ \mathrm{mol}} = 120.1\ \mathrm{g\ mol^{-1}}$

This is less than the molar mass of lead, so the actual molar mass must be some multiple of this value. Indeed, given that the molar mass is under 350 g mol^{-1}, the molar mass must be exactly double this value, i.e. 240.2 g mol^{-1}.

(o) What is the identity of the lead-containing deposit?

- ☐ PbO
- ☐ $Pb(OH)_3$
- ☐ $Pb(OH)_4$
- ☐ PbO_2
- ☐ $PbO(NO_3)$
- ☐ $PbO(NO_3)_2$
- ☐ $Pb(NO_3)_2$
- ☐ $Pb(OH)_3NO_3$

Question 17

For ideal gases, the following relationship between pressure, volume, number of moles and temperature holds, known as the ideal gas law:

$$pV = nRT$$

Where:

- p is the pressure exerted by the gas (kPa)
- V is the volume occupied by the gas (L)
- n is the number of moles of gas present (mol)
- R is a proportionality constant known as the ideal gas constant, equal to 8.314 L kPa mol^{-1} K^{-1}.
- T is the temperature of the gas (K).

To convert temperature from °C to K, add 273.15, i.e. T(K) = T(°C) + 273.15
For this question, assume all gases and mixtures of gases behave ideally.

(a) What volume does 1.12 moles of krypton gas occupy at 85.0 kPa and 290 K?

$$\boldsymbol{V = \frac{nRT}{P} = \frac{1.12 \times 8.314 \times 290}{85.0} = 31.8\ \text{L}}$$

(b) Convert 50.00 °C to K.

T = 50.00 + 273.15 = 323.15 K

(c) What pressure does a mixture of 0.412 moles of helium and 0.850 moles of argon exert when confined to a volume of 12.2 L at 50.0 °C?

$$\boldsymbol{P = \frac{nRT}{V} = \frac{(0.412 + 0.850) \times 8.314 \times (50 + 273.15)}{12.2} = 278\ \text{kPa}}$$

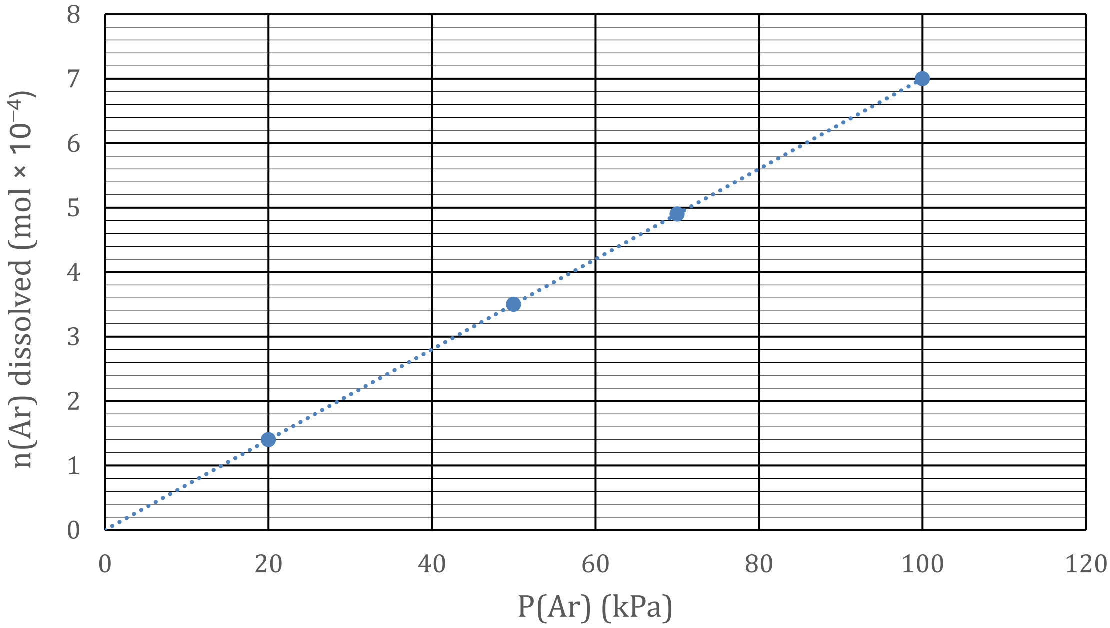
The law governing solubility of gases in water at equilibrium is known as Henry's Law, which states that the solubility of a gas in a liquid is directly proportional to the partial pressure of the gas surrounding that liquid.
The constant of proportionality can be defined in several different ways. One such way is in terms of concentration:

