Mastering Chemistry

- Book 5
- Topic 12 Patterns in the Chemical World

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42.1 Introduction to transition metals (p.36)

- The transition metals are located between Group II and Group III of the Periodic Table.

The first series of transition metals

- Transition metals have certain common physical properties:
  - high melting points and boiling points;
  - high densities;
  - shiny in appearance;
  - can conduct both electricity and heat;
  - hard and rigid.

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42.1 Introduction to transition metals (p.36)

- The table below shows some physical properties of the first series of transition metals.

Element	Scandium	Titanium	Vanadium	Chromium	Manganese	Iron	Cobalt	Nickel	Copper	Zinc
Symbol	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn
Atomic number	21	22	23	24	25	26	27	28	29	30
Electronic arrangement of atom	2,8,9,2	2,8,10,2	2,8,11,2	2,8,13,1	2,8,13,2	2,8,14,2	2,8,15,2	2,8,16,2	2,8,18,1	2,8,18,2
Melting point (°C)	1 541	1 670	1 910	1 907	1 246	1 538	1 495	1 455	1 085	420
Boiling point (°C)	2 836	3 287	3 407	2 671	2 061	2 861	2 927	2 913	2 560	907
Density (g cm^{-3})	3.0	4.5	6.0	7.2	7.3	7.9	8.9	8.9	9.0	7.1

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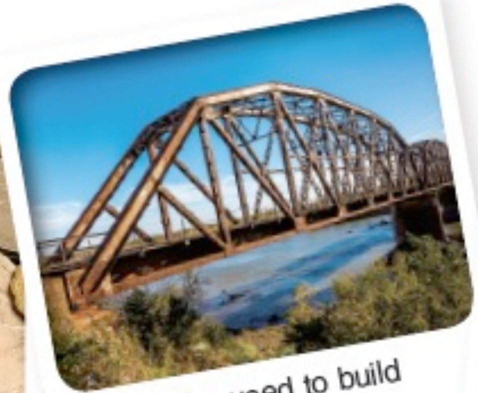
42.1 Introduction to transition metals (p.36)

The coins used in Hong Kong are mainly made of copper, nickel and zinc.



Iron can be used to build bridges.

Highly conductive copper is used in electric wiring.

The artificial hip joint is made of titanium.

Some uses of transition metals

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42.1 Introduction to transition metals (p.36)

Chemical properties of transition metals

- The transition metals have a number of chemical properties that are different from those of other metals.
  - Most of them exhibit variable **oxidation states (氧化態)** in their compounds.
  - Most of them form coloured compounds.
  - Most elements and their compounds can act as catalysts.

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42.1 Introduction to transition metals (p.36)

- The table below compares some properties of Groups I and II metals with those of transition metals.

	Group I and II metals	Transition metals
Physical properties	softer; lower melting points; lower densities	harder; higher melting points; higher densities
Reaction with water	react rapidly, often vigorously	react only slowly with cold water
Oxidation state	oxidation state = group number	variable oxidation states
Colour of compound	colourless	coloured

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42.2 Variable oxidation states of transition metals (p.39)

- Transition metals form compounds with more than one oxidation state. For example, iron forms two chlorides — iron(II) chloride and iron(III) chloride.

	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn
Common oxide(s)	Sc_2O_3	Ti_2O_3 TiO_2	V_2O_3 V_2O_5	Cr_2O_3 CrO_3	MnO MnO_2 Mn_2O_7	FeO Fe_2O_3	CoO Co_2O_3	NiO	Cu_2O CuO	ZnO
Possible oxidation state(s) of element in compound(s)					**+7**					
				+6	+6	+6				
			+5	+5	+5	+5	+5			
		+4	+4	+4	**+4**	+4	+4	+4		
	+3	**+3**	**+3**	**+3**	+3	**+3**	**+3**	+3	+3	
		+2	+2	+2	**+2**	**+2**	**+2**	**+2**	**+2**	**+2**
									+1	

Common oxides of the elements from scandium to zinc and their possible oxidation state(s) in compound(s) (the main oxidation states in bold print)

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42.2 Variable oxidation states of transition metals (p.39)

- The elements at each end of the series in the above figure have only one oxidation state. The closer the elements near the middle of the series, the more the oxidation states they exhibit.

- The +2 state is the main oxidation state for all elements in the second half of the series, whereas +3 is the main oxidation state for all elements in the first part. Across the series, the +2 state becomes more stable relative to the +3 state.

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42.2 Variable oxidation states of transition metals (p.39)

- The lower oxidation states are found in simple ions (e.g. Mn^{2+} and Fe^{3+}). The higher oxidation states are found in covalent compounds (e.g. CrO_3) and polyatomic ions (e.g. CrO_4^{2-} and MnO_4^-). You never find Mn^{7+} or Cr^{6+} as monoatomic ions in ionic compounds.

- A chemical species containing a transition metal in its highest oxidation state is often a strong oxidising agent (e.g. $Cr_2O_7^{2-}$ and MnO_4^-).

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42.2 Variable oxidation states of transition metals (p.39)

Practice 42.1

Find out the oxidation state of the transition metal in each of the following chemical species.

a) VO_3^-

+5

b) Na_2CrO_4

+6

c) MnO_2

+4

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42.3 Coloured compounds of transition metals (p.40)

- Most compounds and ions of transition metals are coloured. For example,
  - copper(II) compounds are mainly blue in colour;
  - iron(II) compounds are pale green in colour;
  - cobalt(II) compounds are pink in colour.
- The table below lists the colours of aqueous ions of some transition metals.

Titanium	Vanadium	Chromium	Manganese	Iron	Cobalt	Nickel	Copper
$Ti^{3+}(aq)$ purple	$V^{3+}(aq)$ green	$Cr^{3+}(aq)$ green	$Mn^{2+}(aq)$ pale pink	$Fe^{2+}(aq)$ pale green	$Co^{2+}(aq)$ pink	$Ni^{2+}(aq)$ green	$Cu^{2+}(aq)$ blue
		$CrO_4^{2-}(aq)$ yellow	$MnO_4^{-}(aq)$ purple	$Fe^{3+}(aq)$ yellow-brown			
		$Cr_2O_7^{2-}(aq)$ orange					

Inspecting compounds of transition metals ***Ref.***

42.3 Coloured compounds of transition metals (p.40)

Aqueous ions of transition metals are usually coloured

42.4 Vanadium chemistry (p.42)

- Vanadium can exist in four common oxidation states (+2, +3, +4 and +5) in compounds.
- The table below lists the names, formulae and colours of four aqueous vanadium-containing ions.

Oxidation state of vanadium	Name of ion	Formula	Colour of aqueous ion
+5	dioxovanadium(V) ion	VO_2^+	yellow
+4	oxovanadium(IV) ion	VO^{2+}	blue
+3	vanadium(III) ion	V^{3+}	green
+2	vanadium(II) ion	V^{2+}	violet

Illustrating the oxidation states of vanadium *Ref.*

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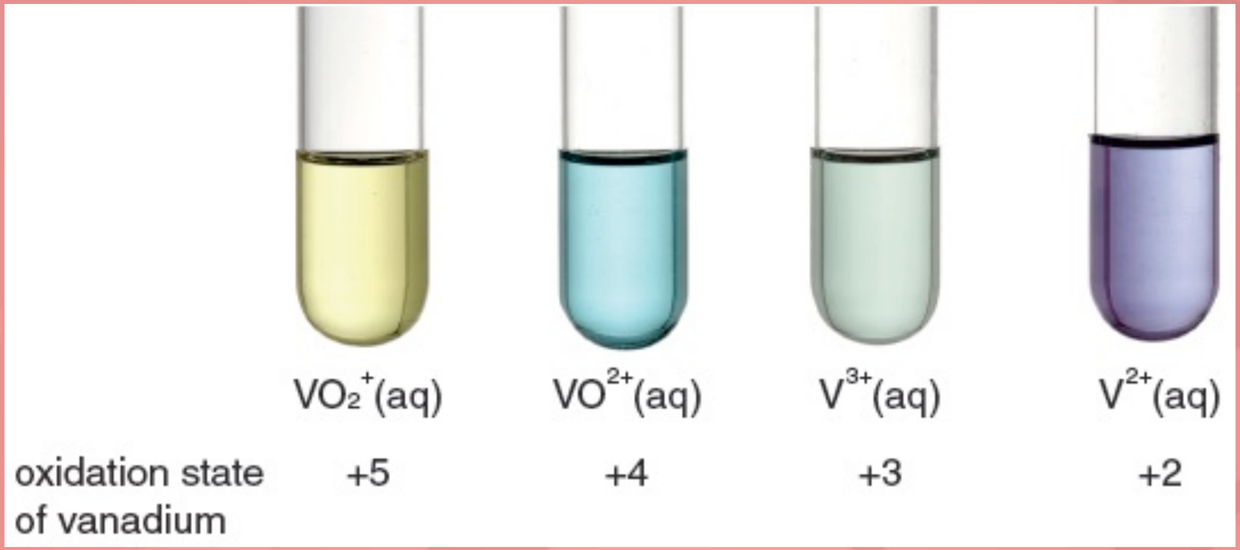
42.4 Vanadium chemistry (p.42)



Samples of aqueous solutions of vanadium-containing ions

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42.4 Vanadium chemistry (p.42)

Reduction of dioxovanadium(V) ion to vanadium(II) ion

- The usual source of vanadium with the oxidation state +5 is the compound ammonium metavanadate (NH_4VO_3).
- In acidic conditions, the metavanadate ion is converted to the yellow dioxovanadium(V) ion, VO_2^+(aq).

$$VO_3^-(aq) + 2H^+(aq) \longrightarrow VO_2^+(aq) + H_2O(l)$$

- This is not a redox reaction because vanadium is in the +5 oxidation state in both VO_3^-(aq) ion and VO_2^+(aq) ion.

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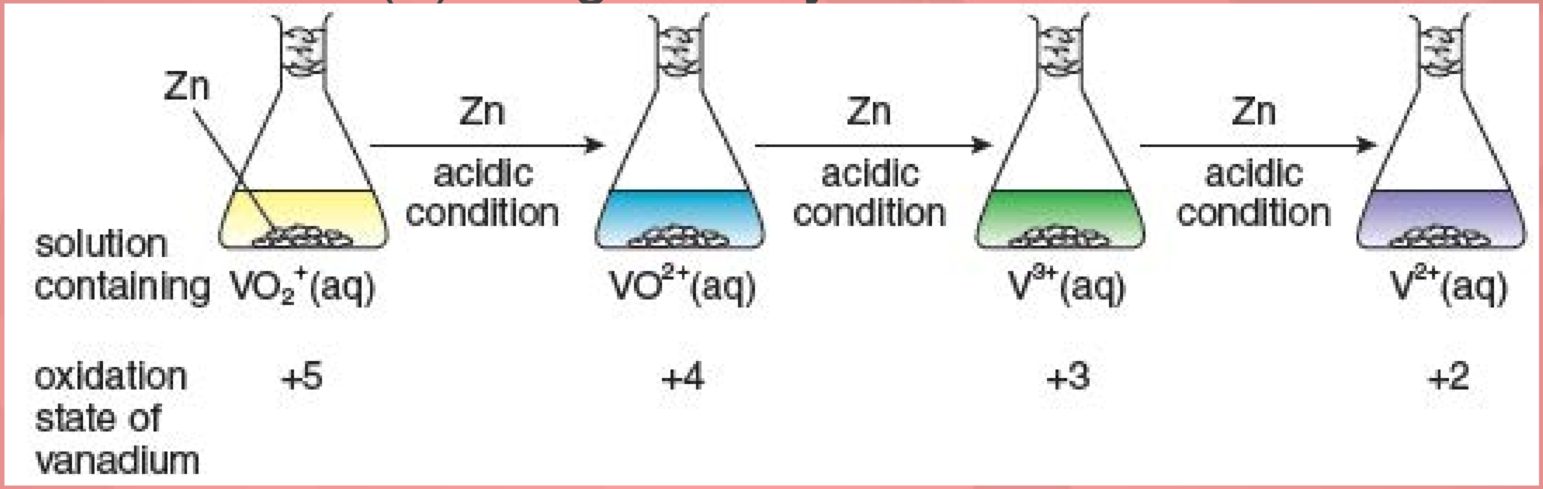
42.4 Vanadium chemistry (p.42)

- Excess zinc, in an acidic solution, reduces dioxovanadium(V) ion to vanadium(II) ion gradually.



- Green colour may be observed temporarily when the oxidation state of vanadium decreases from +5 to +4. This is simply caused by a mixture of the yellow and blue colours of the vanadium ions of these oxidation states.

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42.4 Vanadium chemistry (p.42)

Writing ionic equations for the reduction reactions

higher in electrochemical series

increasing oxidising power (↓) | increasing reducing power (↑)

$$Zn^{2+}(aq) + 2e^- \rightleftharpoons Zn(s)$$

$$V^{3+}(aq) + e^- \rightleftharpoons V^{2+}(aq)$$

$$VO^{2+}(aq) + 2H^+(aq) + e^- \rightleftharpoons V^{3+}(aq) + H_2O(l)$$

$$VO_2^+(aq) + 2H^+(aq) + e^- \rightleftharpoons VO^{2+}(aq) + H_2O(l)$$

lower in electrochemical series

Half equations relevant to the reduction of VO_2^+(aq), VO^{2+}(aq) and V^{3+}(aq) ions by zinc

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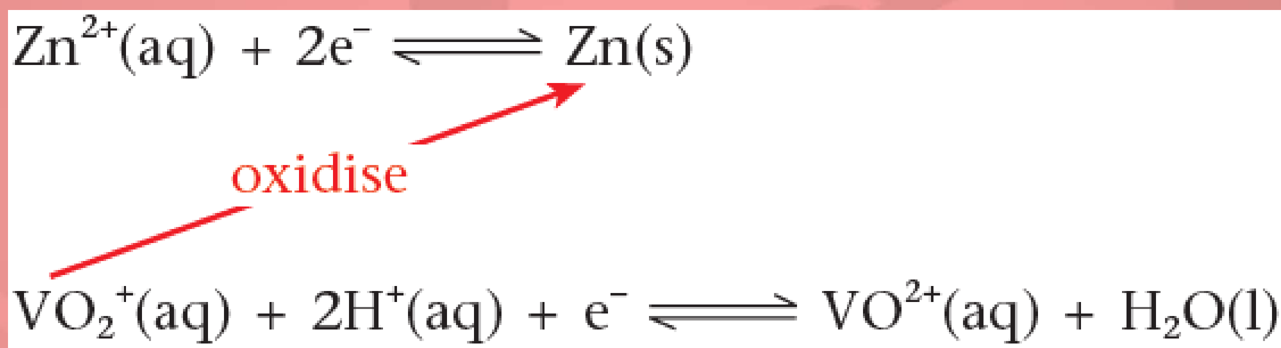
42.4 Vanadium chemistry (p.42)

Reduction of VO_2^+(aq) ion to VO^{2+}(aq) ion

- From the electrochemical series, VO_2^+(aq) ion is a stronger oxidising agent than Zn^{2+}(aq) ion. Hence it can oxidise Zn(s) to Zn^{2+}(aq) ion and is itself reduced to VO^{2+}(aq) ion.



