Oxford Resources for IB

Chemistry – 2023 Edition

Answers

Reactivity 3.1 – Proton transfer reactions

Practice questions (page 540)

1. **a.** $HNO_3(aq) + NaOH(aq) \rightarrow NaNO_3(aq) + H_2O(l)$

   $H^+(aq) + OH^-(aq) \rightarrow H_2O(l)$

   b. $2HBr(aq) + Ba(OH)_2(aq) \rightarrow BaBr_2(aq) + 2H_2O(l)$

   $H^+(aq) + OH^-(aq) \rightarrow H_2O(l)$

2. $HCl(aq) + H_2O(l) \rightarrow H_3O^+(aq) + Cl^-(aq)$

   $H^+(aq) + H_2O(l) \rightarrow H_3O^+(aq)$

Practice questions (page 541)

3. *First equation:*

   HCO_3^- (conjugate acid) and CO_3^{2-} (conjugate base)

   H_3O^+ (conjugate acid) and H_2O (conjugate base)

   Second equation:

   H_2CO_3 (conjugate acid) and HCO_3^-(conjugate base)

   H_2O (conjugate acid) and OH^- (conjugate base)

4. $H_2PO_4^-$
5. CH_3COOH

Activity (page 542)

One species, NH_4^+, can act only as a Brønsted–Lowry acid. It can donate a proton to form the conjugate base NH_3, but it cannot accept any more protons, as none of the atoms in NH_4^+ has a lone electron pair.

Two species, F^- and PO_4^{3-}, can act only as Brønsted–Lowry bases. They can accept protons to form the conjugate acids HF and HPO_4^{2-}, respectively, but they cannot donate any protons (as they have none).

Notice that one more species, Al_2O_3, can theoretically accept a proton and thus also act as a Brønsted–Lowry base, although the corresponding conjugate acid $Al_2O_3H^+$ is unknown.
In aqueous solutions, reactions of Al_2O_3 with excess strong acids produce aluminium cations:

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

Five species, HF, NH_3, H_3PO_4, $H_2PO_4^-$ and HPO_4^{2-}, can act as both Brønsted–Lowry acids and Brønsted–Lowry bases. Each of these species can both donate a proton and accept a proton. Therefore, all five species are amphiprotic.

Six species, HF, NH_3, H_3PO_4, $H_2PO_4^-$, HPO_4^{2-} and Al_2O_3, are amphoteric. Notice that any amphiprotic species is also amphoteric. Aluminium oxide is amphoteric because it can react with both acids and bases, but it is not amphiprotic because it has no protons and thus it cannot act as a proton donor.

Practice questions (page 543)

6. $[H^+] = 2 \times [H_2SO_4] = 0.0200\ mol\ dm^{-3}$

   $pH \approx 1.70$

7. $6.31 \times 10^{-5}\ mol\ dm^{-3}$

Skills questions (page 544)

1. Answers will vary. For example, pH paper values have a larger uncertainty, and are often between two or three integer pH values. Measurements made using the pH probe will have higher precision.

2. pH probes:

- Advantages: higher precision, lower uncertainty, skin contact with the solution is unlikely, *etc.*
- Disadvantages: need calibration against buffer solutions, can be delicate, can be “shocked” by sudden drastic changes in pH, causing them to become miscalibrated, *etc.*

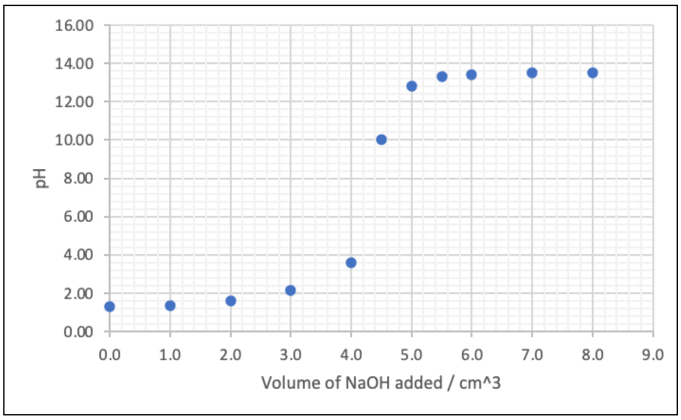
pH paper:

- Advantages: simple to use, good for spot checks when an exact pH value is not required, *etc.*
- Disadvantages: can be coated in toxic substances, may require removing a drop of the solution, non-reusable, imprecise, high uncertainty, *etc.*

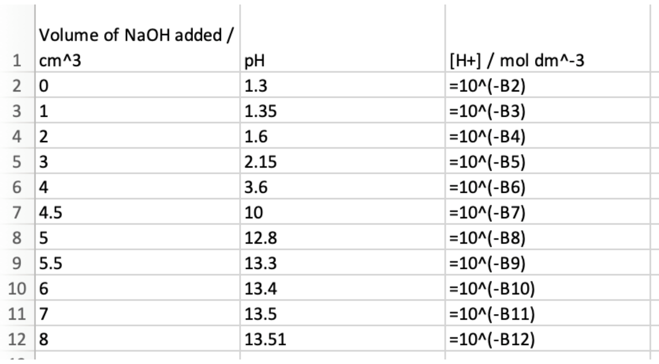
3. Answers will vary depending on the experimental data.

4. Answers will vary depending on the reliability of the pH probe used. Make sure you justify your choice and review the meaning of reliability (*Tool 1*).

6.

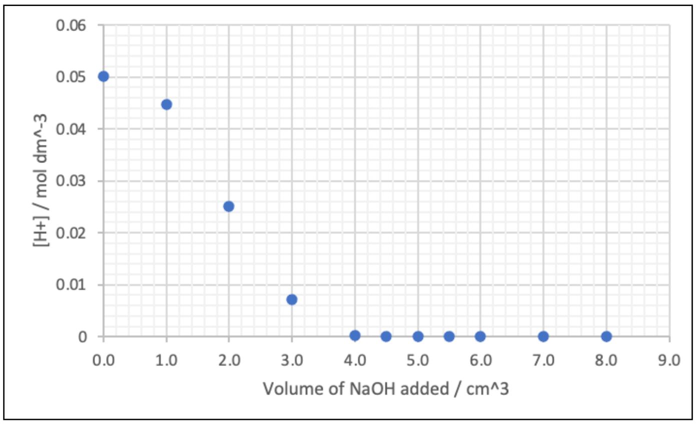


7.



1	Volume of NaOH added / cm^3	pH	[H+] / mol dm^-3
2	0	1.3	=10^(-B2)
3	1	1.35	=10^(-B3)
4	2	1.6	=10^(-B4)
5	3	2.15	=10^(-B5)
6	4	3.6	=10^(-B6)
7	4.5	10	=10^(-B7)
8	5	12.8	=10^(-B8)
9	5.5	13.3	=10^(-B9)
10	6	13.4	=10^(-B10)
11	7	13.5	=10^(-B11)
12	8	13.51	=10^(-B12)

8.