$$H^{cp} = \frac{c_A}{p_A}$$

Where:

- H^{cp} is the Henry concentration constant, which is specific to each gas (mol L^{-1} kPa^{-1}).
- c_A is the concentration of dissolved gas A in the water at equilibrium (mol L^{-1}).
- p_A is the pressure exerted by gas A if all other gases were removed, known as the *partial pressure* (kPa).

An experiment was conducted to determine the Henry concentration constant of argon. A known volume of water was placed in a sealed chamber. The atmosphere inside the chamber was made to be pure argon over a range of different pressures. The amount of argon dissolved in the water at each pressure was then determined and graphed:



(d) What is the gradient of the plot, in mol kPa^{-1}?

Gradient = $(7.0 \times 10^{-4} - 1.4 \times 10^{-4})/(100 - 20) = 7.0 \times 10^{-6}$ mol kPa^{-1}

The volume of water in the chamber was 0.457 L.

(e) Calculate the Henry concentration constant for argon in water, as found by this experiment (in mol L^{-1} kPa^{-1}).

$$\mathbf{H^{cp} = \frac{c_A}{p_A} = \frac{n_A}{V_A \times p_A} = \frac{gradient}{V_A} = \frac{7.0 \times 10^{-6}\ mol\ kPa^{-1}}{0.457\ L}}$$

$$\mathbf{H^{cp} = 1.53 \times 10^{-5}\ mol\ L^{-1}\ kPa^{-1}}$$

The constant of proportionality can also be expressed in terms of a quantity called molality:

$$H^{bp} = \frac{b_A}{p_A}$$

Where:

- H^{bp} is the Henry molality constant, which is specific to each gas (mol kg^{-1} kPa^{-1})
- b_A is the molality of gas A in the solution, which is defined as the number of moles of gas per unit *mass* of solvent (mol kg^{-1})
- p_A is the partial pressure of gas A, as defined previously. (kPa)

The Henry molality constant and Henry concentration constant can be interconverted.

The Henry concentration constant (H^{cp}) for CO_2 in water is 3.40×10^{-4} mol L^{-1} kPa^{-1}.

(f) Assuming that the density of the solution is 1.013 kg L^{-1} at all concentrations, calculate the Henry molality constant (H^{bp}).

H^{cp} (mol L^{-1} kPa^{-1}) = H^{bp} (mol kg^{-1} kPa^{-1}) × density of solvent (kg L^{-1})

$$\mathbf{H^{bp} = \frac{H^{cp}}{density} = \frac{3.40 \times 10^{-4}\ mol\ L^{-1}\ kPa^{-1}}{1.013\ kg\ L^{-1}} = 3.36 \times 10^{-4}\ mol\ kg^{-1}\ kPa^{-1}}$$

(g) If the solubility (in terms of molality) of O_2 is 1.30×10^{-3} mol kg^{-1} when the partial pressure of O_2 is 100 kPa, what will be the solubility of O_2 in water (in mol kg^{-1}) when the partial pressure is changed to 232 kPa?

$$\mathbf{H^{bp} = \frac{b_A}{p_A} = \frac{1.30 \times 10^{-3}\ mol\ kg^{-1}}{100\ kPa} = 1.30 \times 10^{-5}\ mol\ kg^{-1}\ kPa^{-1}}$$

$$\mathbf{b_A = H^{bp} \times p_A = 1.30 \times 10^{-5}\ mol\ kg^{-1}\ kPa^{-1} \times 232\ kPa}$$

$$\mathbf{= 3.02 \times 10^{-3}\ mol\ kg^{-1}}$$

For the remaining parts of this question, all Henry's Law coefficients are expressed in terms of molarity (H^{cp}).

