Raffles Institution
Year 6 H2 Chemistry 2026
Tutorial 15 – Acid-Base Equilibria

__Self-Check Questions__

1 (a) (i) Outline the Brønsted–Lowry theory of acids and bases.

(ii) Identify the conjugate acid–base pairs in the following reactions:

I. $CH_3COOH + H_2SO_4 \rightleftharpoons CH_3COOH_2^+ + HSO_4^-$

II. $CH_3NH_2(aq) + H_2O(l) \rightleftharpoons CH_3NH_3^+(aq) + OH^-(aq)$

III. $HNO_2(aq) + CN^-(aq) \rightleftharpoons HCN(aq) + NO_2^-(aq)$

(b) (i) Outline the Lewis theory of acids and bases.

(ii) Identify the Lewis acid and base in each of the following reactions:

I. $(CH_3)_3N(g) + BF_3(g) \rightleftharpoons (CH_3)_3NBF_3(s)$

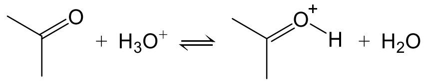
II. $Al(OH)_3(s) + OH^-(aq) \rightleftharpoons [Al(OH)_4]^-(aq)$

(c) Identify the acid and base present in the following reactions, in terms of the Brønsted–Lowry theory, the Lewis theory, or both, as appropriate.

(i) $HBr(g) + H_2O(l) \rightarrow H_3O^+(aq) + Br^-(aq)$

(ii) $HIO + NH_2^- \rightleftharpoons NH_3 + IO^-$

(iii)



2 Calculate the pH of the following solutions at 298 K.

(a) 0.010 mol dm^{-3} H_2SO_4

(b) 0.40 g dm^{-3} NaOH

(c) A solution formed by mixing 14.00 cm^3 of 0.10 mol dm^{-3} H_2SO_4 with 20.00 cm^3 of 0.10 mol dm^{-3} NaOH.

(d) 0.30 mol dm^{-3} CH_3CH_2COOH (pK_a = 4.89)

(e) 2.00 mol dm^{-3} $CH_3CH_2NH_2$ (K_b of $CH_3CH_2NH_2$ = 5.1 x 10^{-4} mol dm^{-3})
[Note: $CH_3CH_2NH_2(aq) + H_2O(l) \rightleftharpoons CH_3CH_2NH_3^+(aq) + OH^-(aq)$]

(f) 0.015 mol dm^{-3} potassium benzoate, $C_6H_5COO^-K^+$
(K_a of benzoic acid, C_6H_5COOH = 6.5 x 10^{-5} mol dm^{-3})

(g) 0.25 mol dm^{-3} methylammonium nitrate, $CH_3NH_3^+ NO_3^-$
(K_b of methylamine CH_3NH_2 = 4.4 x 10^{-4} mol dm^{-3})
[Note: $CH_3NH_3^+(aq) + H_2O(l) \rightleftharpoons CH_3NH_2(aq) + H_3O^+(aq)$]

(h) A solution containing 0.50 mol dm^{-3} $CH_3CH_2COOH(aq)$ and 0.35 mol dm^{-3} $CH_3CH_2COO^-K^+(aq)$.
(K_a of CH_3CH_2COOH = 1.3 x 10^{-5} mol dm^{-3})

(i) A solution containing 0.060 mol dm^{-3} of NH_3 and 0.080 mol dm^{-3} of NH_4Cl.
(K_b of NH_3 = 1.74 x 10^{-5} mol dm^{-3})

3 (a) A solution of 1.00×10^{-3} mol dm^{-3} HX has a pH of 3.25. Calculate the acid dissociation constant of HX.

(b) A solution of 1.00×10^{-2} mol dm^{-3} sodium ethanoate has a pH of 8.37. Calculate the pK_a of ethanoic acid.

(c) A solution of 0.050 mol dm^{-3} ammonium sulfate solution has a pH of 5.12 at 298 K. Calculate the pK_b of ammonia.

4 [N2009/1/6]

What is a property of a solution of dry hydrogen chloride in dry methylbenzene?

A It has a pH less than 7.

B It is a non-conductor of electricity.

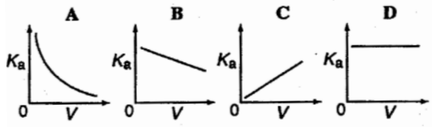
C It reacts with magnesium to give hydrogen.

D It reacts with anhydrous sodium carbonate to give carbon dioxide.

5 [N2008/1/11]

A 1 mol sample of ethanoic acid is diluted at constant temperature to a volume *V*.

Which diagram shows how K_a, the acid dissociation constant, varies with *V*?



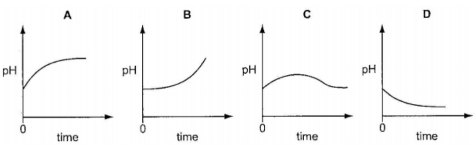
6 [N2010/I/12]

Sulfur dioxide gas is converted to sulfate ions when it is bubbled into aqueous manganate(VII) ions.

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

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

Which graph shows how the pH changes as sulfur dioxide is bubbled at a constant rate into a well-stirred solution of managate(VII) ions until its colour just fades?



7 [N2002/1/8]

Use of the Data Booklet is relevant to this question.