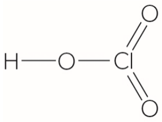
9. When data covers a very large range, log values help us to discern the differences between the values more easily. For example, the hydrogen ion concentrations after the addition of 4.0 cm^3 of NaOH are indistinguishable in graph 2. The first graph, which uses a log value (the pH), can be used to identify the equivalence point and other useful features of pH curves.

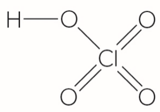
Activity (page 546)

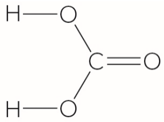
$[OH^-] = 0.0500\ mol\ dm^{-3}$

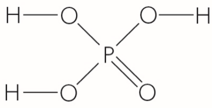
$[H^+] = 2.00 \times 10^{-13}\ mol\ dm^{-3}$

Activity (page 547)









Activity (1) (page 549)

$HBr(aq) \rightarrow H^+(aq) + Br^-(aq)$

$HCN(aq) \rightleftharpoons H^+(aq) + CN^-(aq)$

$HCOOH(aq) \rightleftharpoons HCOO^-(aq) + H^+(aq)$

Activity (2) (page 549)

$HClO$ (Cl is **+1**), $HClO_2$ (Cl is **+3**), $HClO_3$ (Cl is **+5**), $HClO_4$ (Cl is **+7**)

H_3PO_3 (P is **+3**), H_3PO_4 (P is **+5**)

The acid strength increases along with the oxidation state of the central atom.

Activity (page 550)

$H_3PO_4(aq) \rightleftharpoons H^+(aq) + H_2PO_4^-(aq)$

$H_2PO_4^-(aq) \rightleftharpoons H^+(aq) + HPO_4^{2-}(aq)$

$HPO_4^{2-}(aq) \rightleftharpoons H^+(aq) + PO_4^{3-}(aq)$

Practice questions (page 551)

8. a. i. $(CH_3)_2NH(aq) + HCl(aq) \rightarrow (CH_3)_2NH_2Cl(aq)$

$(CH_3)_2NH(aq) + H^+(aq) \rightarrow (CH_3)_2NH_2^+(aq)$

ii. $(CH_3)_3N(aq) + HCl(aq) \rightarrow (CH_3)_3NHCl(aq)$

$(CH_3)_3N(aq) + H^+(aq) \rightarrow (CH_3)_3NH^+(aq)$

b. i. $(CH_3)_2NH$ (conjugate base) and $(CH_3)_2NH_2^+$ (conjugate acid)

ii. $(CH_3)_3N$ (conjugate base) and $(CH_3)_3NH^+$ (conjugate acid)

Practice questions (page 552)

9. a. $CN^-(aq) + H^+(aq) \rightarrow HCN(aq)$

b. $PO_4^{3-}(aq) + H^+(aq) \rightarrow HPO_4^{2-}(aq)$

c. $HPO_4^{2-}(aq) + H^+(aq) \rightarrow H_2PO_4^-(aq)$

Practice questions (page 553)

10. a. $2Li(s) + 2CH_3COOH(aq) \rightarrow 2CH_3COOLi(aq) + H_2(g)$

$2Li(s) + 2CH_3COOH(aq) \rightarrow 2CH_3COO^-(aq) + 2Li^+(aq) + H_2(g)$

b. $2Al(s) + 3H_2SO_4(aq) \rightarrow Al_2(SO_4)_3(aq) + 3H_2(g)$

$2Al(s) + 6H^+(aq) \rightarrow 2Al^{3+}(aq) + 3H_2(g)$

11. a. $Fe_2O_3(s) + 6HCl(aq) \rightarrow 2FeCl_3(aq) + 3H_2O(l)$

$Fe_2O_3(s) + 6H^+(aq) \rightarrow 2Fe^{3+}(aq) + 3H_2O(l)$

b. $Fe_2O_3(s) + 3H_2SO_4(aq) \rightarrow Fe_2(SO_4)_3(aq) + 3H_2O(l)$

$Fe_2O_3(s) + 6H^+(aq) \rightarrow 2Fe^{3+}(aq) + 3H_2O(l)$

Practice questions (page 554)

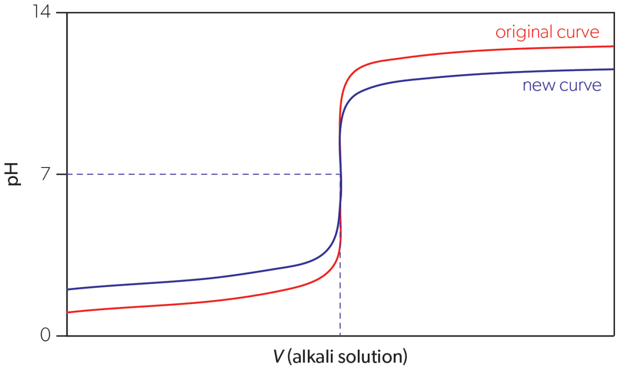
12. a. $2KHCO_3(s) + H_2SO_4(aq) \rightarrow K_2SO_4(aq) + 2CO_2(g) + 2H_2O(l)$

$HCO_3^-(s) + H^+(aq) \rightarrow CO_2(g) + H_2O(l)$

b. $CaCO_3(s) + H_2SO_4(aq) \rightarrow CaSO_4(s) + CO_2(g) + H_2O(l)$

$CaCO_3(s) + 2H^+(aq) + SO_4^{2-}(aq) \rightarrow CaSO_4(s) + CO_2(g) + H_2O(l)$

Activity (page 557)



The *y*-intercept for the new curve will be higher, at pH = 2, as a more dilute acid solution will have a lower $[H^+]$ and thus a higher pH.

The pH at equivalence will not be affected, as both NaCl and KNO_3 are salts of strong acids and strong bases, so neither of these salts undergoes hydrolysis.

The pH at which the curve flattens out will be lower (pH ≈ 12), as a more dilute alkali solution will have a lower $[OH^-]$ and thus a lower pH.

Skills questions (page 559)

1 to 3. Answers will vary depending on the experimental data.

4. a. Before the equivalence point the conductivity decreases as acid-base neutralisation proceeds. Neutralisation decreases the concentration of conductive species in solution because some of the ions are used to create water molecules, which are not conductive.

b. At the equivalence point, conductivity is at a minimum because the solution contains NaCl and water. Of these, NaCl(aq) conducts electricity, but not water.

c. After the equivalence point, conductivity increases again due to the presence of excess aqueous sodium hydroxide, which is an electrical conductor.

5. Answers will depend on the experimental values obtained. The decrease in conductivity before the equivalence point, as H^+ ions in the acid are replaced by Na^+ ions from the added alkali, suggests that hydrogen ions are better electrical conductors than sodium ions.

6. pH is a measure of concentration, so the volume of the solution is significant because it increases with each addition of NaOH. Keeping the volume approximately constant allows us to focus on the effect of changing concentration due to the amount of ions.

7. Answers will vary, but it is likely that the experimentally determined graph shows a decrease in conductivity before the equivalence point, while the graph in figure 11 shows an increase. This is due to the low electrical conductivity of weak acids.