$$H^{cp} = \frac{c_A}{p_A}$$

Where:

- H^{cp} is the Henry concentration constant, which is specific to each gas (mol L^{-1} kPa^{-1}).
- c_A is the concentration of dissolved gas A in the water at equilibrium (mol L^{-1}).
- p_A is the pressure exerted by gas A if all other gases were removed, known as the *partial pressure* (kPa).

The average global carbon dioxide level in the atmosphere has reached 424.3 parts per million (ppm), which means out of every million molecules in the atmosphere, on average 424.3 of them are CO_2 molecules.

(h) Consider a 2839 L volume of air at 101.3 kPa and 298 K. What is the chemical amount (in mol) of CO_2 contained within this volume?

$$\mathbf{n(air) = \frac{PV}{RT} = \frac{101.3\times2839}{8.314\times298} = 116.1\ mol}$$

$$\mathbf{n(CO_2) = \frac{424.3}{10^6} \times 116.1\ mol = 4.92 \times 10^{-2}\ mol}$$

(i) Hence or otherwise, calculate the partial pressure of CO_2 in the atmosphere, in kPa.

$$\mathbf{P(CO_2) = 101.3\ kPa \times \frac{n(CO_2)}{n(air)}}$$

$$\mathbf{= 101.3\ kPa \times \frac{4.92 \times 10^{-2}\ mol}{116.1\ mol} = 4.30 \times 10^{-2}\ kPa}$$

OR

$$\mathbf{P(CO_2) = \frac{424.3}{10^6} \times 101.3\ kPa = 4.30 \times 10^{-2}\ kPa}$$

(j) What is the concentration (in mol L^{-1}) of dissolved CO_2 in a body of pure water exposed to the atmosphere, given that the Henry concentration coefficient (H^{cp}) of CO_2 is 3.40×10^{-4} mol L^{-1} kPa^{-1}? Ignore any reactions CO_2 might have with water.

$$\mathbf{[CO_2] = P(CO_2) \times H^{cp} = 4.30 \times 10^{-2}\ kPa \times 3.40 \times 10^{-4}\ mol\ L^{-1}\ kPa^{-1}}$$

$$\mathbf{[CO_2] = 1.46 \times 10^{-5}\ mol\ L^{-1}}$$

Henry's law plays a special role in the chemistry of soft drink cans, where cans are highly pressurised with carbon dioxide so that solubility of carbon dioxide in the drink is high. Once the can is opened and the pressure is released, the solubility drops, and the carbon dioxide escapes from the solution as bubbles.

Consider a sealed can with total volume 580 mL which is filled with 517 mL of water, with the remaining space in the can being occupied by pressurised CO_2. After coming to equilibrium at 298 K, the pressure of CO_2 in the can is measured to be 5000 kPa.

(k) Calculate the amount (in mol) of gaseous CO_2 in the can.

$$\mathbf{n(CO_2, gas) = \frac{PV}{RT} = \frac{5000 \times (0.580 - 0.517)}{8.314 \times 298} = 0.127\ mol}$$

(l) Calculate the amount (in mol) of dissolved CO_2 contained in the can. Use $H^{cp}(CO_2) = 3.40 \times 10^{-4}$ mol L^{-1} kPa^{-1}.

$$\mathbf{[CO_2, aq] = \boldsymbol{P}(CO_2) \times \boldsymbol{H}^{cp}}$$

$$\mathbf{[CO_2, aq] = 5000\ kPa \times 3.40 \times 10^{-4}\ mol\ L^{-1}\ kPa^{-1} = 1.70\ mol\ L^{-1}}$$

$$\mathbf{n(CO_2, aq) = 1.70\ mol\ L^{-1} \times 0.517\ L = 0.879\ mol}$$

An empty balloon is placed over the mouth of the can, and the can is opened. CO_2 gas leaves the solution, and the balloon inflates until the pressure inside the balloon is equal to the ambient atmospheric pressure (101.3 kPa).