Ionic equation for the reaction:

$$2VO_2^+(aq) + 4H^+(aq) + Zn(s) \longrightarrow 2VO^{2+}(aq) + 2H_2O(l) + Zn^{2+}(aq)$$

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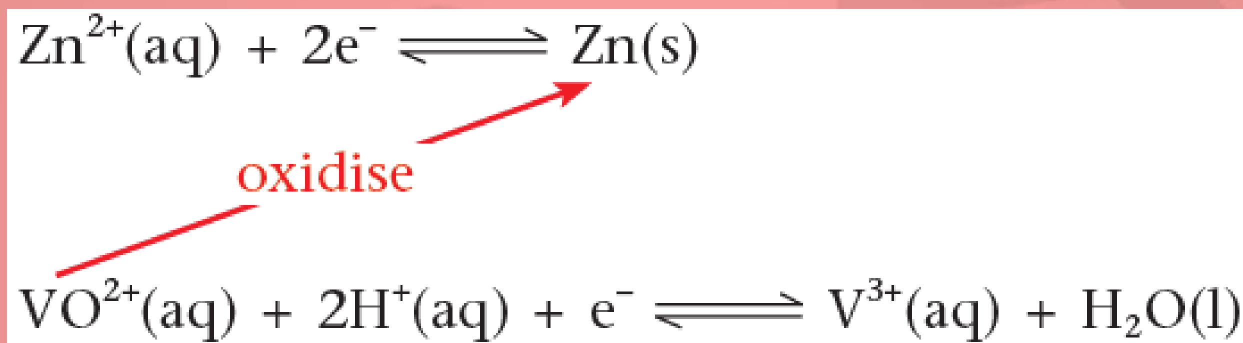
42.4 Vanadium chemistry (p.42)

Reduction of VO^{2+}(aq) ion to V^{3+}(aq) ion

- VO_2^+(aq) ion oxidises Zn(s) to Zn^{2+}(aq) ion and is itself reduced to V^{3+}(aq) ion.



Ionic equation for the reaction:

$$2VO^{2+}(aq) + 4H^+(aq) + Zn(s) \longrightarrow 2V^{3+}(aq) + 2H_2O(l) + Zn^{2+}(aq)$$

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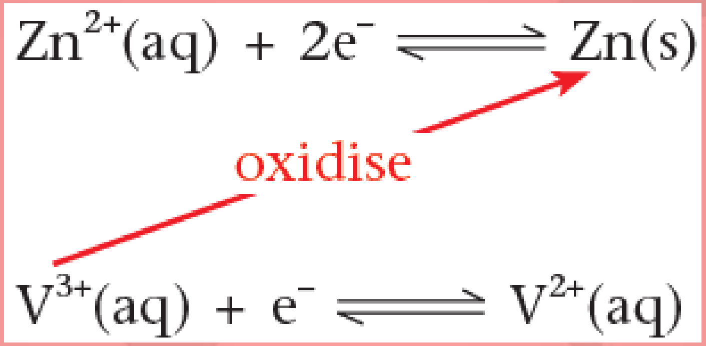
42.4 Vanadium chemistry (p.42)

Reduction of V^{3+}(aq) ion to V^{2+}(aq) ion

- V^{3+}(aq) ion oxidises Zn(s) to Zn^{2+}(aq) ion and is itself reduced to V^{2+}(aq) ion.



Ionic equation for the reaction:

$2V^{3+}(aq) + Zn(s) \longrightarrow 2V^{2+}(aq) + Zn^{2+}(aq)$

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42.4 Vanadium chemistry (p.42)

Q (Example 42.1)

In the presence of an acid, 1 mole of VO_2^+(aq) ion and 1 mole of SO_2(g) react to form SO_4^{2-}(aq) ion and one vanadium-containing chemical species.

a) By considering the amount of electrons transferred, identify the vanadium-containing species that is formed in the reaction.

b) Write the ionic equation for the reaction involved.

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42.4 Vanadium chemistry (p.42)

Q (Example 42.1) (continued)

A

a) 1 mole of $SO_2(g)$ releases 2 moles of electrons when it reacts to form $SO_4^{2-}(aq)$ ion.

$$SO_2(g) + 2H_2O(l) \longrightarrow SO_4^{2-}(aq) + 4H^+(aq) + 2e^-$$

1 mole of $VO_2^+(aq)$ ion gains 2 moles of electrons to become 1 mole of $V^{3+}(aq)$ ion.

b) Half equations relevant to the reaction:

$$SO_2(g) + 2H_2O(l) \longrightarrow SO_4^{2-}(aq) + 4H^+(aq) + 2e^-$$

$$VO_2^+(aq) + 4H^+(aq) + 2e^- \longrightarrow V^{3+}(aq) + 2H_2O(l)$$

Ionic equation for the reaction:

$$SO_2(g) + VO_2^+(aq) \longrightarrow SO_4^{2-}(aq) + V^{3+}(aq)$$

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42.4 Vanadium chemistry (p.42)

Practice 42.2

Excess zinc was added to a flask containing an acidified solution of VO_2^+(aq) ion. The flask was stoppered with some cotton wool and gently swirled. The following colour changes due to the changing oxidation states of vanadium were observed.

$$\underset{\text{(yellow)}}{VO_2^+(aq)} \xrightarrow{\textit{Reaction 1}} \underset{\text{(blue)}}{VO^{2+}(aq)} \xrightarrow{\textit{Reaction 2}} \underset{\text{(green)}}{V^{3+}(aq)} \xrightarrow{\textit{Reaction 3}} \underset{\text{(violet)}}{V^{2+}(aq)}$$

a) It was observed that the yellow solution turned green before turning blue in *Reaction 1*. Suggest why.

Both the yellow VO_2^+(aq) ion and blue VO^{2+}(aq) ion were present. This gave a green colour. (1)

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42.4 Vanadium chemistry (p.42)

Practice 42.2 (continued)

b) Write the ionic equation for the reaction between VO_2^+(aq) ion and Zn(s) to give V^{2+}(aq) ion and Zn^{2+}(aq) ion.

$$2VO_2^+(aq) + 3Zn(s) + 8H^+(aq) \longrightarrow 2V^{2+}(aq) + 3Zn^{2+}(aq) + 4H_2O(l) \quad (1)$$

c) When the cotton wool stopper was removed after consuming all the zinc, the violet solution slowly changed back to blue. Suggest why there was such a colour change.

Oxygen in the air oxidised the V^{2+}(aq) ion. (1)

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42.5 Chromium chemistry (p.46)

- Chromium can exist in three common oxidation states (+2, +3 and +6) in compounds.
- Chromium has the oxidation state of +6 in both chromate ion (CrO_4^{2-}) and dichromate ion ($Cr_2O_7^{2-}$).

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42.5 Chromium chemistry (p.46)

- In potassium dichromate solution, the dichromate ion is in equilibrium with chromate ion.

$$\underset{\text{orange}}{Cr_2O_7^{2-}(aq)} + H_2O(l) \rightleftharpoons \underset{\text{yellow}}{2CrO_4^{2-}(aq)} + 2H^+(aq)$$

- Addition of an alkali drives the equilibrium to the right by the removal of hydrogen ion. This will cause the colour of the solution to change from orange to yellow.
- Addition of an acid to an aqueous solution of chromate ion drives the equilibrium to the left, turning the colour of the solution from yellow to orange.

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42.5 Chromium chemistry (p.46)

- The dichromate ion is a powerful oxidising agent.
- The half equation below shows how it reacts with reducing agents in an acidified aqueous solution. The reduction results in the formation of the green chromium(III) ion.

$$Cr_2O_7^{2-}(aq) + 14H^+(aq) + 6e^- \longrightarrow 2Cr^{3+}(aq) + 7H_2O(l)$$

- Zinc can reduce chromium(III) ion to blue chromium(II) ion under acidic conditions.

$$Zn(s) + 2Cr^{3+}(aq) \longrightarrow Zn^{2+}(aq) + 2Cr^{2+}(aq)$$

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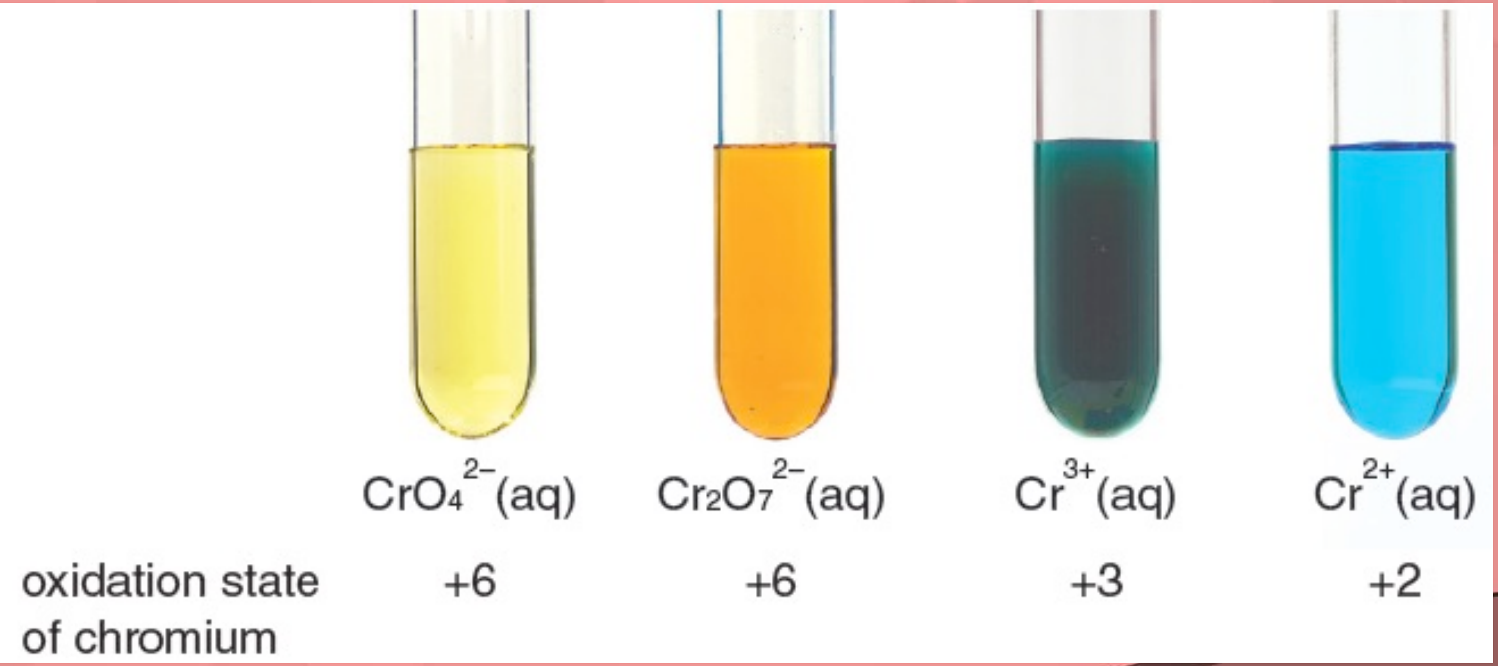
42.5 Chromium chemistry (p.46)

- Chromium(II) ion is a powerful reducing agent which is rapidly converted to chromium(III) ion by oxygen in the air. Air has to be excluded when zinc is used to reduce chromium(III) ion to chromium(II) ion.



Samples of aqueous solutions of chromium-containing ions

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42.6 Manganese chemistry (p.47)

- Manganese can exist in four common oxidation states (+2, +4, +6 and +7) in compounds.
- The most familiar manganese compound is potassium permanganate, which dissolves in water to give a deep purple solution which contains permanganate ions (MnO_4^-). Manganese has the +7 oxidation state in a permanganate ion.
- Potassium permanganate solution is commonly used as an oxidising agent in the presence of dilute sulphuric acid. Under this condition, the permanganate ion is reduced to manganese(II) ion. The purple solution is decolourised.

$$MnO_4^-(aq) + 8H^+(aq) + 5e^- \longrightarrow Mn^{2+}(aq) + 4H_2O(l)$$

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42.6 Manganese chemistry (p.47)

- In neutral or slightly alkaline conditions, the permanganate ion is reduced to black manganese(IV) oxide in which manganese has the +4 oxidation state.

$$MnO_4^-(aq) + 2H_2O(l) + 3e^- \longrightarrow MnO_2(s) + 4OH^-(aq)$$

- In very strong alkaline solutions, the permanganate ion is reduced to green manganate ion (MnO_4^{2-}) in which manganese has the +6 oxidation state.

$$MnO_4^-(aq) + e^- \longrightarrow MnO_4^{2-}(aq)$$

- Manganese(II) salts are pale pink in colour. Manganese(II) chloride and manganese(II) sulphate are prepared by reacting manganese with dilute hydrochloric acid and dilute sulphuric acid respectively.