Similarities between the two graphs include a change in conductivity at the equivalence point, and subsequent increase in conductivity as excess base is added.

Practice questions (page 561)

13. a. 2

b. 2.00×10^{-5} mol dm^{-3}

Practice questions (page 564)

14. a. 5.45

b. 8.28

Practice questions (page 565)

15. a. pK_a: $HCO_3^-(aq) \rightleftharpoons H^+(aq) + CO_3^{2-}(aq)$

pK_b: $HCO_3^-(aq) + H_2O(l) \rightleftharpoons H_2CO_3(aq) + OH^-(aq)$

b. p$K_a(H_2CO_3) = 14 - 7.64 = 6.36$

p$K_b(CO_3^{2-}) = 14 - 10.32 = 3.68$

Practice question (page 566)

16. p$K_b(CH_3COO^-) = 14 -$ p$K_a(CH_3COOH) = 14 - 4.76 = 9.24$

This pK_b value is typical for weak bases listed in table 8. As a base, the ethanoate ion has approximately the same strength as phenylamine, and it is much weaker than ammonia.

Practice questions (page 567)

17. a. $KCN(aq) + H_2O(l) \rightleftharpoons KOH(aq) + HCN(aq)$

$CN^-(aq) + H_2O(l) \rightleftharpoons OH^-(aq) + HCN(aq)$

$[H^+] < [OH^-]$, basic solution

b. $H_2O(l) \rightleftharpoons H^+(aq) + OH^-(aq)$

$[H^+] = [OH^-]$, neutral solution

c. $HCOONH_3CH_3(aq) \rightleftharpoons HCOOH(aq) + CH_3NH_2(aq)$

$HCOO^-(aq) + CH_3NH_3^+(aq) \rightleftharpoons HCOOH(aq) + CH_3NH_2(aq)$

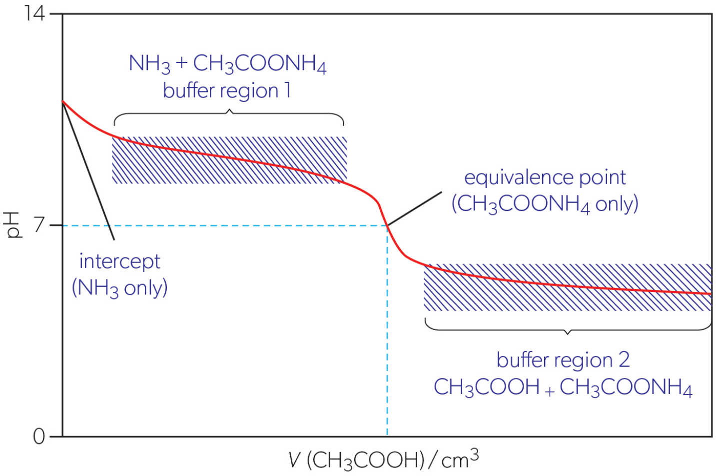
$[H^+] \approx [OH^-]$, neutral solution

d. $CH_3NH_3Br(aq) \rightleftharpoons CH_3NH_2(aq) + HBr(aq)$

$CH_3NH_3^+(aq) \rightleftharpoons CH_3NH_2(aq) + H^+(aq)$

$[H^+] > [OH^-]$, acidic solution

Activity (page 571)



The pH at equivalence is approximately 7, as the pK_a of the acid and pK_b of the base have nearly identical numerical values.

At double-equivalence (at the right-hand side of the second buffer region), pH = p$K_a(CH_3COOH)$.

At half-equivalence (in the middle of the first buffer region), pOH = p$K_b(NH_3)$.

Practice questions (page 573)

18. a. methyl orange

b. bromothymol blue

c. phenolphthalein

19. Any of the following: methyl orange, bromophenol blue, bromocresol green, methyl red.

Practice question (page 575)

20. Any strong base (OH^-) added to the buffer is neutralized by the conjugate acid of the buffer system (NH_4^+):

$NH_4^+(aq) + OH^-(aq) \rightleftharpoons NH_3(aq) + H_2O(l)$

The strong base is replaced with a weak base (NH_3), so the buffer pH does not change significantly.

Any strong acid (H^+) added to the buffer is neutralized by the conjugate base of the buffer system (NH_3):

$NH_3(aq) + H^+(aq) \rightleftharpoons NH_4^+(aq)$

The strong acid is replaced with a weak acid (NH_4^+), so the buffer pH does not change significantly.

Activity (page 576)

Any three of the following:

- solutions of ammonia and ammonium chloride are mixed together
- solid ammonium chloride is dissolved in an ammonia solution
- excess ammonia solution is mixed with hydrochloric acid
- excess ammonium chloride solution is mixed with a sodium hydroxide solution

Other methods are also possible.

Practice questions (page 576)

21. a. 6.80

b. 8.95

End of topic questions (page 578–579)

1. Answers will depend on the student, but a possible answer might be: Protons are transferred from Brønsted–Lowry acids (proton donors) to Brønsted–Lowry bases (proton acceptors) in neutralization reactions. Amphiprotic species, such as water, can act as both Brønsted–Lowry acids and Brønsted–Lowry bases by donating and accepting protons, respectively. The concentration of protons in aqueous solutions can vary over a broad range, so it is often expressed using the pH scale, where $\text{pH} = -\log_{10}[H^+]$. Any two species differing by a single proton are known as a conjugated acid–base pair. When both conjugates are weak, they can form a buffer solution that resists change in pH upon the addition of small amounts of acids or bases.

2. D

3. B

4. A

5. a. HNO_3 and $Ca(OH)_2$

b. H_2SO_4 and $Fe(OH)_3$

c. H_2CO_3 and NH_3 (or NH_4OH)

6. a. $Ca(OH)_2(aq) + 2HNO_3(aq) \rightarrow Ca(NO_3)_2(aq) + 2H_2O(l)$

b. $2Fe(OH)_3(s) + 3H_2SO_4(aq) \rightarrow Fe_2(SO_4)_3(aq) + 6H_2O(l)$

c. $NH_3(aq) + H_2CO_3(aq) \rightarrow NH_4HCO_3(aq)$

Note that carbonic acid is unstable, so the last equation can also be written as follows:

$NH_3(aq) + CO_2(g) + H_2O(l) \rightarrow NH_4HCO_3(aq)$

7. a. The reaction of $CaCO_3(s)$ with a strong acid will be more vigorous than that with a weak acid, provided that the calcium carbonate used in both experiments is in the same form (e.g. powder of the same dispersity or pieces of the same size).

b. Strong acid:

$2HX(aq) + CaCO_3(s) \rightarrow CaX_2(aq) + CO_2(g) + H_2O(l)$

$2H^+(aq) + CaCO_3(s) \rightarrow Ca^{2+}(aq) + CO_2(g) + H_2O(l)$

Weak acid:

$2HY(aq) + CaCO_3(s) \rightarrow CaY_2(aq) + CO_2(g) + H_2O(l)$

$2HY(aq) + CaCO_3(s) \rightarrow Ca^{2+}(aq) + 2Y^-(aq) + CO_2(g) + H_2O(l)$

8.