(m) What amount of CO_2 (in mol) leaves the solution?

$$\mathbf{[CO_2, aq] = \boldsymbol{P}(CO_2) \times \boldsymbol{H}^{cp}}$$

$$\mathbf{[CO_2, aq] = 101.3\ kPa \times 3.40 \times 10^{-4}\ mol\ L^{-1}\ kPa^{-1} = 0.0344\ mol\ L^{-1}}$$

$$\mathbf{n(CO_2, aq) = 0.0344\ mol\ L^{-1} \times 0.517\ L = 0.0178\ mol}$$

$$\mathbf{n(CO_2, leaving\ solution) = 0.879\ mol - 0.0178\ mol = 0.861\ mol}$$

(n) What is the final volume of the inflated balloon?

$$\boldsymbol{n(CO_2, total)} = \mathbf{0.127\ mol + 0.879\ mol = 1.006\ mol}$$

$$\boldsymbol{n(CO_2, gas)} = \mathbf{1.006\ mol - 0.0178\ mol = 0.988\ mol}$$

$$\boldsymbol{V = \frac{nRT}{P}} = \mathbf{\frac{0.988 \times 8.314 \times 298}{101.3} = 24.2\ L}$$

Beverage companies have recently started experimenting with pressurising soft drinks with a mixture of nitrogen and carbon dioxide, instead of just carbon dioxide.

A mixture of nitrogen and carbon dioxide is added to a can with total volume 440 mL, already filled with 336 mL of water, and the can is sealed. The gas is then allowed to dissolve into the water until equilibrium is reached. Assume that the can only contains liquid water, N_2 and CO_2, and the temperature of the can is maintained at 298 K at all times.

(o) For every mole of gaseous CO_2 contained in the can, how many moles of CO_2 are dissolved in aqueous solution? Use $H^{cp}(CO_2) = 3.40 \times 10^{-4}$ mol L^{-1} kPa^{-1}.

$P(CO_2) = nRT/V = 1 \times 8.314 \times 298 / ((440\text{-}336)/1000) = 2.38 \times 10^4$ kPa

$[CO_2] = H^{cp} \times P(CO_2) = 3.40 \times 10^{-4}$ mol L^{-1} kPa^{-1} $\times 2.38 \times 10^4$ kPa = 9.00 mol L^{-1}

So $n(CO_2) = 9.00$ mol L^{-1} $\times$ 0.336 L = 2.72 mol

For every mole of gaseous N_2 contained in the can, there are 0.132 moles of N_2 dissolved in aqueous solution.

(p) Calculate $H^{cp}(N_2)$, in mol L^{-1} kPa^{-1}.

$n(N_2) = 0.132$ mol / 0.336 L = 0.393 mol L^{-1}

$P(N_2) = nRT/V = 1 \times 8.314 \times 298 / ((440\text{-}336)/1000) = 2.38 \times 10^4$ kPa

$H^{cp} = [N_2] / P(N_2) = 0.393$ mol L^{-1} / 2.38×10^4 kPa = 1.65×10^{-5} mol L^{-1} kPa^{-1}

The mixture of nitrogen and carbon dioxide initially added to the can contained 0.300 mol of gas in total. The pressure in the can reveals 0.152 mol of undissolved gas in the can.

(q) What is the amount (in mol) of nitrogen in the can?