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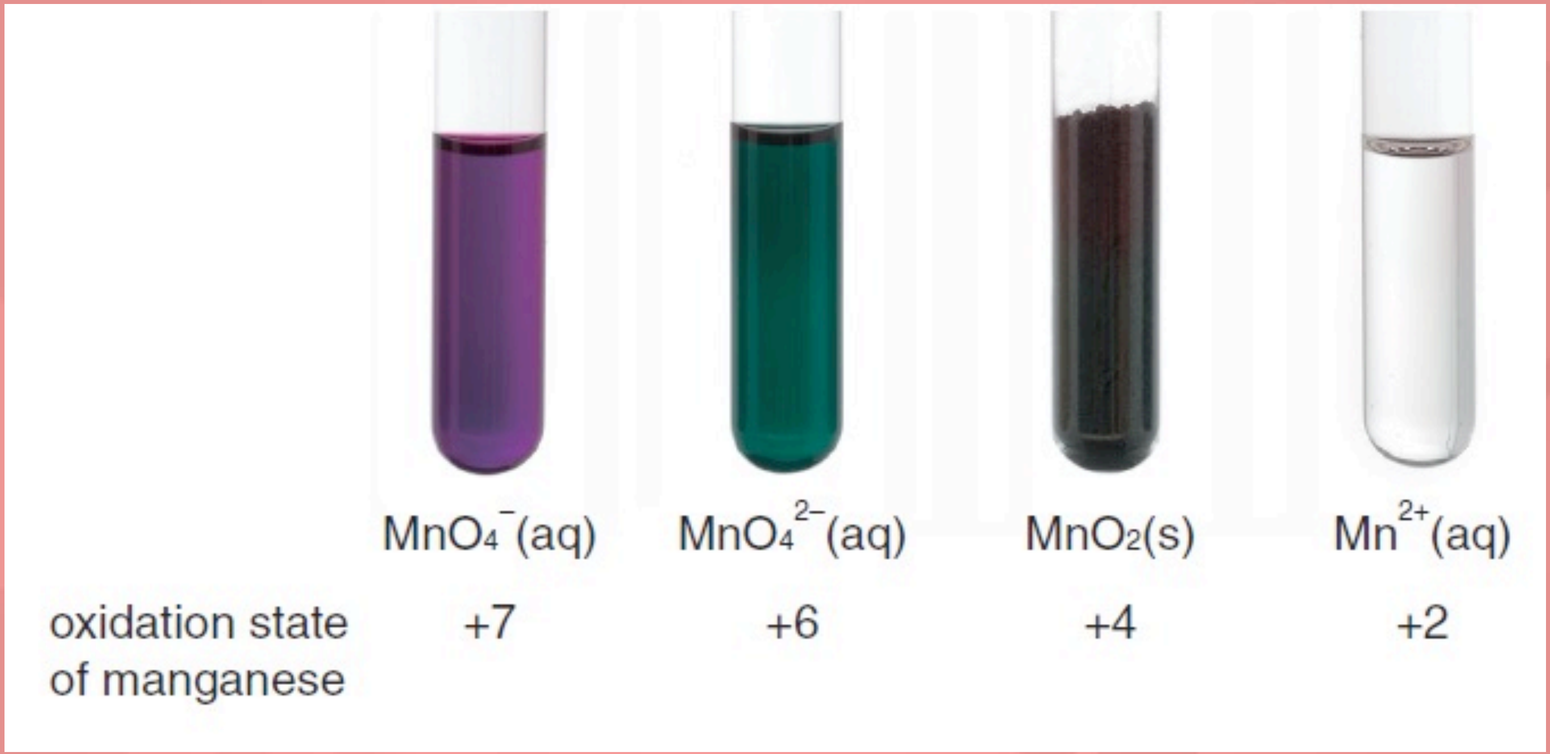
42.6 Manganese chemistry (p.47)



Samples of manganese-containing species

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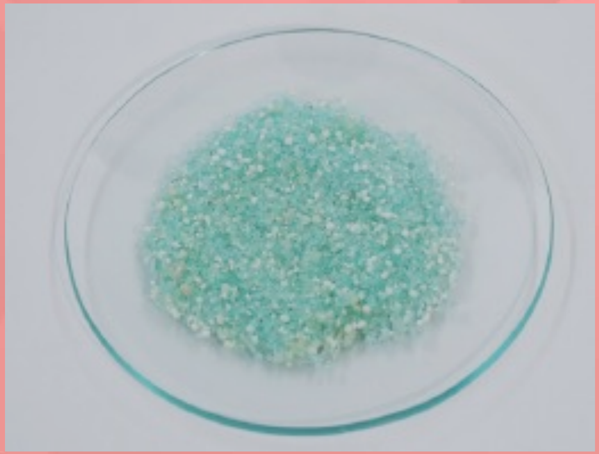
42.7 Iron chemistry (p.48)

- The two common oxidation states of iron are +2 and +3.
- Soluble iron(II) salts, such as hydrated iron(II) sulphate, are green crystalline solids which release iron(II) ions in solution.
- The solutions of iron(II) salts give a green precipitate of iron(II) hydroxide when treated with an alkali.

$$Fe^{2+}(aq) + 2OH^{-}(aq) \longrightarrow Fe(OH)_2(s)$$



Hydrated iron(II) sulphate is a green crystalline solid

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42.7 Iron chemistry (p.48)

- Aqueous solutions of iron(II) salts are common reducing agents. They are readily oxidised by oxidising agents, for example, aqueous chlorine.

$$Fe^{2+}(aq) \longrightarrow Fe^{3+}(aq) + e^-$$

A pale green aqueous solution of iron(II) salt

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42.7 Iron chemistry (p.48)

- Soluble iron(III) salts, such as hydrated iron(III) chloride, are usually yellow or brown crystalline solids which release iron(III) ions in aqueous solutions.
- The solutions of iron(III) salts give a reddish brown precipitate when treated with an alkali.

$$Fe^{3+}(aq) + 3OH^{-}(aq) \longrightarrow Fe(OH)_3(s)$$

Hydrated iron(III) chloride is a yellow crystalline solid

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42.7 Iron chemistry (p.48)

- Aqueous solutions of iron(III) salts are common oxidising agents. They are readily reduced by a variety of reducing agents, for example, iodide ion.

$$Fe^{3+}(aq) + e^{-} \longrightarrow Fe^{2+}(aq)$$

A yellow-brown aqueous solution of iron(III) salt

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42.7 Iron chemistry (p.48)

Practice 42.3

1 Potassium and iron are Period 4 elements.

a) State TWO differences in their physical properties.

Any two of the following:

- Iron is harder.
- Iron has a higher melting point / boiling point.
- Iron has a higher density.

b) State TWO differences in their chemical properties.

Any two of the following:

- Potassium reacts with cold water; iron does not.
- Potassium has one oxidation state; iron has more than one.
- Potassium forms white or colourless compounds; iron forms coloured compounds.
- Iron and its compounds are catalysts; potassium and its compounds are not.

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42.7 Iron chemistry (p.48)

Practice 42.3 (continued)

2 In the absence of air, excess zinc can reduce dichromate ion to chromium(III) ion under acidic conditions. Then the chromium(III) ion changes further to chromium(II) ion.

a) Describe the colour change that you would observe when dichromate ion is reduced to chromium(III) ion.

From orange to green

b) Write the ionic equation for the reaction between $Cr_2O_7^{2-}(aq)$ ion and Zn(s) to give $Cr^{2+}(aq)$ ion and $Zn^{2+}(aq)$ ion.

$$Cr_2O_7^{2-}(aq) + 14H^+(aq) + 4Zn(s) \longrightarrow 2Cr^{2+}(aq) + 4Zn^{2+}(aq) + 7H_2O(l)$$

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42.8 Transition metals and their compounds as catalysts (p.50)

- Catalysts affect the rate of a reaction without undergoing any permanent chemical changes themselves.
- Transition metals and their compounds are used as catalysts to improve the profits of industrial processes.
- A catalyst reduces the time required to make a product. It also allows a reaction to proceed at a lower temperature and pressure, thus saving valuable energy resources.
- The exhaust system of modern cars has a catalytic converter coated with platinum, rhodium, and sometimes palladium. These metals act as catalysts to help the conversion of carbon monoxide, nitrogen oxides and unburnt petrol to carbon dioxide, nitrogen and water.

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42.8 Transition metals and their compounds as catalysts (p.50)

The Haber process

- The **Haber process (哈柏法)** is used to make ammonia from the reaction between nitrogen and hydrogen.
- The catalyst for the process is iron in finely ground powder form in order to increase the surface area.

$$N_2(g) + 3H_2(g) \underset{450\ ^\circ C,\ 250\ atm}{\overset{\text{Fe catalyst}}{\rightleftharpoons}} 2NH_3(g)$$

- Much of the ammonia produced in the Haber process is used in manufacturing agricultural fertilisers.

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42.8 Transition metals and their compounds as catalysts (p.50)

The Contact process

- The **Contact process (接觸法)** produces a vital industrial chemical — sulphuric acid.
- The key stage in the process involves converting sulphur dioxide into sulphur trioxide:

$$2SO_2(g) + O_2(g) \xrightleftharpoons[450\ ^\circ C,\ 1\ atm]{V_2O_5\ catalyst} 2SO_3(g)$$

This is catalysed by vanadium(V) oxide.

Vanadium(V) oxide is used as a catalyst in the Contact process

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42.8 Transition metals and their compounds as catalysts (p.50)

- Sulphuric acid is an important inorganic chemical with many uses including the production of fertilisers, detergents, adhesives and explosives, and also as the electrolyte in car batteries.

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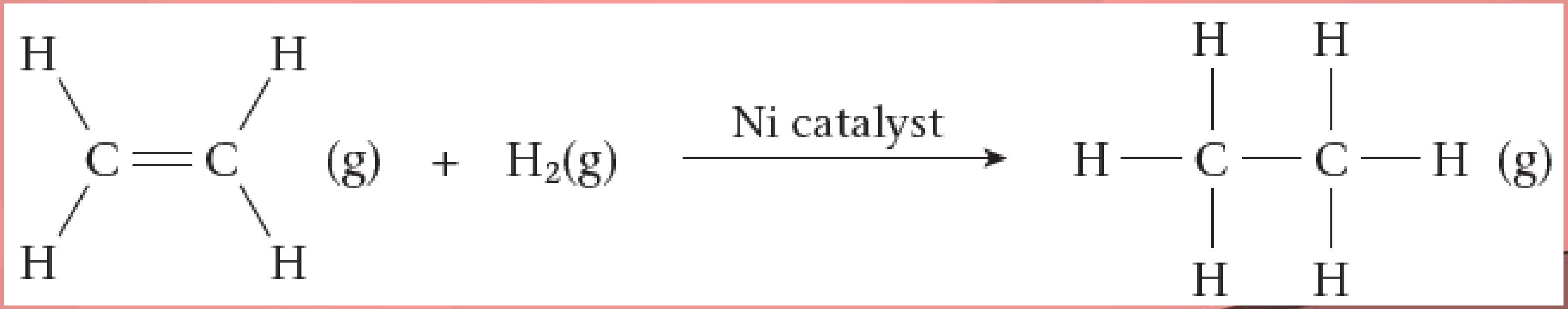
42.8 Transition metals and their compounds as catalysts (p.50)

Hydrogenation of alkenes

- Unsaturated compounds can be made into saturated compounds by adding hydrogen across the carbon-carbon double bonds of the unsaturated compounds. The process is called hydrogenation.
- For example, the hydrogenation of ethene produces ethane. The catalyst used is nickel metal.



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42.8 Transition metals and their compounds as catalysts (p.50)

- Saturated vegetable fats are solid at room temperature and have a higher melting point than unsaturated vegetable oils. Hence saturated vegetable fats are more suitable for making margarine.
- Unsaturated vegetable oils can be 'hardened' to form saturated vegetable fats by reacting them with hydrogen.

Margarine

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42.8 Transition metals and their compounds as catalysts (p.50)

Autocatalysis

- A chemical reaction is said to have undergone **autocatalysis (自催化作用)** if a reaction product acts as a catalyst for that reaction.
- Typically the reaction starts slowly and then speeds up as the products are formed.

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42.8 Transition metals and their compounds as catalysts (p.50)

Reaction of permanganate ion and ethanedioate ion

- A common example of autocatalysis is the reaction between permanganate ion and ethanedioate ion under acidic conditions.

$$2MnO_4^-(aq) + 5C_2O_4^{2-}(aq) + 16H^+(aq) \longrightarrow 2Mn^{2+}(aq) + 10CO_2(g) + 8H_2O(l)$$

- The reaction between permanganate ion and ethanedioate ion is slow initially as the two negative ions repel each other. However, the reaction is catalysed by the manganese(II) ion formed in the reaction. The reaction rate increases dramatically as manganese(II) ion is formed.

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42.8 Transition metals and their compounds as catalysts (p.50)

- The manganese(II) ion catalyses the reaction in two steps:
  - The manganese(II) ion reduces the permanganate ion to manganese(III) ion.
    $4Mn^{2+}(aq) + MnO_4^{-}(aq) + 8H^{+}(aq) \longrightarrow 5Mn^{3+}(aq) + 4H_2O(l)$
  - The manganese(III) ion then oxidises the ethanedioate ion to carbon dioxide. You can also find manganese(II) ions amongst the products.
    $2Mn^{3+}(aq) + C_2O_4^{2-}(aq) \longrightarrow 2Mn^{2+}(aq) + 2CO_2(g)$
- The colour intensity of the reaction mixture decreases as the reaction proceeds because permanganate ion is purple in colour while manganese(II) ion is pale pink.