Species	Conjugate acid	Conjugate base
H_2O	H_3O^+	OH^-
Cl^-	HCl	does not exist
HF	H_2F^+	F^-
NH_3	NH_4^+	NH_2^-
$(CH_3)_3N$	$(CH_3)_3NH^+$	$(CH_3)_2NCH_2^-$
HCO_3^-	H_2CO_3	CO_3^{2-}
CO_3^{2-}	HCO_3^-	does not exist

9. First pair: cation (conjugate acid) + zwitterion (conjugate base)

Second pair: zwitterion (conjugate acid) + anion (conjugate base)

10. a. At 10 °C, $K_w = \dfrac{1.00 \times 10^{-14}}{3.47} \approx 2.88 \times 10^{-15}$

$[H^+] = \sqrt{K_w} = \sqrt{2.88 \times 10^{-15}} \approx 5.37 \times 10^{-8}\ \text{mol dm}^{-3}$

$pH = -\log[H^+] = -\log(5.37 \times 10^{-8}) \approx 7.27$

b. Pure water remains neutral at any temperature, as its dissociation produces $[H^+]$ and $[OH^-]$ in equal concentrations: $H_2O(l) \rightleftharpoons H^+(aq) + OH^-(aq)$

If $[H^+] = [OH^-]$, the solution is neutral, regardless of the numerical value of $[H^+]$ and thus regardless of pH.

11. a. 1.82

b. 1.70

c. 12.30

12. $V_{\text{final}} = 1.000\ \text{dm}^3$; $c(KOH)_{\text{final}} = 0.0020\ \text{mol dm}^{-3}$; pOH = 2.70; pH = 11.3

13. a. 1.82

b. $3.16 \times 10^{-10}\ \text{mol dm}^{-3}$

14. a. $[H^+] = 1.12 \times 10^{-3}\ \text{mol dm}^{-3}$; $K_a = 6.29 \times 10^{-5}$; $pK_a = 4.20$

b. $[H^+] = 2.51 \times 10^{-3}\ \text{mol dm}^{-3}$; pH = 2.60

15. a. $K_b = 4.57 \times 10^{-4}$; $[OH^-] = 2.14 \times 10^{-3}\ \text{mol dm}^{-3}$; pOH = 2.67; pH = 11.33

b. $K_a = 1.74 \times 10^{-5}$; $[H^+] = 1.87 \times 10^{-4}\ \text{mol dm}^{-3}$; pH = 3.73

16. a. K_a: $H_2PO_4^-(aq) \rightleftharpoons H^+(aq) + HPO_4^{2-}(aq)$

K_b: $H_2PO_4^-(aq) + H_2O(l) \rightleftharpoons H_3PO_4(aq) + OH^-(aq)$

b. $pK_a(H_3PO_4) = 14 - 11.88 = 2.12$

$pK_b(HPO_4^{2-}) = 14 - 7.20 = 6.80$

17. a. $HCOONa(aq) + H_2O(l) \rightleftharpoons HCOOH(aq) + NaOH(aq)$

$HCOO^-(aq) + H_2O(l) \rightleftharpoons HCOOH(aq) + OH^-(aq)$

$[H^+] < [OH^-]$, so the solution will be basic.

b. $H_2O(l) \rightleftharpoons H^+(aq) + OH^-(aq)$

$[H^+] = [OH^-]$, so the solution will be neutral.

c. $NH_4CN(aq) \rightleftharpoons NH_3(aq) + HCN(aq)$

$NH_4^+(aq) + CN^-(aq) \rightleftharpoons NH_3(aq) + HCN(aq)$

$[H^+] \approx [OH^-]$, so the solution will be neutral or almost neutral.

d. $(CH_3)_3NHCl(aq) \rightleftharpoons (CH_3)_3N(aq) + HCl(aq)$

$(CH_3)_3NH^+(aq) \rightleftharpoons (CH_3)_3N(aq) + H^+(aq)$

$[H^+] > [OH^-]$, so the solution will be acidic.

18. a. $pH = 3.75 + \log(0.50/0.25) \approx 4.05$

b. $pK_a(CH_3NH_3^+) = 14 - pK_b(CH_3NH_2) = 14 - 3.34 = 10.66$

$pH = 10.66 + \log(0.50/0.20) \approx 11.06$

19. In both cases, a strong acid, $H^+(aq)$, is neutralized by the weak base of the buffer system, and a strong base, $OH^-(aq)$, is neutralized by the weak acid of the buffer system:

a. $HCOO^-(aq) + H^+(aq) \rightarrow HCOOH(aq)$

$HCOOH(aq) + OH^-(aq) \rightarrow HCOO^-(aq) + H_2O(l)$

b. $CH_3NH_2(aq) + H^+(aq) \rightarrow CH_3NH_3^+(aq)$

$CH_3NH_3^+(aq) + OH^-(aq) \rightarrow CH_3NH_2(aq) + H_2O(l)$

20. a. Weak base and strong acid, so at equivalence $pH < 7$. The most suitable indicator is methyl orange ($pK_a < 7$).

b. Weak acid and strong base, so at equivalence $pH > 7$. The most suitable indicator is phenolphthalein ($pK_a > 7$).

Reactivity 3.2 – Electron transfer reactions

Practice questions (page 585)

1. a. reactants: 0, –1; products: –1, 0

b. iodine is oxidized, chlorine is reduced

c. Cl_2 is oxidizing agent, KI is reducing agent

2. a. OA = PbO, RA = H_2

b. OA = CuO, RA = C

c. OA = Cl_2, RA = Mg

d. OA = Br_2, RA = KI

Practice questions (page 588)

3. a. $Zn(s) + SO_4^{2-}(aq) + 4H^+(aq) \rightarrow Zn^{2+}(aq) + SO_2(g) + 2H_2O(l)$

b. $2MnO_4^-(aq) + Br^-(aq) + 2H^+(aq) \rightarrow 2MnO_2(s) + BrO_3^-(aq) + H_2O(l)$

c. $I_2(s) + 5OCl^-(aq) + H_2O(l) \rightarrow 2IO_3^-(aq) + 5Cl^-(aq) + 2H^+(aq)$

d. $Cr_2O_7^{2-}(aq) + 3C_2O_4^{2-}(aq) + 14H^+(aq) \rightarrow 2Cr^{3+}(aq) + 6CO_2(g) + 7H_2O(l)$

Approaches to learning questions (page 592)

Answers will vary. For example:

- Copper is less reactive than hydrogen and therefore does not displace hydrogen from the acid. Hence no reaction observed in 1. Zinc is more reactive than hydrogen and therefore displaces it from the sulfuric acid.
- Once there is contact between copper and zinc in 2, a potential difference is established, causing a flow of electrons between the two metals.
- Metals are electrical conductors due to the mobility of delocalised electrons, so electrons travelling from the zinc through the copper wire in 2 and 3 reduce some of the hydrogen ions in solution releasing hydrogen gas.