$n(N_2\ g) + n(CO_2\ g) = 0.152$ mol

$n(N_2\ aq) + n(CO_2\ aq) = 0.300$ mol – 0.152 mol = 0.148 mol

$n(N_2\ aq) / n(N_2\ g) = 0.132$ mol

$n(CO_2\ aq) / n(CO_2\ g) = 2.72$ mol

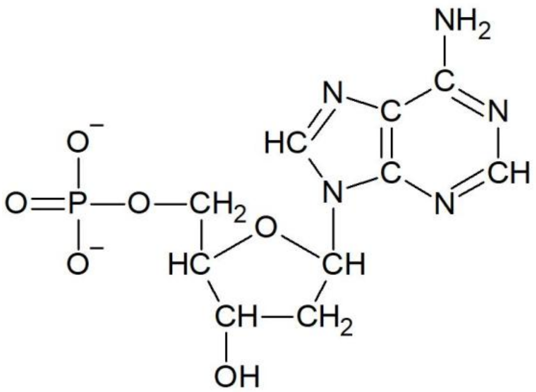
$0.132 \times n(N_2\ g) + 2.72\ n(CO_2\ g) = 0.148$ mol

Solving simultaneously, $n(N_2) = 0.103$ mol

Question 18

The DNA of all living beings is made from the same set of chemical units which are bonded together. DNA encodes essential information on how to build all the proteins needed by a certain organism.

Here the structure of one of these units:



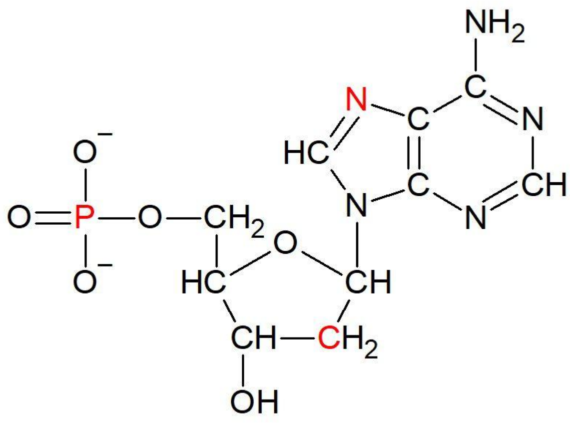
(a) What is the chemical formula for this unit?

$C_{10}H_{12}N_5O_6P$

(b) Calculate molar mass (in g mol^{-1}) of this unit.

$10 \times 12.01 + 12 \times 1.008 + 5 \times 14.01 + 6 \times 16.00 + 30.97 = 329.2$ g mol^{-1}

(c) Complete the following sentences about the molecular geometry of the atoms highlighted in red in the following DNA unit.



The red carbon atom has **_4_** bonding domains and has a **_tetrahedral_** geometry.

The red phosphorus atom has **_4_** bonding domains and has a **_tetrahedral_** geometry.

The red nitrogen atom has **_2_** bonding domains and has a **_bent_** geometry.

DNA is double-stranded, meaning that each molecular unit on one strand of DNA is paired via hydrogen bonding to another unit on the other strand, forming what is called a **base pair**. The average mass of a single base **pair** is 1.086×10^{-21} g.

Recall that a collection of 6.022×10^{23} entities that make up a substance is called a mole of that substance.

(d) Find the average molar mass of a single (unpaired) molecular unit of DNA, in g mol^{-1}.

MM(base pairs) = 6.022×10^{23} mol^{-1} $\times$ 1.086×10^{-21} g = 654.0 g mol^{-1}

MM(unpaired unit) = 654.0 / 2 = 327.0 g mol^{-1}

The human genome, which contains our complete sequence of DNA, comprises about 3.200×10^{9} DNA base pairs.

(e) Calculate the mass of DNA in the human genome, in picograms (pg, 1 pg = 10^{-12} g)

m(DNA) = $3.200 \times 10^{9} \times 1.086 \times 10^{-21}$ x 10^{12} = 3.475 pg

The total DNA content in cells is stored across multiple condensed strands of DNA called chromosomes. The most common cells in the human body are called somatic cells, which have 23 pairs of chromosomes, comprising of 23 chromosomes inherited from the father, and 23 inherited from the mother. For 22 of these chromosome pairs, the copies from both parents are very similar. The final pair are the sex chromosomes, referred to as X and Y.

The mass of DNA content in a somatic cell with an XY chromosome was found to be 7.020 pg (1 pg = 10^{-12} g).