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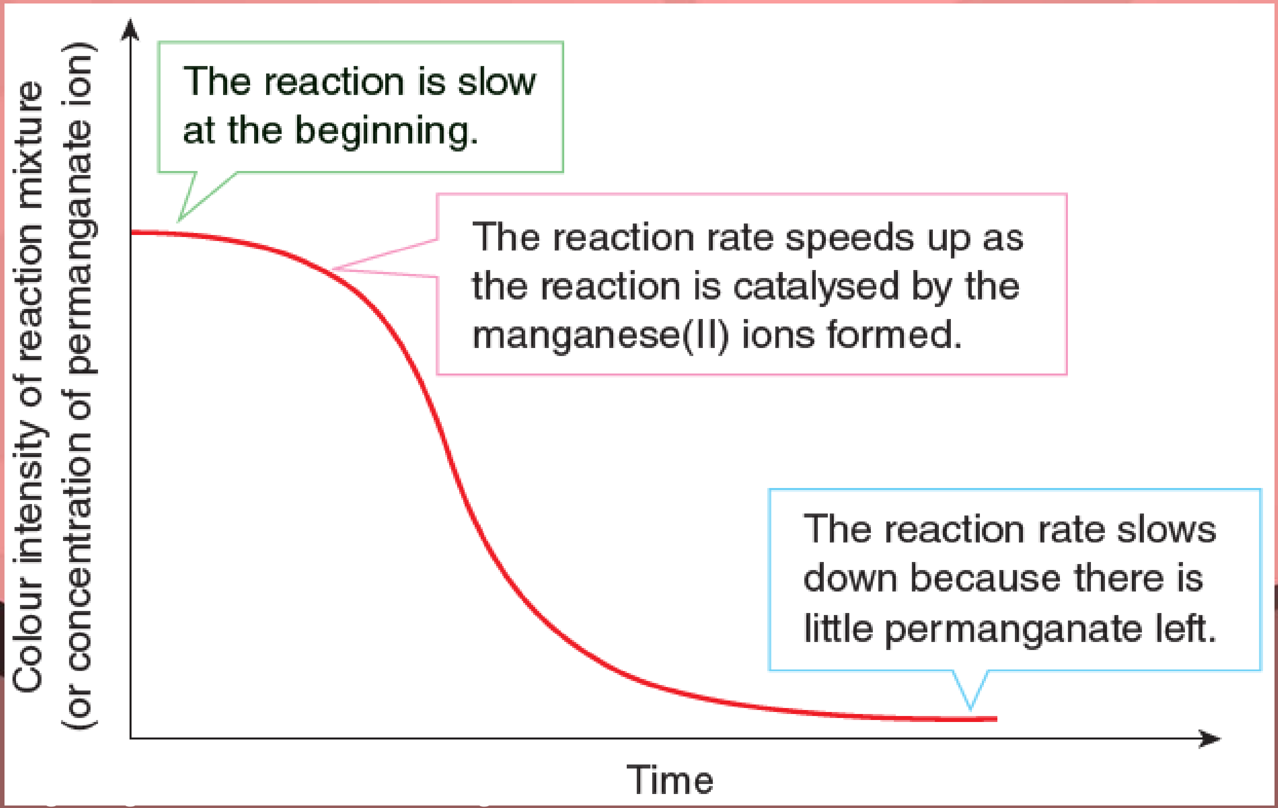
42.8 Transition metals and their compounds as catalysts (p.50)

- A graph of the colour intensity of the reaction mixture against time looks like the one shown in the figure below. The colour intensity is proportional to the concentration of permanganate ion in the reaction mixture.



42.8 Transition metals and their compounds as catalysts (p.50)

- In the above example, the ion of manganese can act as a catalyst as manganese has variable oxidation states. The ability to change oxidation state is important for a transition metal or its ion to act as a catalyst.
- Group I and II metals are not able to act as catalysts as they do not have variable oxidation states in their compounds.

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42.8 Transition metals and their compounds as catalysts (p.50)

Practice 42.4

A student conducted an experiment to study the reaction between $MnO_4^-(aq)$ ion and $C_2O_4^{2-}(aq)$ ion under acidic conditions.

$$2MnO_4^-(aq) + 5C_2O_4^{2-}(aq) + 16H^+(aq) \longrightarrow 2Mn^{2+}(aq) + 10CO_2(g) + 8H_2O(l)$$

a) Name an equipment that could be used to monitor the concentration of $MnO_4^-(aq)$ ion in the reaction mixture.

Colorimeter

b) The reaction between $MnO_4^-(aq)$ ion and $C_2O_4^{2-}(aq)$ ion is an example of a reaction that is autocatalysed.

i) Give the meaning of the term 'autocatalysed'.

A reaction product as a catalyst for a reaction.

ii) Identify the autocatalyst in this reaction.

Manganese(II) ion

iii) Suggest how the student could show that the chemical species identified in (ii) is a catalyst for the reaction.

Repeat the experiment with a few drops of $Mn^{2+}(aq)$ ion firstly added to the reaction mixture. Consumption of $MnO_4^-(aq)$ ion will be faster at the beginning if $Mn^{2+}(aq)$ ion is a catalyst.

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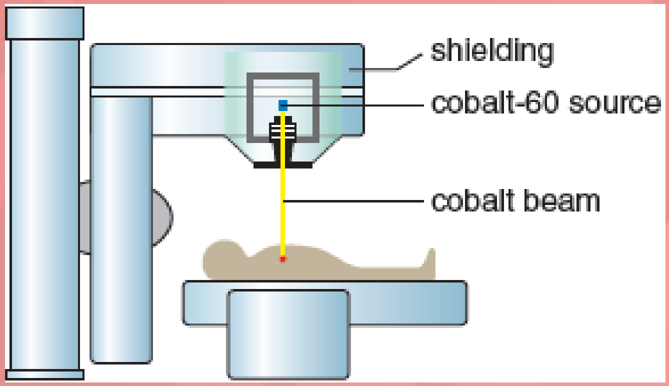
42.9 Transition metals in medical applications (p.55)

Radioactive isotopes of transition metals

- Radioactive isotopes of transition metals have many medical applications. For example, cobalt-60 is extensively employed as a radiation source to treat cancer.



Cobalt-60 can be used to treat cancer

- Technetium-99 is used as a biological tracer, helping doctors find hidden tumors in the body. It is injected into a body and included into a protein that is capable of binding to cancer cells.

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42.9 Transition metals in medical applications (p.55)

Compounds of transition metals in drugs

- Many transition metals are toxic when overdosed. Hence there are only a few examples of them being used for pharmaceutical purposes.
- An example is zinc ethanoate used in the treatment of Wilson's disease, which involves the accumulation of copper in the body. Zinc ethanoate helps to hinder the absorption of copper in the digestive system.
- Recent studies show that vanadium(IV) sulphate may be effective in treating type 2 diabetes.

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Key terms (p.58)

oxidation state	氧化態	Contact process	接觸法
dioxovanadium(V) ion	二氧合釩(V)離子	autocatalysis	自催化作用
oxovanadium(V) ion	氧合釩(IV) 離子	radioactive isotope	放射性同位素
Haber process	哈柏法	trace element	微量元素

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Summary (p.59)

1 Transition metals have certain common physical properties:

- high melting points and boiling points;
- high densities;
- shiny in appearance;
- can conduct both electricity and heat;
- hard and rigid.

2 Typical chemical properties of most transition metals include:

- They exhibit variable oxidation states in their compounds.
- They form coloured compounds.
- The elements and their compounds can act as catalysts.

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Summary (p.59)

3 The following table lists the colours of aqueous ions of some transition metals:

Titanium	Vanadium	Chromium	Manganese	Iron	Cobalt	Nickel	Copper
Ti^{3+}(aq) purple	V^{3+}(aq) green	Cr^{3+}(aq) green	Mn^{2+}(aq) pale pink	Fe^{2+}(aq) pale green	Co^{2+}(aq) pink	Ni^{2+}(aq) green	Cu^{2+}(aq) blue
		CrO_4^{2-}(aq) yellow	MnO_4^-(aq) purple	Fe^{3+}(aq) yellow-brown			
		$Cr_2O_7^{2-}$(aq) orange					

4 The following reductions occur when a solution containing dioxovanadium(V) ion (VO_2^+(aq)) is shaken with zinc powder under acidic conditions.

	+5		+4		+3		+2
	VO_2^+(aq)	⟶	VO^{2+}(aq)	⟶	V^{3+}(aq)	⟶	V^{2+}(aq)
Name	dioxovanadium(V) ion		oxovanadium(IV) ion		vanadium(III) ion		vanadium(II) ion
Colour	yellow		blue		green		violet

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Summary (p.59)

5 Dichromate ion is a powerful oxidising agent in acidic solution. In the presence of a reducing agent, dichromate ion is reduced to chromium(III) ion.

$$\overset{+6}{Cr_2O_7^{2-}(aq)} + 14H^+(aq) + 6e^- \longrightarrow \overset{+3}{2Cr^{3+}(aq)} + 7H_2O(l)$$

orange → green

6 Permanganate ion is a powerful oxidising agent. In the presence of dilute sulphuric acid and a reducing agent, permanganate ion is reduced to manganese(II) ion.

$$\overset{+7}{MnO_4^-(aq)} + 8H^+(aq) + 5e^- \longrightarrow \overset{+2}{Mn^{2+}(aq)} + 4H_2O(l)$$

purple → pale pink

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Summary (p.59)

7 The following table lists examples in which transition metals and their compounds act as catalysts.

Catalyst	Reaction catalysed
Iron (Fe)	<u>Haber process</u> $N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$
Vanadium(V) oxide (V_2O_5)	<u>Contact process</u> $2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)$
Nickel (Ni)	<u>Hydrogenation of alkenes</u> $C_2H_4(g) + H_2(g) \longrightarrow C_2H_6(g)$

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Summary (p.59)

8 The reaction between permanganate ion and ethanedioate ion under acidic conditions is an example of autocatalysis.

$$2MnO_4^-(aq) + 5C_2O_4^{2-}(aq) + 16H^+(aq) \longrightarrow 2Mn^{2+}(aq) + 10CO_2(g) + 8H_2O(l)$$

The reaction is catalysed by the manganese(II) ion formed in the reaction. The reaction is slow initially. The reaction rate increases dramatically as manganese(II) ion is formed.

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Unit Exercise (p.61)

Note: Questions are rated according to ascending level of difficulty (from 1 to 5):

👍 **question targeted at level 3 and above;**
👍👍 **question targeted at level 4 and above;**
👍👍👍 **question targeted at level 5.**
‘ * ’ indicates 1 mark is given for effective communication.

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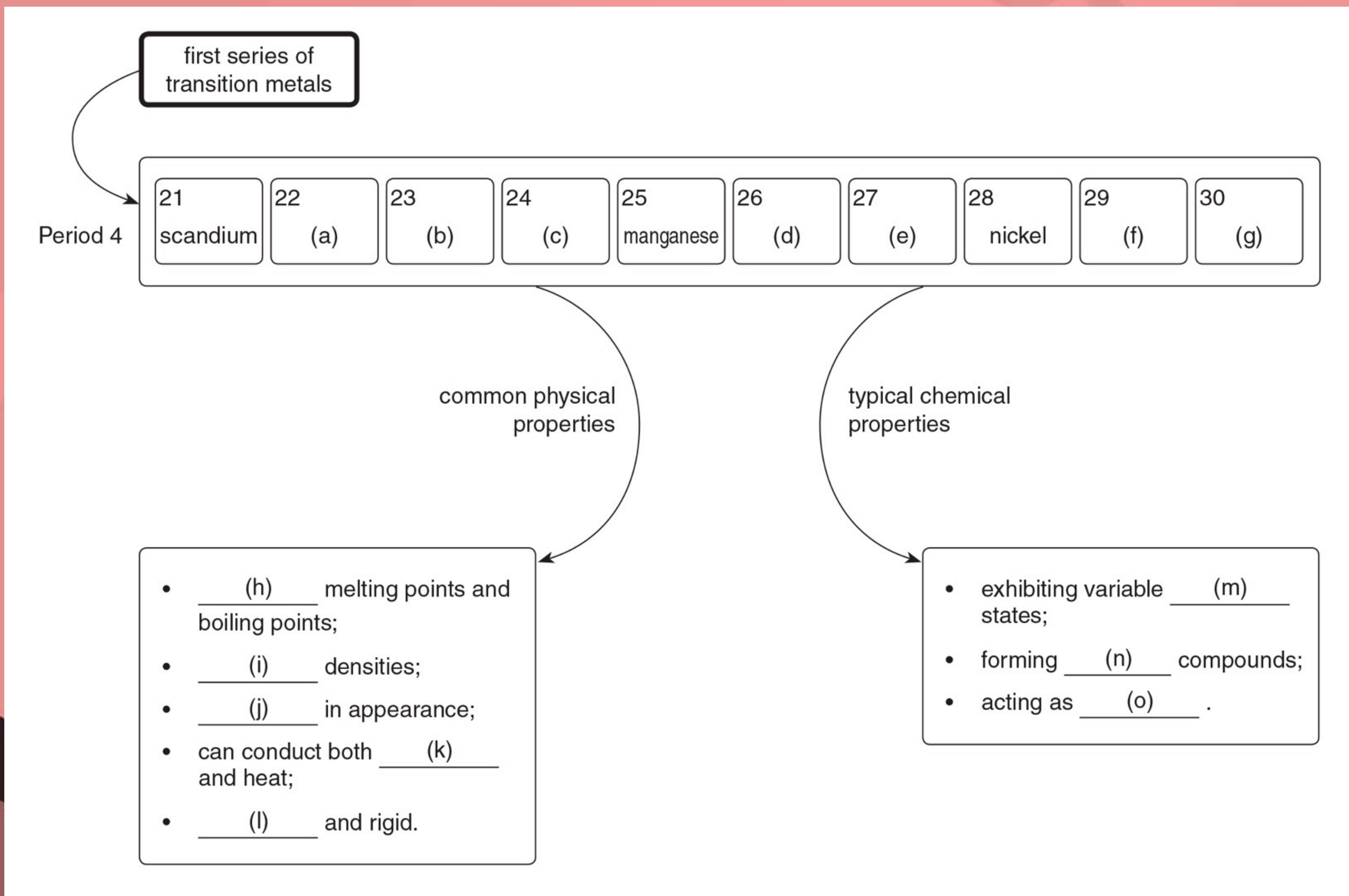
Unit Exercise (p.61)

PART I KNOWLEDGE AND UNDERSTANDING

1 Complete the following concept map.



a) titanium
b) vanadium
c) chromium
d) iron
e) cobalt
f) copper
g) zinc
h) high
i) high
j) shiny
k) electricity
l) hard
m) oxidation
n) coloured
o) catalysts

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Unit Exercise (p.61)

PART II MULTIPLE CHOICE QUESTIONS

2 The table below lists the information of four elements W, X, Y and Z (the letters are NOT symbols of the elements).

Element	Electrical conductivity	Density ($g\ cm^{-3}$)	Melting point (°C)
W	good	7.89	1 540
X	good	0.89	98
Y	poor	2.33	7
Z	poor	3.58	1 620

Which letter shows the element which is a transition metal?