Possible linking questions:

Why are acid-metal reactions redox reactions, whereas acid-base reactions are not? (Link to *Reactivity 3.1*)

How is electricity conducted through different materials? (Link to *Structure 2.1*, *2.2* and *2.3*)

Skills questions (page 592–593)

1. Oxidation: $Fe^{2+} \rightarrow Fe^{3+} + e^-$

Reduction: $MnO_4^- + 8H^+ + 5e^- \rightarrow Mn^{2+} + 4H_2O$

2. $5Fe^{2+} + MnO_4^- + 8H^+ \rightarrow 5Fe^{3+} + Mn^{2+} + 4H_2O$

3. Answers depend on experimental data. Guidance:

- Determine the amount, in moles, of potassium manganate(VII) that reacted.
- Determine the amount, in moles, of iron in a 25 cm^3 sample of iron tablet solution.
- Determine the amount, in moles, of iron in the 250 cm^3 iron tablet solution.
- Determine the mass of iron in the 250 cm^3 iron tablet solution.
- Determine the mass of iron in a single tablet.
- Calculate the percentage by mass of iron in one tablet.

4. Answers depend on the measurement uncertainties. Follow the guidance in *Tool 3* to propagate the uncertainties.

5. Answers depend on experimental values and those stated on the label.

6. Answers will vary depending on the results.

7. Answers will vary. For example:

- Difficulty determining the endpoint as the colour change is not always clear. Minimize by: placing a white sheet of paper behind the flask and establishing a time during which the solution must remain pale pink.

- Not all the iron in the tablet dissolves in the solution. Minimize by leaving the solution in step three for a longer period of time.

- Age of the tablets. Older tablets may contain a different amount of iron than stated on the label. Minimise by using new tablets.

8. This allows a relatively large amount of iron to be obtained, lowering the relative and percentage uncertainty.

9. This allows the iron to fully dissolve in the acid solution.

10. Redox reactions such as this are accompanied by a colour change. Therefore, indicators do not need to be added to this titration. By contrast, an acid-base titration typically involves clear and colourless reactants and products, so an acid-base indicator must be added to identify the endpoint.

Practice questions (page 601)

4. **a.** $Cd(s) + 2NiO(OH)(s) + 2H_2O(l) \rightarrow Cd(OH)_2(s) + 2Ni(OH)_2(s)$

b. $Cd(s) \mid Cd(OH)_2(s) \parallel Ni(OH)_2(s) \mid NiO(OH)(s)$

Notice that many variations of this cell diagram are possible, depending on the battery construction. In particular, the cathode can be made of nickel metal (or nickel-plated steel) instead of the pressed powder of NiO(OH)(s), and hydroxide ions can be shown in one or both half-cells, for example:

$Cd(s) \mid Cd(OH)_2(s), OH^-(aq) \parallel Ni(OH)_2(s), NiO(OH)(s), OH^-(aq) \mid Ni(s)$

c. anode: $Cd(OH)_2(s) + 2e^- \rightarrow Cd(s) + 2OH^-(aq)$

cathode: $Ni(OH)_2(s) + OH^-(aq) \rightarrow NiO(OH)(s) + H_2O(l) + e^-$

Practice question (page 602)

5. The PEM separates the anode and cathode half-cells. It allows H^+ ions to pass through but prevents the diffusion of other ions, molecules and electrons.

Practice question (page 604)

6. cathode: $Pb^{2+} + 2e^- \rightarrow Pb(l)$

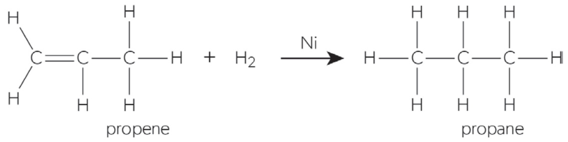
anode: $2Br^- \rightarrow Br_2(g) + 2e^-$

overall equation: $Pb^{2+} + 2Br^- \rightarrow Pb(l) + Br_2(g)$

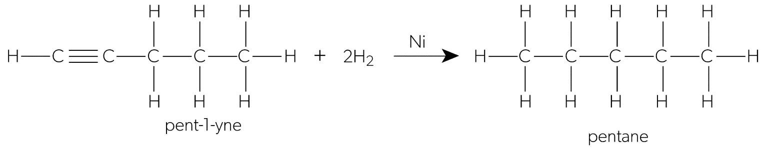
Notice that the states of ions in the molten electrolyte are not shown, as $Pb^{2+}(l)$ and $Br^-(l)$ cannot exist as individual phases. The melting point of $PbBr_2$ is high (371 °C), so lead and bromine are produced in liquid and gaseous states, respectively.

Practice questions (page 609)

7. a.



b.



Practice question (page 610)

8. lithium, calcium, aluminium, tin

Practice questions (page 614)

9. a. Yes, because $\Delta G^{\ominus}$ is negative.

b. $E^{\ominus}_{cell} = -\dfrac{-152000\,\mathrm{J\,mol^{-1}}}{2 \times 96500\,\mathrm{C\,mol^{-1}}} \approx 0.788\,\mathrm{V}$

According to section 19 of the data booklet, $E^{\ominus}_{\mathrm{cell}} = +0.34\,\mathrm{V} - (-0.45\,\mathrm{V}) = 0.79\,\mathrm{V}$. This value is very close to the previous result.

Skills questions (page 615)

1. $E^{\ominus} = E^{\ominus}_{\mathrm{red}} - E^{\ominus}_{\mathrm{ox}} = 0.34 - (-0.76) = +1.10\,\mathrm{V}$
2. Answers will vary depending on experimental value.
3. Answers may include: non-standard temperature, change in the ion concentration over time, variations in the resistance of the components of the circuit, etc.
4. $\Delta G = -nFE^{\ominus}$

   $= -2 \times (9.65 \times 10^{4}\,\mathrm{C\,mol^{-1}}) \times (1.10\,\mathrm{V}) = -212080\,\mathrm{J\,mol^{-1}} \approx -212\,\mathrm{kJ\,mol^{-1}}$ (3 sf)
5. Answers will vary.

Practice question (page 618)

10. cathode: $2H^{+}(aq) + 2e^{-} \rightarrow H_2(g)$

anode: $2H_2O(l) \rightarrow O_2(g) + 4H^{+}(aq) + 4e^{-}$

overall equation: $2H_2O(l) \rightarrow 2H_2(g) + O_2(g)$

Practice questions (page 619)

11. a. i. cathode: $Ag^{+}(aq) + e^{-} \rightarrow Ag(s)$

ii. anode: $Ag(s) \rightarrow Ag^{+}(aq) + e^{-}$

b. The concentration of silver(I) nitrate will not change because the amount of silver(I) ions reduced at the cathode will be equal to the amount of silver metal atoms oxidized at the anode. In other words, each $Ag^{+}(aq)$ ion that leaves the solution and deposits as Ag(s) at the cathode will be replaced with another $Ag^{+}(aq)$ ion that is produced from Ag(s) at the anode.

c. The mass of the cathode will increase because Ag(s) will deposit at the nickel surface. The mass of the anode will decrease because Ag(s) will be oxidized into $Ag^{+}(aq)$, so the anode will gradually dissolve.