(f) Find the number of base pairs of DNA in this cell.

Number of base pairs = 7.02×10^{-12} / (1.086×10^{-21}) = 6.464×10^{9} bp

Gametes have only half the DNA content of a somatic cell, since they have 23 chromosomes instead of 46.

- An X gamete cell has 23 chromosomes in total, with one being X
- A Y gamete cell has 23 chromosomes in total, with one being Y
- One type of somatic cell has 46 chromosomes in total, with one pair being XX
- Another type of somatic cell has 46 chromosomes in total, with one pair being XY

(g) An X gamete is known to be about 3.131 Gbp in size (1 Gbp = 10^{9} bp). Using the information above, complete the table.

Cell type	Size (Gbp)
X gamete	3.131
Y gamete	**6.464 – 3.131 = 3.333**
XX somatic cell	**2 × 3.131 = 6.262**
XY somatic cell	**6.464**

Even though the reported size of the human genome is about 3,200,000,000 base pairs, most human cells have double the DNA content due to having two copies of each chromosome. For that reason, humans are classified as diploid organisms. Other living beings can exhibit polyploidy, where their cells can have more than two copies of each chromosome.

A species of plant, *Paspalum almum* Chase, is diploid and has a total DNA content of 1.40 pg. Another species *Paspalum densum* Poir, is tetraploid and has a measured DNA content of 2.20 pg.

(h) Calculate how much larger (as a percentage) the plant genome of the first plant species is compared to the second.

Mass of a single copy of DNA plant 1: 1.40/2 = 0.70 pg
Mass of a single copy of DNA plant 2: 2.20/4 = 0.55 pg
% difference = 0.70/0.55 = 27.3% larger

There are many mechanisms of plant reproduction which affect the number of copies of chromosomes found in plant cells.

In the following description, **every cell prior to fertilisation has the same relative DNA content**.

The female organ of a flowering plant has egg cells and other cells called polar nuclei. In pollination, sperm cells (pollen) from one plant are carried to another plant. One sperm cell can combine with an egg cell to form the embryo. One sperm cell also combines with two polar nuclei to form the endosperm.

(i) What is the ratio of DNA content in the embryo to DNA content in the endosperm?

2 to 3

The ability for the ES complex to form depends largely on the intermolecular forces that exist between the substrate and the enzyme.

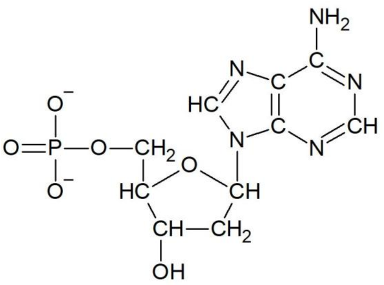
If your previous answer was 1:2, then the mechanism of plant reproduction would be reported as (1C+2C).

Another plant species was studied and the DNA content of its embryo and endosperm was found to be 1.85 pg and 4.625 pg respectively. Its genome (a single copy of each chromosome) was sequenced and found to be approximately 0.426 Gbp. Recall that the average mass of a single base **pair** is 1.086×10^{-21} g.

(j) Complete the following sentences:

- The reproduction mechanism of this plant is **__2C + 5C__**.
- Its ploidy number (the number of copies of each chromosome in a somatic cell) is **__4__**.
- The number of copies of chromosomes in the endosperm is **__10__**.

The structure of one of the repeating units of DNA is again shown below:

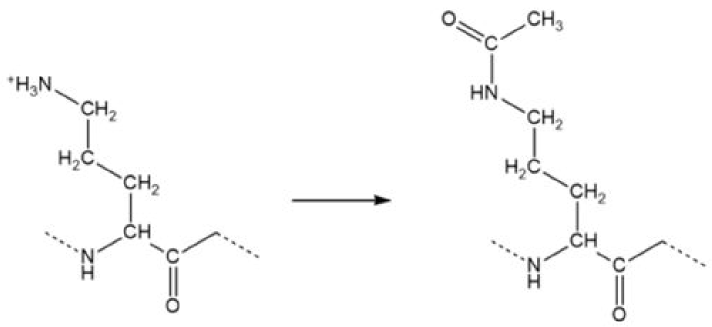


Chromosomes are a highly condensed form of DNA that are very space-efficient. This condensed structure contains a molecule of DNA wrapped around proteins called histones, and is maintained by charge-based interactions between the DNA and histones. In this condensed form, DNA is inaccessible to other proteins.