A W

B X

C Y

D Z

Answer: A

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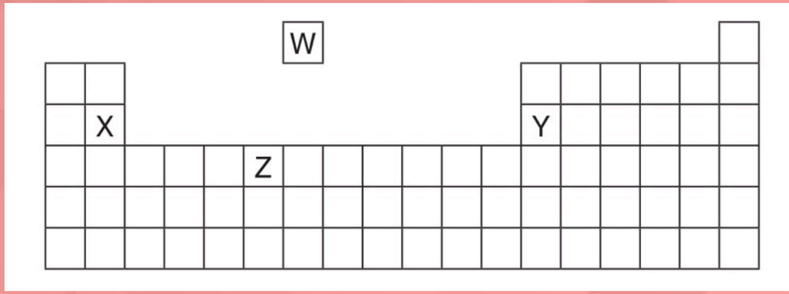
Unit Exercise (p.61)

3 The positions of four elements in the Periodic Table are shown by the letters W, X, Y and Z (the letters are NOT symbols of the elements).



Which letter shows the position of the element which forms a coloured oxide?

A W
B X
C Y
D Z

Answer: D

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Unit Exercise (p.61)

4 Which of the following chemical species does NOT exist?

A $Mn^{7+}(aq)$
B $V^{3+}(aq)$
C $Sc_2O_3(s)$
D $TiCl_4(l)$

Answer: A

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Unit Exercise (p.61)

5 Which of the following is NOT a characteristic property of transition metals?

A They form coloured compounds.
B They exhibit variable oxidation numbers in their compounds.
C They react with dilute hydrochloric acid to give hydrogen gas.
D They exhibit catalytic property in elemental state or as compounds.

Answer: C

(HKDSE, Paper 1A, 2013, 26)

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Unit Exercise (p.61)

6 In which of the following lists are the transition metals all in the +6 oxidation state?

A	$KMnO_4$	K_2CrO_4	K_3CoO_4
B	$K_2Cr_2O_7$	KVO_3	K_2MnO_4
C	K_2MnO_4	$K_2Cr_2O_7$	K_2FeO_4
D	K_2FeO_4	K_3CoO_4	KVO_3

Answer: C

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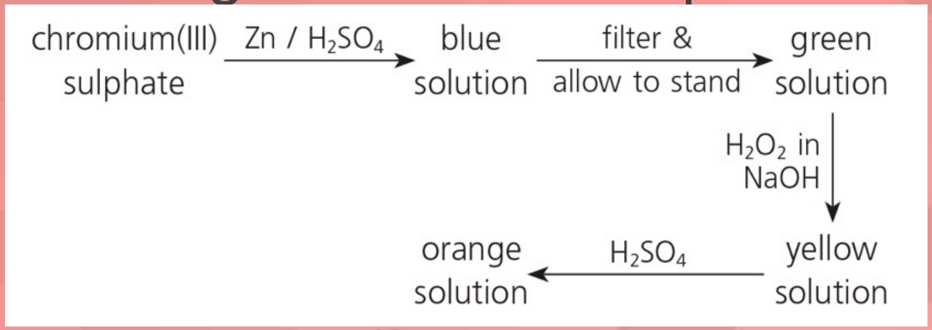
Unit Exercise (p.61)

7 The diagram below summarises a sequence of reactions involving chromium compounds.



How many different oxidation states of chromium are involved in this sequence?

A 2

B 3

C 4

D 5

Explanation:

Blue solution contains Cr^{2+}(aq) ions.

Green solution contains Cr^{3+}(aq) ions.

Yellow solution contains CrO_4^{2-}(aq) ions.

Answer: B

(Edexcel International Advanced Level, Unit 5, Jan. 2015, 11)

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Unit Exercise (p.61)

8 Which of the following statements concerning manganese is correct?

A Mn^{2+}(aq) ion is pale pink in colour.
B The oxidation state of manganese in MnO_4^{2-} is +7.
C MnO_4^-(aq) ion is a good reducing agent.
D Manganese is found as a free metal in nature.

Answer: A

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Unit Exercise (p.61)

9 Which of the following statements concerning iron is correct?

A Fe^{2+}(aq) ion gives a reddish brown precipitate when mixed with NaOH(aq).
B Fe^{3+}(aq) ion is pale green in colour.
C Iron has a high density.
D Iron belongs to Period 5 of the Periodic Table.

Answer: C

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Unit Exercise (p.61)

10 Copper metal is oxidised to Cu^{2+} by nitrate ions which are reduced to nitrogen monoxide, NO.

By considering the changes to the oxidation numbers of copper and nitrogen, it can be deduced that in this reaction

A 2 mol of copper reacts with 3 mol of nitrate ions.
B 2 mol of copper reacts with 5 mol of nitrate ions.
C 3 mol of copper reacts with 2 mol of nitrate ions.
D 3 mol of copper reacts with 2 mol of nitrate ions.

(Edexcel Advanced Level GCE, Unit 5, Jun. 2014, 2)

Explanation:
The ions ionic equation for the reaction between copper and nitrate ions is shown below.

$$3Cu(s) + 2NO_3^-(aq) + 8H^+(aq) \longrightarrow 3Cu^{2+}(aq) + 2NO(g) + 4H_2O(l)$$

Answer: C

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Unit Exercise (p.61)

11 In which of the following reactions is the transition metal species NOT acting as a catalyst?

A Action of Ni(s) on a mixture of $H_2C{=}CH_2$(g) and H_2(g) at high temperature

B Action of Pt(s) on a mixture of CO(g) and O_2(g) at high temperature

C Action of V_2O_5(s) on a mixture of SO_2(g) and O_2(g) at high temperature

D Action of Fe^{3+}(aq) on SO_3^{2-}(aq) at room temperature

Answer: D

Explanation:

SO_3^{2-}(aq) can reduce Fe^{3+}(aq) to Fe^{2+}(aq).

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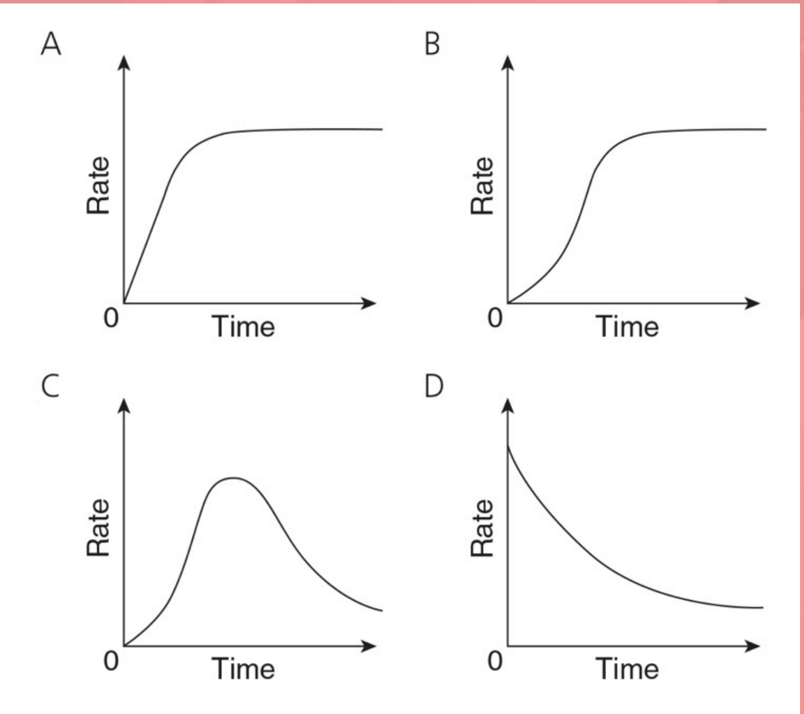
Unit Exercise (p.61)

12 An autocatalytic reaction is a reaction in which one of the products catalyses the reaction.
Which curve was obtained if the rate of reaction was plotted against time for an autocatalytic reaction?



Answer: C

(Cambridge International Examinations GCE 9701/11, Paper 1, Oct. 2013, 5)

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Unit Exercise (p.61)

13 Which of the following salts form coloured solutions when dissolved in water?

(1) $ScCl_3$
(2) $FeCl_3$
(3) $NiCl_2$

A (1) and (2) only
B (1) and (3) only
C (2) and (3) only
D (1), (2) and (3)

Answer: C

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Unit Exercise (p.61)

14 Which of the following statements concerning cobalt are correct?

(1) Cobalt has a high melting point.
(2) Co^{2+}(aq) ion is blue in colour.
(3) Co-60 is radioactive.

A (1) and (2) only
B (1) and (3) only
C (2) and (3) only
D (1), (2) and (3)

Answer: B

Explanation:
(2) Co^{2+}(aq) ion is pink in colour.

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Unit Exercise (p.61)

15 Which of the following processes can illustrate the characteristics of transition metals?

(1) Mixing $AgNO_3(aq)$ and NaCl(aq)
(2) Mixing $FeSO_4(aq)$ and $Br_2(aq)$
(3) Mixing $CuSO_4(s)$ and $H_2O(l)$

A (1) only
B (2) only
C (1) and (3) only
D (2) and (3) only

Answer: D

(HKDSE, Paper 1A, 2018, 32)

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Unit Exercise (p.61)

PART III STRUCTURED QUESTIONS

16 Give the oxidation state of the transition metal in each of the following chemical species.

a) $[Cr(OH)_6]^{3-}$

+3 (1)

b) $K_3Fe(CN)_6$

+3 (1)

c) NH_4VO_3

+5 (1)

d) $[Co(NH_3)_6]^{2+}$

+2 (1)

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Unit Exercise (p.61)

17 Potassium permanganate and potassium dichromate are both used as oxidising agents in acidic solutions.

a) Write an ionic equation for the reaction between

i) $KMnO_4$(aq) and $FeSO_4$(aq) in dilute H_2SO_4(aq);

$MnO_4^-(aq) + 8H^+(aq) + 5Fe^{2+}(aq) \longrightarrow Mn^{2+}(aq) + 4H_2O(l) + 5Fe^{3+}(aq)$ (1)

ii) $K_2Cr_2O_7$(aq) and SO_2(g) in dilute H_2SO_4(aq).

$MnO_4^-(aq) + 8H^+(aq) + 5Fe^{2+}(aq) \longrightarrow Mn^{2+}(aq) + 4H_2O(l) + 5Fe^{3+}(aq)$ (1)

b) What colour changes would you observe when each of these oxidising agents is completely reduced?

i) $KMnO_4$

From purple to colourless (1)

ii) $K_2Cr_2O_7$

From orange to green (1)

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Unit Exercise (p.61)

18 Chromium metal and its compounds have a number of important uses.

a) State ONE use of chromium and explain why chromium is suitable for this purpose.

Any one of the following:

- Stainless steel; corrosion resistant (1)
- Alloys / making tools; very hard (1)
- Chrome plating; prevents rusting / corrosion (1)

b) $Cr_2O_7^{2-}$ ion and CrO_4^{2-} ion are both oxidising agents. They exist in the following equilibrium.

$$2CrO_4^{2-}(aq) + 2H^+(aq) \rightleftharpoons Cr_2O_7^{2-}(aq) + H_2O(l)$$

i) Show that this equilibrium does NOT represent a redox reaction.

No change in oxidation number (1)

ii) What colour change occurs in the forward reaction?

From yellow to orange (1)

iii) What reagent would you add to reverse the colour change stated in (ii)?

Adding an alkali (e.g. NaOH) (1)

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Unit Exercise (p.61)

19 Vanadium is a transition metal.

a) Complete the table below by giving the colours and oxidation states of some aqueous vanadium-containing ions.

Ion	Colour	Oxidation state
$V^{2+}(aq)$	+2 (1)	violet (1)
$VO_2^+(aq)$	+5 (1)	yellow (1)
$VO^{2+}(aq)$	+4 (1)	blue (1)
$V^{3+}(aq)$	+3 (1)	green (1)

b) In an acidic solution containing excess KI(aq), 1.0 mole of $VO^{2+}(aq)$ ion reacted with only 1.0 mole of KI(aq), forming $I_2(aq)$ and one of the above vanadium-containing ions.

i) By considering the amount of electrons transferred, identify the vanadium-containing ion formed.

1 mole of $VO_2^+(aq)$ ions gains 1 mole of electrons from 1 mole of KI(aq) to form 1 mole of <u>$VO^{2+}(aq)$ ions</u>. (1)

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Unit Exercise (p.61)

19 (continued)

b) ii) Write the ionic equation for the reaction involved.

$$2VO_2^{+}(aq) + 4H^{+}(aq) + 2I^{-}(aq) \longrightarrow 2VO^{2+}(aq) + I_2(aq) + 2H_2O(l) \quad (1)$$

iii) Hence compare the reducing power of $I^{-}(aq)$ ion with $V^{3+}(aq)$ ion and $VO^{2+}(aq)$ ion, and fill in the spaces provided below.

$V^{3+}(aq)$ > $I^{-}(aq)$ > $VO^{2+}(aq)$ (1)

decreasing reducing power →

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Unit Exercise (p.61)

20 Iron is a typical transition metal.

a) i) State ONE reason why transition metals are good catalysts.

They have variable oxidation states. (1)

ii) State ONE example of iron or a compound of iron being used as a catalyst in industry.

In Haber process (1)

b) Describe how dilute sodium hydroxide solution can be used to distinguish between iron(II) sulphate solution and iron(III) sulphate solution.

Iron(II) sulphate solution gives a green precipitate. (1)
Iron(III) sulphate solution gives a reddish brown precipitate. (1)

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Unit Exercise (p.61)

20 (continued)

c) Under certain conditions, iron can be oxidised to form sodium ferrate, Na_2FeO_4. This is a red-purple coloured substance that has properties very similar to that of potassium permanganate.

Deduce the oxidation state of iron in sodium ferrate, Na_2FeO_4.