End of topic questions (pages 620–621)

1. See page 580.

2. D

3. A

4. B

5. D

6. A

7. C

8. D

9. C

10. B

11. A

12. D

13. a. +3

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

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

14. a. ionic bonding; electrostatic attraction between cations and anions / oppositely charged ions

b. when solid: ions are unable to move (when a potential difference is applied) **AND** when liquid/molten: ions are able to move (when a potential difference is applied)

c. i. cathode: $Na^+ + e^- \rightarrow Na(l)$ **ii.** anode: $2Cl^- \rightarrow Cl_2(g) + 2e^-$

d. $4OH^-(aq) \rightarrow O_2(g) + 2H_2O(l) + 4e^-$

e. *Any two:*

the solution/electrolyte turns pink at the cathode/negative electrode

bubbles of a colourless gas are produced at cathode/negative electrode

bubbles of a greenish-yellow gas are produced at the anode/positive electrode

damp litmus paper bleached if held near the anode

15. a. gain of electrons = reduction and occurs at the cathode; charging reaction;

b. $LiCoO_2(s) \rightarrow Li^+ + e^- + CoO_2(s)$

c. lithium is highly reactive and battery could explode if exposed to air or moisture

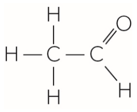
16. a. $C_2H_5OH + 3O_2 \rightarrow 2CO_2 + 3H_2O$

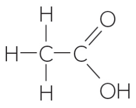
b. i. +4

ii. –2

iii. oxidized **AND** oxidation state increases (from –2 to +4)

c. i. ethanal and ethanoic acid;





ii. ethanal/aldehyde: distillation **AND** ethanoic acid/carboxylic acid: reflux

17. a. Z, X, Y

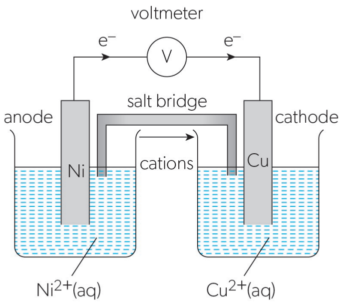
b. *Any two:*

Z did not react with dilute acid **AND** copper does not react with dilute acids

Z is a red-brown solid **AND** copper is a red-brown solid

Aqueous $Z(NO_3)_2$ is blue **AND** copper(II) nitrate is a blue water-soluble solid

c. i. *1 mark for every two correct labels:*



ii. $Ni(s) + Cu^{2+}(aq) \rightarrow Cu(s) + Ni^{2+}(aq)$

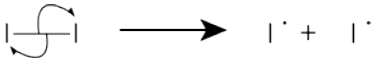
d. 0.60 V

Reactivity 3.3 – Electron sharing reactions

End of topic questions (page 627)

1. A species that possesses an unpaired electron is called a radical. It is formed by the homolytic fission of a pair of bonding electrons involved in a covalent bond between two atoms. Radicals are highly reactive and are normally considered to be intermediates as their existence is brief and they quickly react with other radicals to form new covalently bonded compounds.
2. B
3. A
4. D
5. **a.** In homolytic fission, two electrons of a covalent bond are split evenly between two atoms resulting in two radicals that each have a single electron. The reaction mixture must be exposed to ultraviolet (UV) light, or heated.

   b.



6. **a.** reaction type: substitution; mechanism name: radical substitution (S_R)

   b. *Two propagation steps:*

   $C_2H_6 + {\bullet}Cl \rightarrow {\bullet}C_2H_5 + HCl$

   ${\bullet}C_2H_5 + Cl_2 \rightarrow C_2H_5Cl + {\bullet}Cl$

   One termination step:

   ${\bullet}C_2H_5 + C_2H_5{\bullet} \rightarrow C_4H_{10}$

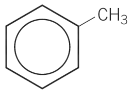
   OR

   ${\bullet}C_2H_5 + {\bullet}Cl \rightarrow C_2H_5Cl$

   OR

   ${\bullet}Cl + {\bullet}Cl \rightarrow Cl_2$

7. **a.**



   b. UV light provides the energy required to break chemical bonds in the homolytic fission of certain molecules, e.g. chlorine.

   c. $Cl_2 \rightarrow 2Cl{\bullet}$

   d. Propagation:

   $C_6H_5CH_3 + Cl{\bullet} \rightarrow C_6H_5CH_2{\bullet} + HCl$

   $C_6H_5CH_2{\bullet} + Cl_2 \rightarrow C_6H_5CH_2Cl + Cl{\bullet}$

   Termination:

   $2Cl{\bullet} \rightarrow Cl_2$

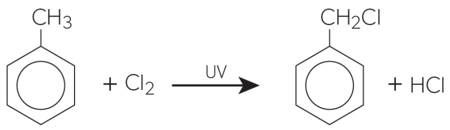
   OR

   $2C_6H_5CH_2{\bullet} \rightarrow C_6H_5CH_2CH_2C_6H_5$

   OR

   $C_6H_5CH_2{\bullet} + Cl{\bullet} \rightarrow C_6H_5CH_2Cl$

   e.



Reactivity 3.4 – Electron-pair sharing reactions

Practice questions (page 629)

1. B

2. D

Practice questions (page 630)

3. **a.** $(CH_3)_3CBr + KOH \rightarrow (CH_3)_3COH + KBr$

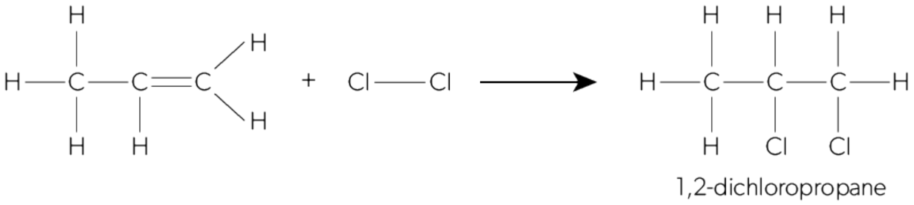
The hydroxide ion, OH^-, is the nucleophile and the bromide ion, Br^-, is the leaving group.

b. $C_5H_{11}Br + CN^- \rightarrow C_5H_{11}CN + Br^-$

The cyanide ion, CN^-, is the nucleophile and the bromide ion, Br^-, is the leaving group.

Practice questions (page 633)

4. **a.**



b. When iodine reacts with an unsaturated alkene, there will be a colour change from yellow/brown/purple to colourless as the iodine reacts and leaves the solution.