(k) If the interaction between histones and DNA is weakened, will DNA processing by other proteins will be increased or decreased?

Increased

The structure below shows a change to the structure of part of a histone:



(l) With this change, will DNA processing by other proteins will be increased or decreased?

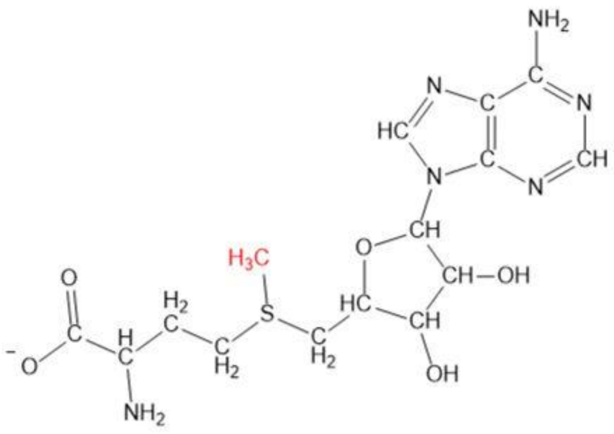
Increased

The structure below shows another change to the structure of part of a histone:

(m) With this change, will DNA processing by other proteins will be increased or decreased?

Increased

DNA transcription can also be regulated by modifications to DNA rather than the histone proteins. One example is the addition of a methyl (CH_3) group in a process called methylation. One of the biological molecules that is consumed in this process has the following structure:



The methyl group shown in red is transferred to DNA in the methylation process.

(n) How many valence electrons does a sulfur atom have?

6

(o) Given that the sulfur atom in the structure above is surrounded by 8 electrons, how many non-bonding electrons does it have?

2

When counting the electrons localised on a particular atom, we include non-bonding electrons and one electron in each covalent bond.

(p) How many localised electrons does this sulfur atom have?

5

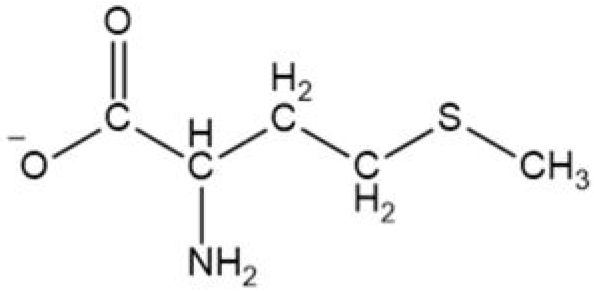
(q) Is this sulfur atom positively charged, negatively charged, or neutral?

Positive

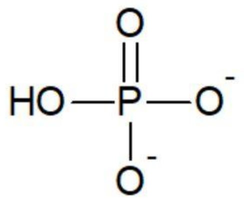
An incomplete chemical equation for the biosynthesis of this molecule is shown below:

$C_{10}H_{12}N_5O_{13}P_3^{4-}$ + ... $\rightarrow$ $C_{15}H_{21}N_6O_5S^{-}$ + ...

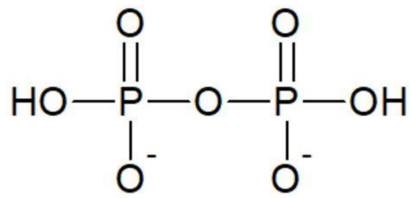
(r) Identify the following structures as reactants or products:



reactant



product



product

Even with the addition of the above structures, the chemical equation is still incomplete because it is not balanced.

(s) What is the missing species, and what is its molar mass?

H_2O, 18 g mol^{-1}

<u>END OF EXAM</u>