+6 (1)

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Unit Exercise (p.61)

20 (continued)

d) The half equation for the reduction of ferrate ion, FeO_4^{2-}, in acidic conditions is shown below.

$$FeO_4^{2-}(aq) + 8H^+(aq) + 4e^- \longrightarrow Fe^{2+}(aq) + 4H_2O(l)$$

Acidified FeO_4^{2-}(aq) ion can oxidise I^-(aq) ion.

i) Write the ionic equation for the redox reaction that occurs between FeO_4^{2-}(aq) and I^-(aq) ions in the presence of H^+(aq) ion.

$$FeO_4^{2-}(aq) + 8H^+(aq) + 4I^-(aq) \longrightarrow Fe^{2+}(aq) + 4H_2O(l) + 2I_2(aq) \quad (1)$$

ii) Predict the colour of the mixture when FeO_4^{2-}(aq) ion is added to an excess of I^-(aq) ion in the presence of H^+(aq) ion.

Orange / yellow / brown (1)

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Unit Exercise (p.61)

21 High-strength low-alloy steels are used to fabricate TV masts. They contain about 1% copper to improve resistance to atmospheric corrosion. When dissolved in nitric acid, a sample of this steel gives a pale blue solution.

a) What chemical species is responsible for the pale blue colour?

Cu^{2+}(aq) ion (1)

b) Describe and explain what you would observe when dilute aqueous ammonia is added to this solution until in excess.

Pale blue precipitate of $Cu(OH)_2$(s) dissolves to give a deep blue solution, (1)
containing $[Cu(NH_3)_4]^{2+}$(aq) ions. (1)

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Unit Exercise (p.61)

22 An acidified solution of ammonium metavanadate undergoes a series of reduction reactions where it is stirred with zinc.

a) Complete the table below, giving the colours of VO^{2+}(aq) and V^{3+}(aq) ions formed at different stages.

Ion	Colour
VO_2^{+}(aq)	yellow
VO^{2+}(aq)	blue (1)
V^{3+}(aq)	green (1)
V^{2+}(aq)	violet

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Unit Exercise (p.61)

22 (continued)

b) Chromium will also reduce VO^{2+}(aq) ion. In the presence of an acid, 3 moles of VO^{2+}(aq) ion and 1 mole of Cr(s) react to form Cr^{3+}(aq) ion and one vanadium-containing species.

i) By considering the amount of electrons transferred, identify the vanadium-containing species that is formed in the reaction.

3 moles of VO_2^{+}(aq) ions gain 3 moles of electrons from 1 mole of Cr(s) to form 3 moles of VO^{2+}(aq) ions. (1)

ii) Write the equation for the reaction involved.

$$3VO_2^{+}(aq) + 6H^+(aq) + Cr(s) \longrightarrow 3VO^{2+}(aq) + 3H_2O(l) + Cr^{3+}(aq) \quad (1)$$

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Unit Exercise (p.61)

23 Compound A is a green solid containing one cation and one anion. It dissolves in water to form a green solution.

a) A student adds dilute sodium hydroxide solution, drop by drop, to an aqueous solution of A. A green precipitate is formed, which does not dissolve in excess sodium hydroxide solution.

i) Give the formula of the cation in A.

Fe^{2+} (1)

ii) Give a chemical formula for the green precipitate.

$Fe(OH)_2$ (1)

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Unit Exercise (p.61)

23 (continued)

b) The student adds a few drops of acidified potassium permanganate solution to another sample of a solution of A in a test tube.

i) State the colour change that occurs.

From purple to colourless (1)

ii) Write the ionic equation for the reaction involved.

$$MnO_4^-(aq) + 8H^+(aq) + 5Fe^{2+}(aq) \longrightarrow Mn^{2+}(aq) + 4H_2O(l) + 5Fe^{3+}(aq) \quad (1)$$

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Unit Exercise (p.61)

23 (continued)

c) The student acidifies 2 cm^3 of a solution of A with dilute nitric acid in a test tube and then adds a few drops of aqueous silver nitrate solution. A white precipitate is formed.

Give the chemical formula of the anion in A.

Cl^- (1)

(Edexcel Advanced GCE, Paper 3, Sample Assessment Material, Feb. 2015, 2(b)–(d)(i))

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Unit Exercise (p.61)

24 Metal ion Q^{2+} in acidified aqueous solution can be oxidised by $K_2Cr_2O_7$(aq).

25.0 cm^3 of 0.140 mol dm^{-3} solution of Q^{2+}(aq) require 29.2 cm^3 of 0.0400 mol dm^{-3} $K_2Cr_2O_7$(aq) for complete reaction.

a) Write the half equation for the reduction of $Cr_2O_7^{2-}$(aq) ion in acidic solution.

$Cr_2O_7^{2-}(aq) + 14H^+(aq) + 6e^- \longrightarrow 2Cr^{3+}(aq) + 7H_2O(l)$ (1)

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Unit Exercise (p.61)

24 (Continued)

b) By considering the amount of electrons transferred, determine the oxidation state of metal Q after the reaction of solution of Q^{2+}(aq) with $K_2Cr_2O_7$(aq).

Number of moles of $Cr_2O_7^{2-}$(aq) ions = 0.0400 mol dm^{-3} x $\frac{29.2}{1\,000}$ dm^3

= 0.00117 mol

Number of moles of Q^{2+}(aq) ions = 0.140 mol dm^{-3} x $\frac{25.0}{1\,000}$ dm^3

= 0.00350 mol

1 mole of $Cr_2O_7^{2-}$(aq) ions needs 6 moles of electrons for reduction.

i.e. number of moles of electrons involved = 6 x 0.00117 mol

= 0.00702 mol (1)

Number of moles of electrons provided by 1 mole of Q^{2+}(aq) ions

= $\frac{0.00702}{0.00350}$ mol

= 2 mol (1)

Thus, the oxidation state of metal Q after the reaction is +4 (i.e. Q^{4+}(aq)). (1)

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Unit Exercise (p.61)

*25 Suggest TWO differences in properties between main group metals and transition metals, illustrating your answer with examples using magnesium and iron.

Any two of the following:

- Main group metals exhibit only one oxidation state while transition metals exhibit variable oxidation states. (1)
  For example, magnesium exhibits only one oxidation state (+2) while iron exhibits variable oxidation states (e.g. +2 and +3). (1)
- Main group metals form colourless compounds while transition metals form coloured compounds. (1)
  For example, magnesium sulphate is colourless while iron(II) sulphate is green in colour. (1)
- Main group metals do not demonstrate catalytic activity while transition metals do. (1)
  For example, magnesium is not used as a catalyst while iron is used as a catalyst in the manufacture of ammonia from nitrogen and hydrogen. (1)

Communication mark (1)

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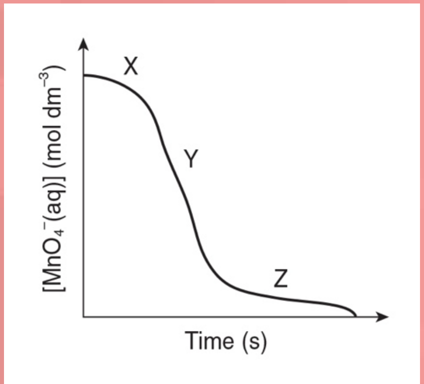
Unit Exercise (p.61)

26 The reaction of ethanedioate ion with acidified permanganate is fairly slow at 25 °C. As the reaction progresses, Mn^{2+} ion is formed which acts as a catalyst.
The student decides to measure the progress of the reaction at 25 °C and obtains the graph shown below.



a) Describe and explain the changes in the reaction rate between:

i) X and Y

Reaction rate increases.
The rate speeds up as (catalyst) Mn^{2+} ion is formed. (1)

ii) Y and Z

Reaction rate decreases.
The rate slows as reactants / $C_2O_4^{2-}$ / MnO^{4-} are / is used up / as concentrations of reactants fall. (1)

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Unit Exercise (p.61)

26 (Continued)

b) Suggest ONE method that the student could use to measure the concentration of the permanganate ions, other than by a titration.

Colorimetry (1)

c) During the progress of the reaction, give ONE observation that might be made.

Any one of the following:

- Effervescence / fizzing (1)
- Purple colour fades (1)

(OCR Advanced GCE, Chem. B (Salters), F334, Jun. 2013, 2(d))

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Unit Exercise (p.61)

27 Vanadium(V) oxide, V_2O_5, is a catalyst used in the Contact process. The equations below show its mode of action.

$SO_2 + V_2O_5 \longrightarrow SO_3 + V_2O_4$

$2V_2O_4 + O_2 \longrightarrow 2V_2O_5$

a) Using these equations, write the equation for the reaction V_2O_5 catalyses in the Contact process.

$2SO_2 + \cancel{2V_2O_5} \longrightarrow 2SO_3 + \cancel{2V_2O_4}$

$\cancel{2V_2O_4} + O_2 \longrightarrow \cancel{2V_2O_5}$

$2SO_2 + O_2 \longrightarrow 2SO_3$ (1)

b) Explain why V_2O_5 is a catalyst based on the equations.

V_2O_5 does NOT undergo any permanent chemical changes in the process. (1)

c) Explain why a compound of vanadium is able to act as a catalyst in this reaction. Vanadium can exhibit variable oxidation states in its compounds. (1)

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Unit Exercise (p.61)

28 Permanganate ion reacts with ethanedioate ion. The half equations for the reaction involved are given below.

$MnO_4^-(aq) + 8H^+(aq) + 5e^- \longrightarrow Mn^{2+}(aq) + 4H_2O(l)$

$C_2O_4^{2-}(aq) \longrightarrow 2CO_2(g) + 2e^-$

a) Write the ionic equation for the reaction between permanganate ion and ethanedioate ion.

$2MnO_4^-(aq) + 5C_2O_4^{2-}(aq) + 16H^+(aq) \longrightarrow 2Mn^{2+}(aq) + 10CO_2(g) + 8H_2O(l)$ (1)

b) Explain why the progress of this reaction can be followed by colorimetry.

$MnO_4^-(aq)$ ion is purple in colour while the other chemical species are colourless.

The absorbance of the reaction mixture falls with time as the purple permanganate ion is consumed. (1)

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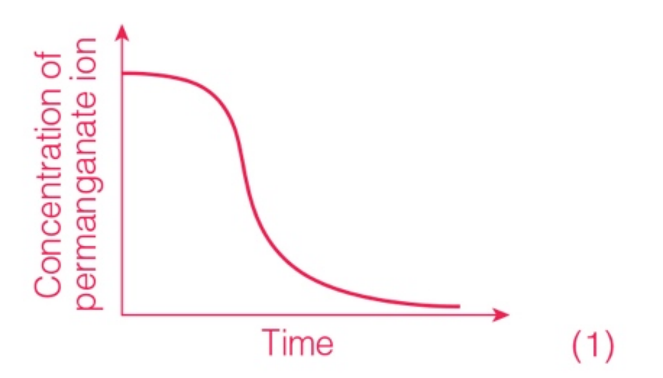
Unit Exercise (p.61)

28 (Continued)

c) Sketch a graph of the concentration of permanganate ion against time. Explain the shape of the graph.



The concentration of permanganate ion / reaction rate decreases slowly at the beginning. (1)
As manganese(II) ions begin to form, the reaction speeds up and the concentration of permanganate ion decreases more rapidly. (1)
Eventually, the reaction slows down as there is little permanganate left. (1)

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Topic Exercise (p.69)

Note: Questions are rated according to ascending level of difficulty (from 1 to 5):

 **question targeted at level 3 and above;**

 **question targeted at level 4 and above;**

 **question targeted at level 5.**

‘ * ’ indicates 1 mark is given for effective communication.

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Topic Exercise (p.69)

PART I MULTIPLE CHOICE QUESTIONS

1 Which of the following statements concerning the Periodic Table is correct?

A The melting point of the Group I elements increases down the group.
B The boiling point of the Group VII elements increases down the group.
C The elements are arranged in the order of increasing relative atomic mass.
D The electrical conductivity of the third period elements increases from left to right.

Answer: B

(HKDSE, Paper 1A, 2015, 25)

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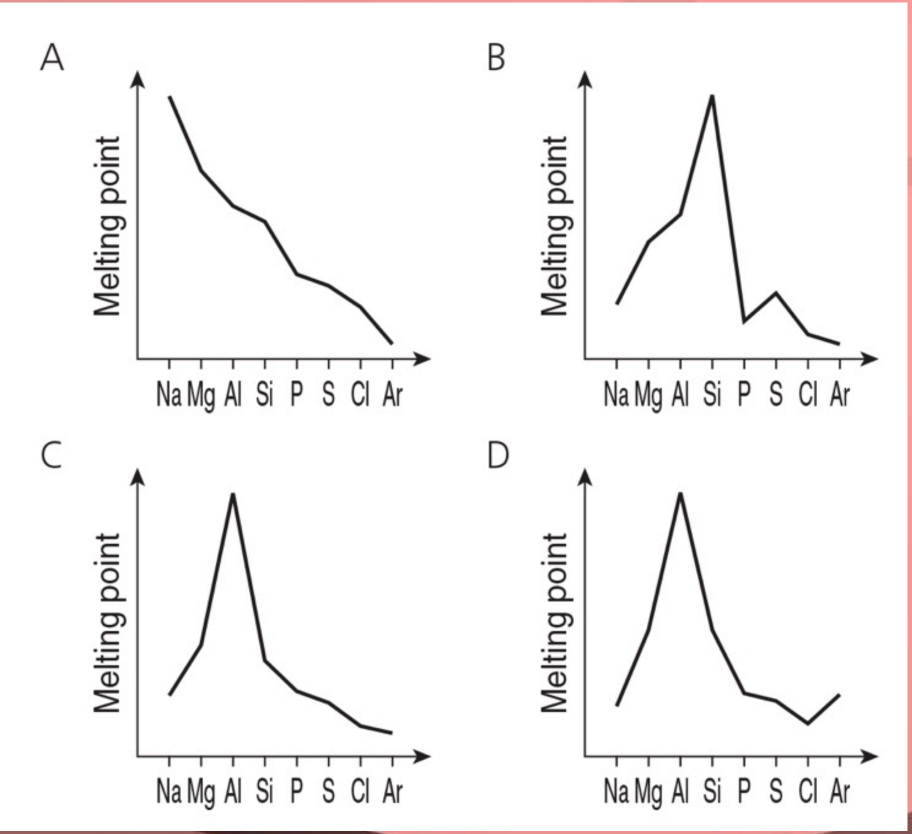
Topic Exercise (p.69)

2 Which of the following graphs (not drawn to scale) shows the variation in melting points of the elements in the third period of the Periodic Table?