Practice questions (page 634)

5. **a.** $CH_3C(CH_3)CHCH_3 + HF \rightarrow CH3CF(CH3)CH2CH3$

b. $CH_3CHCHCH_2CH_3 + I_2 \rightarrow CH_3CHICHICH_2CH_3$

c. $CH_2CH_2 + H_2O \rightarrow CH_3CH_2OH$

d. $C_6H_{10} + HCl \rightarrow C_6H_{11}Cl$

e. $CH_3C(CH_3)CH_2 + H_2 \rightarrow CH_3CH(CH_3)CH_3$

Activity (page 635)

Species	BF_3	H_2O	Cu^{2+}	CH_3COOH	OH^-	NH_3	HF
Brønsted–Lowry acid	No	Yes	No	Yes	No	No	Yes
Brønsted–Lowry base	No	Yes	No	No	Yes	Yes	No
Lewis acid	Yes	No	Yes	No	No	No	No
Lewis base	No	Yes	No	No	Yes	Yes	No

Practice question (page 635)

6. A

Practice questions (page 637)

7. D

8. A

Practice questions (page 639)

9. **a.** chromium(III) ion, Cr^{3+}

b. nickel(II) ion, Ni^{2+}

c. platinum(IV) ion, Pt^{4+}

d. iron(III) ion, Fe^{3+}

e. palladium(II) ion, Pd^{2+}

10. a. 3+

b. 2–

c. 0

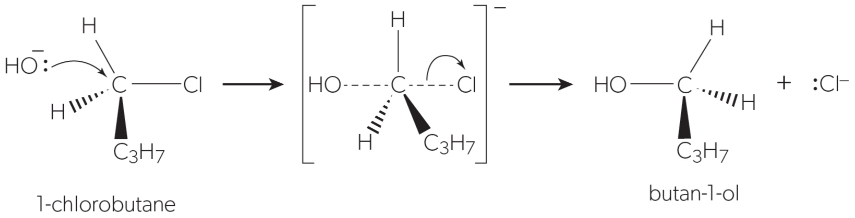
d. 2+

e. 2–

Practice questions (page 640)

11. a. $C_4H_9Cl + KOH \rightarrow C_4H_9OH + KCl$

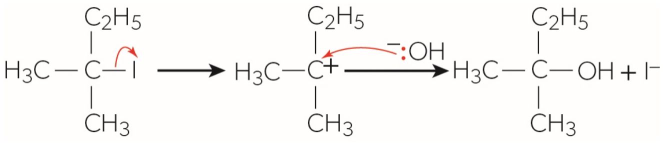
b.



Practice questions (page 641)

12. a. $C_5H_{11}I + NaOH \rightarrow C_5H_{11}OH + NaI$

b.

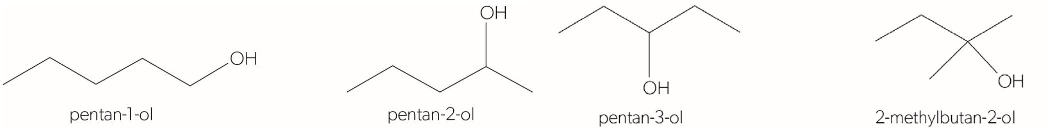


Practice question (page 642)

13. (highest) 2-iodopropane, 2-bromopropane, 2-chloropropane (lowest)

Data-based questions (page 643)

1. pentan-1-ol: primary
pentan-2-ol: secondary
pentan-3-ol: secondary
2-methylbutan-2-ol: tertiary

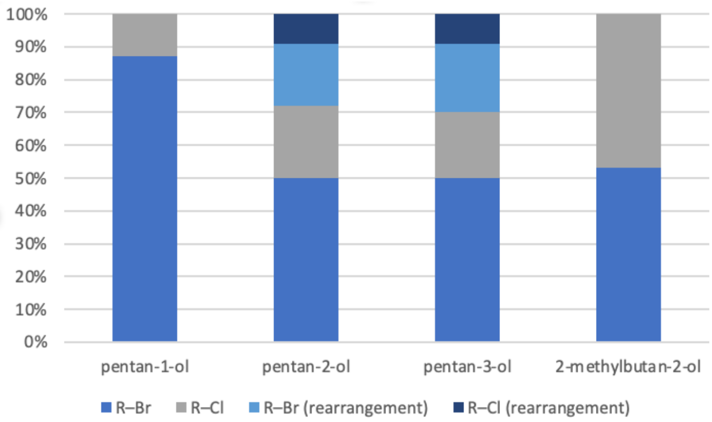


2. Independent variable: Alcohol reactant
Dependent variable: Percentage of each halogenoalkane product formed.

3. Answers will vary.

4. Answers will vary.

5. Answers will vary and may include bar charts, pie charts, etc. For example:



6. Answers may include:
   - In all cases, a higher percentage of the products were bromoalkanes than chloroalkanes.
   - The difference in the percentage of the products was more pronounced for the primary alcohol, pentan-1-ol.
   - Secondary alcohols, pentan-2-ol and pentan-3-ol, led to the production of a mixture of products.
   - The chloroalkane and bromoalkane products were present close to a 50 : 50 ratio in the case of the tertiary alcohol, 2-methylbutan-2-ol.
7. The reactions were carried out in aqueous solution. In all cases, the bromoalkane product was present in a higher percentage than the corresponding chloroalkane product.
8. **a.** Primary alcohols such as pentan-1-ol react predominantly via an S_N2 mechanism.

   b. Tertiary alcohols such as 2-methylbutan-2-ol react predominantly via an S_N1 mechanism.
9. The results for pentan-2-ol and pentan-3-ol suggest a rearrangement has taken place because the halide ion was not exclusively added to the hydroxyl carbon.
10. Answers will vary depending on the answers to 3 and 4.
11. Answers will vary. Make sure you follow the guidance in the inquiry cycle chapter.

Practice question (page 646)

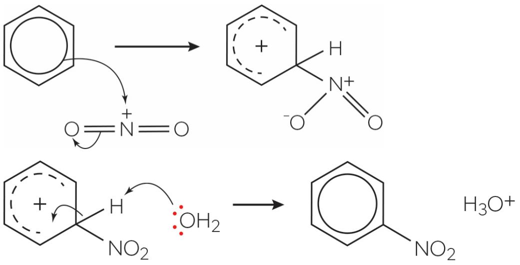
14. C

Practice questions (page 649)

15. a. benzene: electrophilic substitution/S_E

AND cyclohexene: electrophilic addition/A_E

b.



The marks in this question are typically awarded for the following features of the mechanism:

- curly arrow going from benzene ring to N of $^+NO_2$
- carbocation with correct formula and positive charge on partially broken ring (shown as dashed curve)
- curly arrow going from C–H bond to partially broken ring of cation
- formation of organic product and H^+/H_3O^+

End of topic questions (pages 650–651)

1. Answers will depend on the student, but a possible answer might be: The homolytic fission of a pair of bonding electrons involved in a covalent bond between two atoms creates two fragments. One fragment receives both bonding electrons. The species formed is called a nucleophile. The nucleophile is an electron-rich species that attacks an electron-poor species, known as an electrophile. The new bond that is formed between these two species is called a covalent coordination bond. A nucleophile is also described as a Lewis base as it can donate a pair of electrons. When a transition metal ion is bonded to several Lewis base molecules or ions, the result is the formation of a complex ion. When a Lewis base is a part of a complex ion, it is known as a ligand. Ligands are electron-rich species that can be neutral or charged anions. The metal ion acts as an electrophile accepting the electron pair from the nucleophile / Lewis base.