Answer: B

(HKDSE, Paper 1A, 2017, 25)

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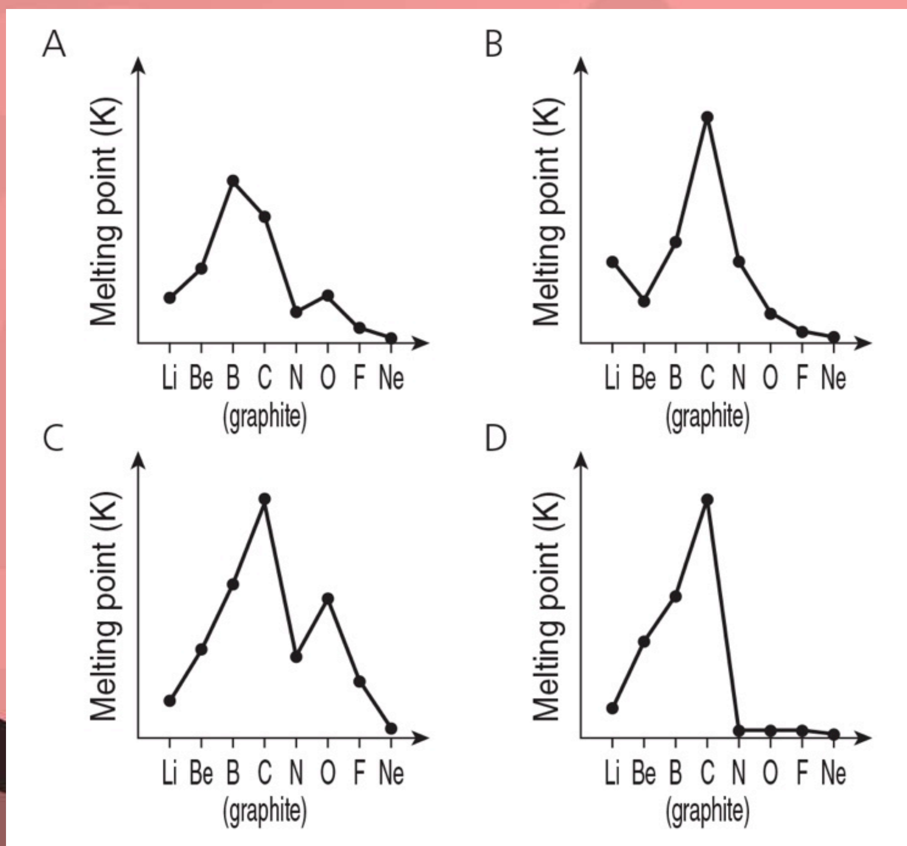
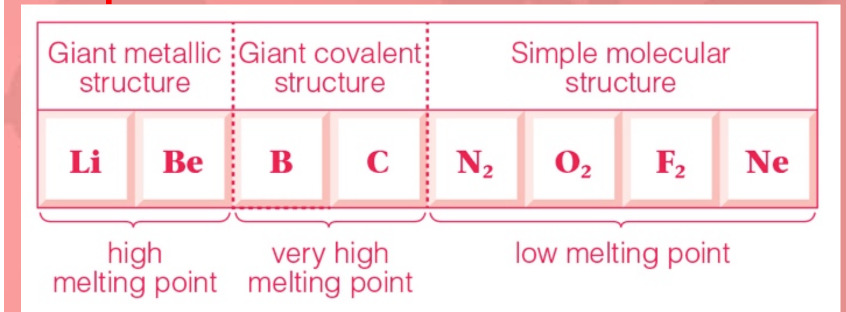
Topic Exercise (p.69)

3 Which of the following graphs (not drawn to scale) shows the variation in melting points of the elements in the second period of the Periodic Table?



Explanation:



Answer: D

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Topic Exercise (p.69)

4 Some properties of four elements W, X, Y and Z (the letters are NOT symbols of the elements) are listed below.
W melts at 1 410 °C and it forms an acidic oxide.
X has a high density and its oxide can act as a catalyst.
Y can be drawn in wires and its oxide reacts with acids.
Z is a reddish brown solid and its oxide can be reduced by carbon.

Explanation:
W is a non-metal as it forms an acidic oxide.

Which letters show the elements which are metals?

A W and Y only
B X and Y only
C X and Z only
D X, Y and Z only

Answer: D

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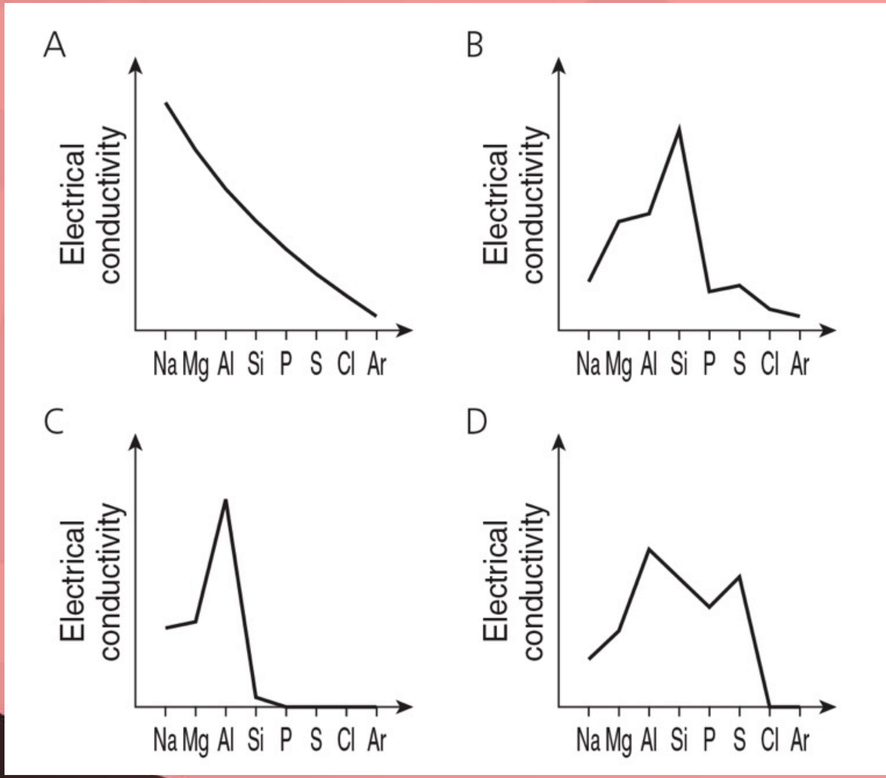
Topic Exercise (p.69)

5 Which of the following graphs (not drawn to scale) correctly shows the variation in electrical conductivity of the elements in the third period of the Periodic Table at room temperature?



Answer: C

(HKDSE, Paper 1A, 2014, 30)

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Topic Exercise (p.69)

6 Element X is on the left-hand side of the Periodic Table. Which of the following combinations about the oxide of X is correct?

	Type of bonding	Acid-base nature
A	covalent	acidic
B	covalent	basic
C	ionic	acidic
D	ionic	basic

Answer: D

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Topic Exercise (p.69)

7 Which of the following oxides, when mixed with water, will produce the most acidic solution?

A Al_2O_3
B CO_2
C P_4O_{10}
D SiO_2

Explanation:

Option B — Carbon dioxide is moderately soluble in cold water, forming a slightly acidic solution.

$CO_2(g) + H_2O(l) \rightleftharpoons H_2CO_3(aq)$

Answer: C

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Topic Exercise (p.69)

8 Which of the following Period 3 elements requires the LEAST number of moles of oxygen for the complete combustion of one mole of the element?

A Aluminium
B Phosphorus
C Silicon
D Sodium

Answer: D

Explanation:

Period 3 element	Na	Al	Si	P
Formula of oxide	Na_2O	Al_2O_3	SiO_2	P_4O_6 / P_4O_{10}
Number of mole(s) of oxygen atoms combining with one mole of atoms	0.5	1.5	2	1.5 / 2.5

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Topic Exercise (p.69)

9 Which of the following conversions involves the reduction of chromium?

A $CrO_4^{2-} \longrightarrow CrO_3$
B $Cr(OH)_6^{3-} \longrightarrow CrO_4^{2-}$
C $CrO_3 \longrightarrow CrO_2Cl_2$
D $CrO_2Cl_2 \longrightarrow Cr_2O_3$

Explanation:

oxidation number	+6		+3
	CrO_2Cl_2	$\longrightarrow$	Cr_2O_3

Answer: D

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Topic Exercise (p.69)

10 Which of the following chemical species is colourless?

A $Fe^{2+}(aq)$
B $Ni^{2+}(aq)$
C $Ti^{3+}(aq)$
D $Zn^{2+}(aq)$

Answer: D

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Topic Exercise (p.69)

11 Which of the following statements concerning Period 3 elements (from sodium to argon) and their compounds is / are correct?

(1) The elements become more electronegative from sodium to chlorine.

(2) Silicon dioxide is the only oxide which is insoluble in water.

(3) The maximum oxidation state is shown by sulphur.

A (1) only
B (2) only
C (1) and (3) only
D (2) and (3) only

Explanation:

(2) Aluminium oxide is also insoluble in water.

(3) The maximum oxidation state is shown by chlorine. The oxidation number of Cl in Cl_2O_7 is +7.

Answer: A

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Topic Exercise (p.69)

12 Which properties are typical of most non-metals in Period 3 (Na to Ar)?

(1) They form ions by losing one or more electrons.
(2) They are poor conductors of heat and electricity.
(3) They have high melting points.

A (1) only
B (2) only
C (1) and (3) only
D (2) and (3) only

Answer: B

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Topic Exercise (p.69)

13 Which of the following statements concerning copper and its compounds is / are correct?

(1) Copper is a main constituent of brass.
(2) Copper(II) oxide is an acidic oxide.
(3) Copper(II) sulphate solution gives a deep blue solution upon mixing with excess NaOH(aq).

A (1) only
B (2) only
C (1) and (3) only
D (2) and (3) only

Explanation:
(2) Covalent oxides formed from non-metals are acidic.
(3) Copper(II) sulphate solution gives a deep blue solution upon mixing with excess NH_3(aq).

Answer: A

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Topic Exercise (p.69)

Directions:
Each question (Questions 14–16) consists of two separate statements. Decide whether each of the two statements is true or false; if both are true, then decide whether or not the second statement is a correct explanation of the first statement. Then select one option from A to D according to the following table :

A	Both statements are true and the 2nd statement is a correct explanation of the 1st statement.
B	Both statements are true but the 2nd statement is NOT a correct explanation of the 1st statement.
C	The 1st statement is false but the 2nd statement is true.
D	Both statements are false.

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Topic Exercise (p.69)

14 1st statement

The melting point of silicon is higher than that of aluminium.

2nd statement

The number of electrons in a silicon atom is greater than that in an aluminium atom.

(HKDSE, Paper 1A, 2015, 35)

Answer: B

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Topic Exercise (p.69)

15 1st statement

Aluminium oxide is soluble in water.

2nd statement

Aluminium oxide is an amphoteric oxide.

(HKDSE, Paper 1A, 2014, 36)

Answer: C

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Topic Exercise (p.69)

16 1st statement

Both aluminium oxide and magnesium oxide exhibit similar acid-base properties.

2nd statement

Both aluminium oxide and magnesium oxide are ionic oxides.

(HKDSE, Paper 1A, 2013, 36)

Answer: C

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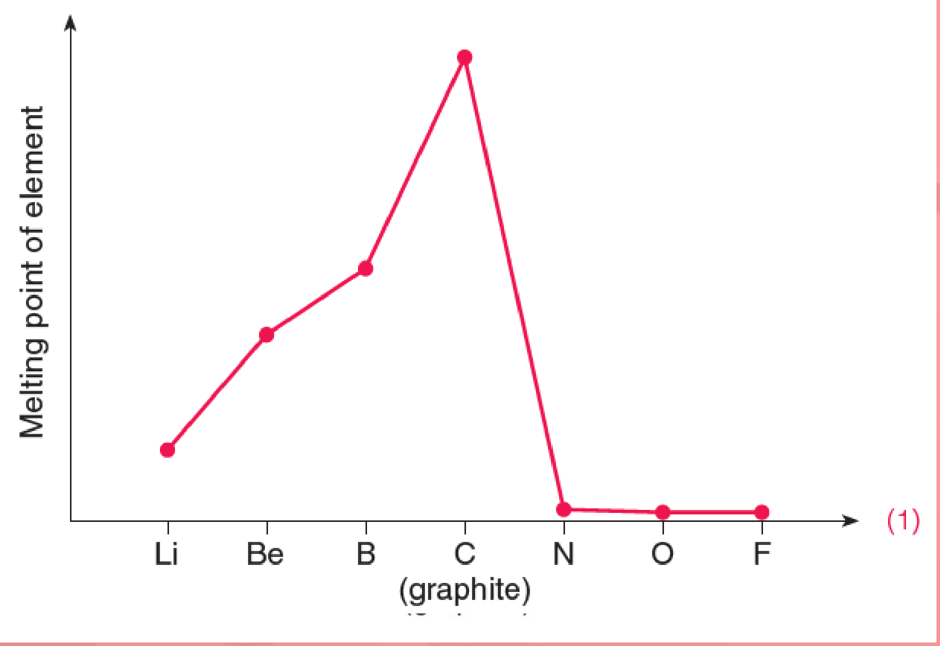
Topic Exercise (p.69)

PART III STRUCTURED QUESTIONS

17 Sketch the variation of melting points of Period 2 elements. Briefly account for the trend.



Li and Be have giant metallic structures. (1)
To melt the element, a lot of heat is needed to overcome the attractive forces between the metal ions and the 'sea' of delocalised electrons. Hence the elements have high melting points. (1)
B and C (graphite) have giant covalent structures. (1)
Lots of strong covalent bonds between atoms have to be broken in melting. A lot of heat is needed. Hence the elements have very high melting points. (1)
N, O and F have simple molecular structures. (1)
To melt the elements, very little heat is needed to overcome the weak van der Waals' forces between molecules and separate the molecules far apart. Hence the elements have low melting points. (1)

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Topic Exercise (p.69)

18 The table below shows the melting points of elements in Period 3, Na to Cl.

Element	Na	Mg	Al	Si	P	S	Cl
Melting point (K)	371	923	933	1 687	317	388	172

a) Explain the difference in melting points between the elements Na and Mg.