2. A (because it has no lone electron pairs)

3. D

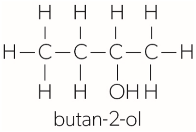
4. C

5. D

6. D

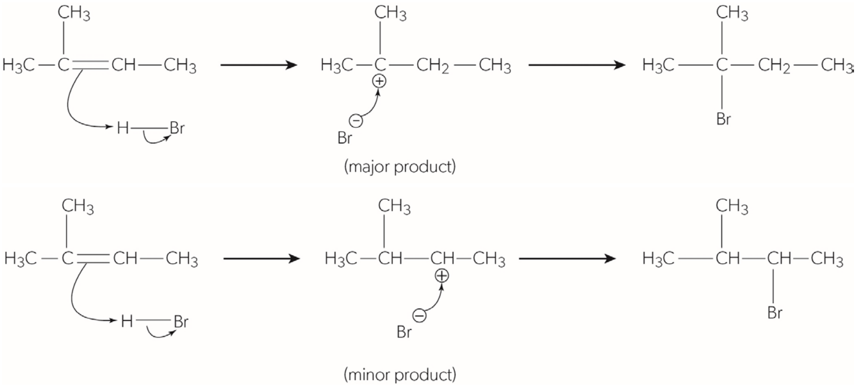
7. C

8. **a.**



butan-2-ol

b.



c. 2-bromo-2-methylbutane involves formation of more stable tertiary carbocation/intermediate

OR

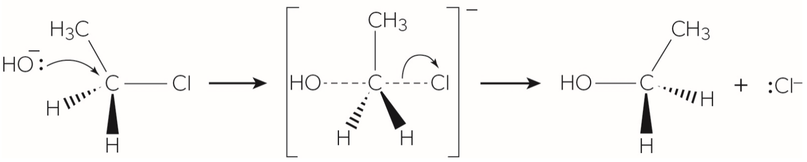
2-bromo-3-methylbutane involves formation of less stable secondary carbocation/intermediate

intermediate is more stable due to increased positive inductive/electron-releasing effect of extra methyl group

9. **a.** radical substitution

b. chloroethane, as the C–Cl bond is weaker (324 kJ mol^{-1}) than the C–H bond (414 kJ mol^{-1}) and thus breaks more easily

c. This reaction is S_N2 nucleophilic substitution.



The marks in this question are typically awarded for any three of the following features of the mechanism:

- curly arrow going from lone pair/negative charge on ^{-}OH to carbon atom in CH_2
- curly arrow showing Cl^- leaving. Curly arrow must start at the bond between the carbon and chlorine atom and finish on the chlorine atom.
- representation of transition state showing negative charge, square brackets and partial bonds
- correct structure of the final product and leaving group (chloride ion).

10. **a.** **i.** electrophilic addition

ii. 2-chloropropane

iii. secondary carbocation/carbonium ion is more stable

OR carbocation/carbonium ion is stabilized by two/more alkyl groups

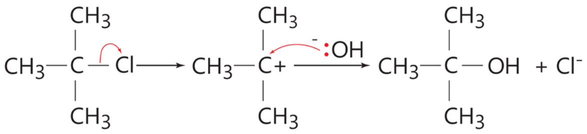
iv. $CH_3CHClCH_3(l) + OH^-(aq) \rightarrow CH_3CH(OH)CH_3(aq) + Cl^-(aq)$

OR $CH_3CHClCH_3(l) + NaOH(aq) \rightarrow CH_3CH(OH)CH_3(aq) + NaCl(aq)$

b. **i.** first order

ii. The reaction is monomolecular, as otherwise its rate would depend on the [OH$^-$] concentration. Therefore, the rate-limiting (slow) step involves only halogenoalkane, so the mechanism is S_N1.

iii.



The marks in this question are typically awarded for the following features of the mechanism:

curly arrow showing Cl^- leaving

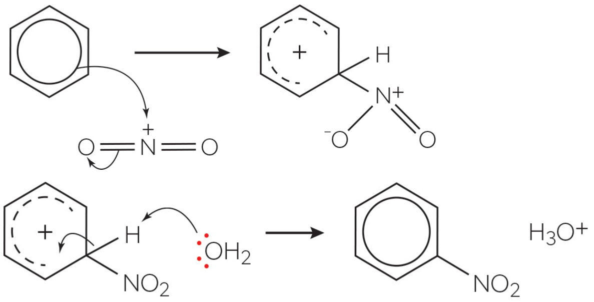
representation of secondary carbocation

curly arrow going from lone pair or negative charge on O in OH^- to C^+.

11. a. $HNO_3 + H_2SO_4 \rightleftharpoons H_2NO_3^+ + HSO_4^-$

$H_2NO_3^+ \rightleftharpoons NO_2^+ + H_2O$

b.



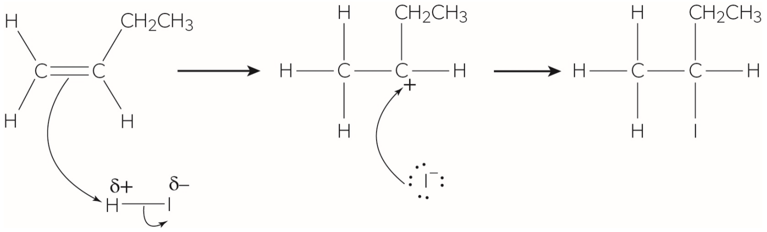
The marks in this question are typically awarded for the following features of the mechanism:

- curly arrow going from benzene ring to N of $+NO_2$
- carbocation with correct formula and positive charge on partially broken ring (shown as dashed curve)
- curly arrow going from C–H bond to partially broken ring of cation
- formation of organic product nitrobenzene and H^+

12. a. 1-iodobutane and 2-iodobutane

b. 2-iodobutane is formed via the more stable secondary carbocation, so this is the major product

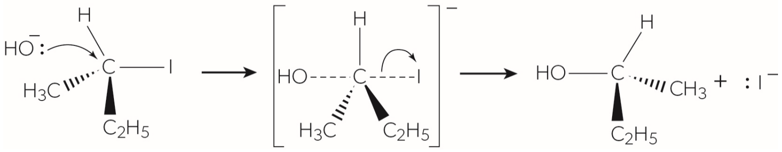
c.



The marks in this question are typically awarded for the following features of the mechanism:

- curly arrow going from C=C to H of HI and curly arrow showing I^- leaving
- representation of carbocation
- curly arrow going from lone pair/negative charge on I^- to C^+
- 2-iodobutane formed

d. S_N2; rate depends on both OH^- and 2-iodobutane



Depending on the reaction conditions, the S_N1 mechanism is also possible.