Na and Mg have giant metallic structures. (1)
The metallic bond in Na is weaker than that in Mg as Na has less delocalised electrons compared with Mg. Thus, the melting point of Na is lower than that of Mg. (1)

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Topic Exercise (p.69)

18 (Continued)

b) Explain why the melting point of silicon is very high.

Silicon has a giant covalent structure. (1)

Lots of strong covalent bonds between atoms have to be broken in melting. A lot of heat is needed.(1)

c) Sulphur exists as S_8 molecules and phosphorus as P_4 molecules. Explain the difference in their melting points.

Both sulphur and phosphorus have simple molecular structures. Only weak van der Waals' forces are needed to be overcome in melting. (1)

A S_8 molecule has a larger size than a P_4 molecule. Thus, stronger van der Waals' forces exist among S_8 molecules. So the melting point of sulphur is higher than that of phosphorus. (1)

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Topic Exercise (p.69)

*19 Arrange sodium, aluminium, silicon and sulphur in decreasing order of electrical conductivity at room conditions, and explain your answer in terms of bonding and structure.

(HKDSE, Pape 1B, 2016, 14)

Answers for the questions of the public examinations in Hong Kong are not provided (if applicable).

Topic Exercise (p.69)

20 There are trends in melting points and electrical conductivities of metals in Period 3. Using Na and Al as your examples, state these trends and explain each trend in terms of the bonding.

The melting point increases from Na to Al. (1)
Metals in Period 3 have giant metallic structures. (1)
The number of delocalised electrons increases from Na to Al. Thus, the order of strength of metallic bonding in the three metals is Al > Mg > Na. (1)
The electrical conductivity increases from Na to Al. (1)
The number of delocalised electrons increases from Na to Al. (1)
Communication mark (1)

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Topic Exercise (p.69)

21 The chemical formulae of oxides of Period 3 elements are shown below.

Na_2O MgO Al_2O_3 SiO_2 P_4O_{10} SO_3

a) Describe the trend in chemical formulae of the oxides.

There is a regular increase in the number of mole(s) of oxygen atoms combining with one mole of atoms of an element across the period. (1)

b) What type of force is overcome when each of the following oxides is melted?

i) Na_2O

Ionic bond (1)

ii) SiO_2

Covalent bond (1)

iii) P_4O_{10}

Van der Waals' forces (1)

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Topic Exercise (p.69)

21 (Continued)

c) Which of the oxides listed above can conduct electricity in molten state?

Na_2O MgO Al_2O_3 (1)

d) Al_2O_3 is amphoteric.

Write an equation to show the reaction between aluminium oxide and

i) dilute sulphuric acid;

$Al_2O_3(s) + 3H_2SO_4(aq) \longrightarrow Al_2(SO_4)_3(aq) + 3H_2O(l)$ (1)

or

$Al_2O_3(s) + 6H^+(aq) \longrightarrow 2Al^{3+}(aq) + 3H_2O(l)$ (1)

ii) hot concentrated sodium hydroxide solution.

$Al_2O_3(s) + 2NaOH(aq) + 3H_2O(l) \longrightarrow 2NaAl(OH)_4(aq)$ (1)

or

$Al_2O_3(s) + 2OH^-(aq) + 3H_2O(l) \longrightarrow 2[Al(OH)_4]^-(aq)$ (1)

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Topic Exercise (p.69)

22 This question is about the properties and reactions of the oxides of some elements.

a) Chlorine dioxide (ClO_2) is an important industrial chemical used to bleach wood pulp for making paper.

i) What is the oxidation state of chlorine in the oxide?

+4 (1)

ii) Assuming the chlorine-oxygen bonds in the oxide are double bonds, predict the shape of the ClO_2 molecule. Explain your answer.

Bent shape or V-shaped (1)

There are two electron groups (due to two chlorine-oxygen bonds), one lone pair and one odd / unpaired electron in the outermost shell of the central chlorine atom. (1)

iii) Give the chemical formula of the oxide of chlorine in its highest oxidation state of +7.

Cl_2O_7 (1)

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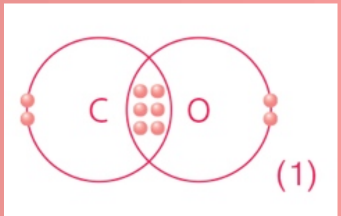
Topic Exercise (p.69)

22 (Continued)

b) Carbon monoxide in the exhaust gases of cars can be removed by catalytic converters.

i) Draw the electron diagram of carbon monoxide, showing electrons in the *outermost shells* only.



ii) Name a metal that is used as a catalyst in a catalytic converter.

Platinum / rhodium / palladium (1)

iii) Write the equation for the reaction that occurs in a catalytic converter to remove carbon monoxide.

$2NO(g) + 2CO(g) \longrightarrow N_2(g) + 2CO_2(g)$ (1)

or $2CO(g) + O_2(g) \longrightarrow 2CO_2(g)$ (1)

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Topic Exercise (p.69)

23 a) The table below contains data that show a trend in the melting points of some oxides of the Period 3 elements.

Oxide	Sodium oxide	Magnesium oxide	Aluminium oxide	Silicon dioxide	Phosphorus pentoxide	Sulphur dioxide
Melting point (K)		3 125	2 345	1 883	573	

i) Use data from the table to predict an approximate melting point for sodium oxide. Tick (✓) ONE box.

- ☐ 250 K
- ☐ 500 K
- ☑ 1 500 K (1)
- ☐ 3 500 K

ii) Explain, in terms of structure and bonding, why sodium oxide has a high melting point.

Sodium oxide has a giant ionic structure. (1)
There are strong ionic bonds between the ions with opposite charges.
It takes a lot of heat to separate the ions in melting. (1)

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Topic Exercise (p.69)

23 (Continued)

a) iii) Use data from the table to predict a value for the melting point of sulphur dioxide.
Suggest, in terms of structure and bonding, why the melting point of sulphur dioxide is different from that of phosphorus pentoxide.

200 K

Both sulphur dioxide and phosphorus pentoxide have simple molecular structures. Only weak van der Waals' forces are needed to be overcome in melting. A SO_2 molecule is smaller than a P_4O_{10} molecule. Thus, the van der Waals' forces among SO_2 molecules are weaker. So the melting point of sulphur dioxide is lower than that of phosphorus pentoxide. (1)

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Topic Exercise (p.69)

23 (Continued)

b) Write an equation for the reaction of sulphur dioxide with water.

$SO_2(g) + H_2O(l) \rightleftharpoons H_2SO_3(aq)$ (1)

Suggest the pH value of the resulting solution.

pH 1 (1)

c) Silicon dioxide is insoluble in water.

Explain, using an equation, why silicon dioxide is classified as an acidic oxide.

Silicon dioxide reacts with bases / alkalis. (1)

$SiO_2(s) + 2NaOH(aq) \longrightarrow Na_2SiO_3(aq) + H_2O(l)$ (1)

or

$SiO_2(s) + 2OH^-(aq) \longrightarrow SiO_3^{2-}(aq) + H_2O(l)$ (1)

(AQA Advanced GCE, Unit 5, Jun. 2015, 5)

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Topic Exercise (p.69)

*24 Period 3 elements bond with oxygen to form oxides. Describe how bonding in the oxides of Period 3 elements changes across the period. Illustrate your answer with examples.

Elements on the left form <u>ionic oxides with giant structures</u>. (1)
Examples Na_2O, MgO, Al_2O_3 (1)
Element in centre forms a <u>covalent oxide with a giant structure</u>. (1)
Example SiO_2 (1)
Elements on the right form <u>covalent oxides with simple molecular structures</u>. (1)
Examples P_4O_{10}, SO_2 / SO_3, Cl_2O (1)
Communication mark (1)

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Topic Exercise (p.69)

*25 Using Na_2O, Al_2O_3 and SO_2 as examples, illustrate the acid-base behaviour of the oxides of the third period elements with the aid of relevant reactions.

(HKDSE, Paper 1B, 2018, 14)

Answers for the questions of the public examinations in Hong Kong are not provided (if applicable).

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Topic Exercise (p.69)

26 Two of the oxidation states of vanadium are +3 and +4.

a) Write the chemical formula of vanadium(IV) oxide.

VO_2 (1)

b) Vanadium(III) oxide is basic, and vanadium(IV) oxide is amphoteric. Describe how you would obtain a sample of vanadium(III) oxide from a mixture of these two oxides.

Add sodium hydroxide solution, (1)
until vanadium(IV) oxide completely dissolves / reacts. (1)
Filter to obtain vanadium(III) oxide. (1)

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Topic Exercise (p.69)

27 a) Cobalt and nickel are both transition metals. Cobalt is placed before nickel despite having a greater relative atomic mass.

i) State why Co is placed before Ni in the Periodic Table.

An atom of Co has fewer protons than an atom of Ni. (1)

ii) Suggest why Co has a greater relative atomic mass than Ni.

On average, isotopes of Co have more neutrons than isotopes of Ni. (1)

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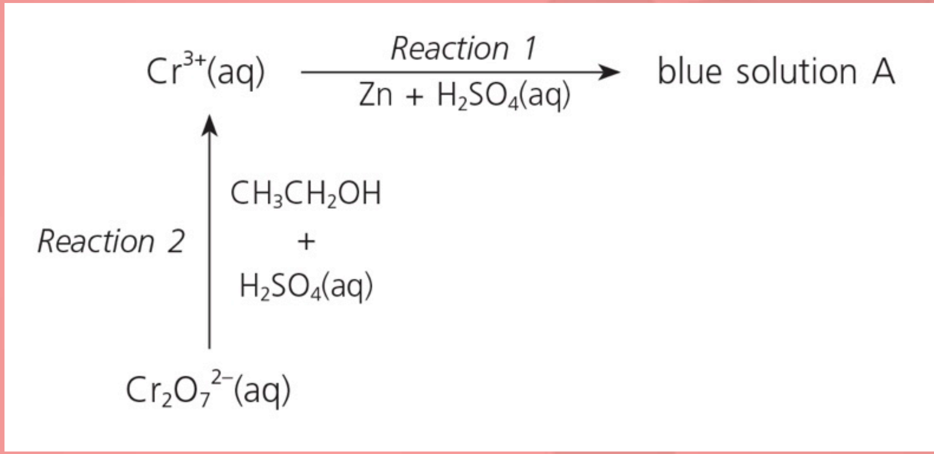
Topic Exercise (p.69)

27 (Continued)

b) The following reaction scheme shows some reactions of chromium-containing species in aqueous solution.



i) Identify the chromium-containing species present in blue solution A formed in *Reaction 1*. State the role of zinc in its formation.

Cr^{2+}(aq) ion (1)

Reducing agent (1)

Topic Exercise (p.69)

27 (Continued)

b) ii) State the expected colour change in *Reaction 2*.

From orange to green (1)

iii) Two organic compounds are formed in *Reaction 2*. One of these compounds has a low boiling point and can be distilled readily from the reaction mixture. The other compound has a higher boiling point and is the main organic product when the reaction mixture is refluxed.

I) Identify the organic product which has a low boiling point.

CH_3CHO (1)

II) Identify the main organic product formed when the reaction mixture is refluxed.

CH_3COOH (1)

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Topic Exercise (p.69)

Answers for the questions of the public examinations in Hong Kong are not provided (if applicable).

28 Vanadium is a transition metal, its chemical symbol is V. The formulae and the colours of three aqueous vanadium-containing ions are shown below:

Formula	$VO^{2+}(aq)$	$V^{3+}(aq)$	$V^{2+}(aq)$
Colour	blue	green	violet

a) Based on the given information, suggest TWO properties of vanadium to characterise it as a transition metal.

b) Vanadium also forms the ion $VO^{2+}(aq)$. In the presence of acid, 1.0 mol of $VO^{2+}(aq)$ ions and 1.0 mol of $SO_2(g)$ react completely to form $SO_4^{2-}(aq)$ ions and one of the above aqueous vanadium-containing ions.

i) By considering the amount of electrons transferred, deduce the final colour of the solution obtained.

ii) Write a chemical equation for the reaction in (i).

(HKDSE, Paper 1B, 2014, 11)

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Topic Exercise (p.69)

29 a) For each of the oxides below, draw its electron diagram, showing electrons in the *outermost shells* only, and state its behaviour in water.

i) Na_2O

ii) Cl_2O

b) Using iron as an example, illustrate TWO characteristics of transition metals.

Answers for the questions of the public examinations in Hong Kong are not provided (if applicable).

(HKDSE, Paper 1B, 2015, 10)

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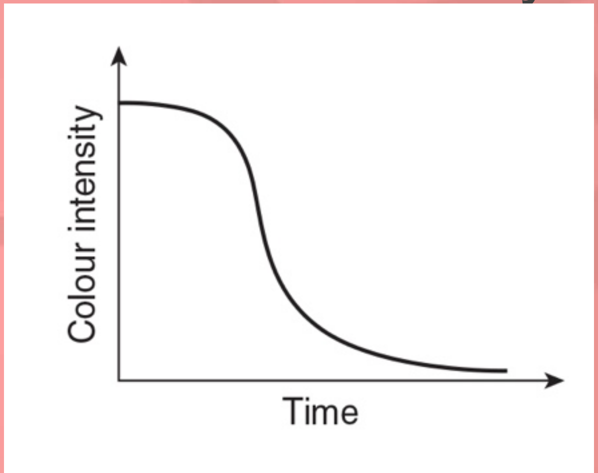
Topic Exercise (p.69)

Answers for the questions of the public examinations in Hong Kong are not provided (if applicable).

*30 At 60 °C, $MnO_4^-(aq)$ reacts with $C_2O_4^{2-}(aq)$ in an acidic medium to give $Mn^{2+}(aq)$, $CO_2(g)$ and $H_2O(l)$. The graph below shows the variation of the colour intensity of the reaction mixture with time.



Based on the information above, write the chemical equation for the reaction and illustrate THREE characteristics of transition metals exhibited by manganese.

(HKDSE, Paper 1B, 2017, 14)