Water dissociates as shown.

$$H_2O \rightleftharpoons H^+ + OH^-$$

At 25 °C, the equilibrium value of [H$^+$] is 10^{-7} mol dm^{-3}; $[H_2O] = \frac{1000}{18}$ mol dm^{-3}.

What is the order of increasing numerical value of pH, pK_a and pK_w for this equilibrium at this temperature?

[pK_w = –log K_w]

	smallest		largest
A	pH	pK_a	pK_w
B	pH	pK_w	pK_a
C	pK_a	pK_w	pH
D	pK_w	pK_a	pH

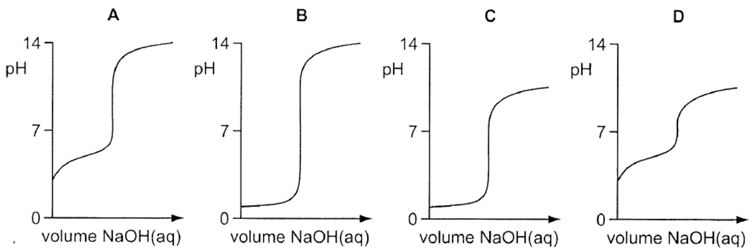
8 [N2012/1/9]

Pyruvic acid is a weak acid that is an important intermediate in many biochemical processes.

CH_3COCO_2H

pyruvic acid

Which graph best represents the change in pH that occurs when a sample of pyruvic acid is titrated with NaOH(aq)?



Practice Questions

1 A sample of apple juice has a pH of 3.50. When 25.0 cm^3 of this apple juice sample is titrated against 0.100 mol dm^{-3} sodium hydroxide using thymolphthalein as the indicator, the average titre value is 27.50 cm^3.

(a) Define pH and calculate the molar concentration of hydrogen ions in apple juice.

(b) Assuming that apple juice contains a single acid HA which is monobasic, calculate the molar concentration of HA in apple juice and hence explain whether HA is a strong or weak acid.

(c) Calculate the degree of dissociation and the acid dissociation constant of the acid HA.

(d) A sample of hydrochloric acid has the same pH as the sample of apple juice. Explain why if 1 dm^3 each of apple juice and this hydrochloric acid were treated separately with the same excess amount of zinc powder, the apple juice would yield a <u>larger</u> volume of hydrogen gas at room temperature.

2 The pK_a for ethanoic acid at 25 °C is 4.74.

(a) (i) Calculate the pH of an aqueous solution of 0.50 mol dm^{-3} ethanoic acid.

(ii) Calculate the pH of the resultant solution when equal volumes of 0.50 mol dm^{-3} ethanoic acid and 0.20 mol dm^{-3} sodium hydroxide are mixed.

(b) A solution that contains only sodium ethanoate of concentration 0.050 mol dm^{-3} has a pH that is above 7.

(i) Write an equation involving the ethanoate ion and explain why the pH of the solution is above 7.

(ii) Write an expression for the base dissociation constant K_b for the ethanoate ion and calculate the value of K_b for the ethanoate ion.

(iii) Hence, calculate the pH of a 0.050 mol dm^{-3} sodium ethanoate solution.

(c) A laboratory assistant wanted to prepare a buffer solution containing ethanoic acid and sodium ethanoate. Find the volume of 0.10 mol dm^{-3} of sodium ethanoate that is needed to be added to 25.0 cm^3 of 0.12 mol dm^{-3} CH_3COOH(aq) to form a buffer solution of pH 5.00.

3 (a) A buffer solution is prepared by mixing 750 cm^3 of 0.20 mol dm^{-3} ammonium chloride solution and 500 cm^3 of 0.10 mol dm^{-3} aqueous ammonia. Calculate the pH of this buffer solution. (K_a for the ammonium ion = 6.00×10^{-10} mol dm^{-3} at 25 °C)

(b) Calculate the change in pH of the buffer solution prepared in (a) after the addition of

(i) 0.002 mol of solid sodium hydroxide,
(ii) 1.0 cm^3 of 2.00 mol dm^{-3} hydrochloric acid.

4 Atmospheric carbon dioxide can dissolve in sea water.
The three inorganic carbon-containing species present in sea water are:

- Dissolved CO_2(g)
- CO_3^{2-}(aq)
- HCO_3^-(aq).

Commented [SL1]: Adapted from 2024/P2/Q6 for new syllabus Ocean Acidification

Increasing levels of CO_2(g) in the atmosphere can change the proportions of these inorganic carbon-containing species present in sea water.

This first happens when atmospheric CO_2 dissolves in sea water:

$$CO_2(g) \rightleftharpoons CO_2(aq)$$

This can lead to ocean acidification.

Reactions 4.1 and 4.2 show the two equilibria that regulate the concentration of the three inorganic carbon-containing species present in sea water and the values of their equilibrium constants. In reaction 4.1, the value for K_1 assumes that the concentration of water is constant.

reaction 4.1 $CO_2 + H_2O \rightleftharpoons HCO_3^- + H^+$ $K_1 = 1.45 \times 10^{-6}$ mol dm^{-3} at 298 K
reaction 4.2 $HCO_3^- \rightleftharpoons CO_3^{2-} + H^+$ $K_2 = 1.10 \times 10^{-9}$ mol dm^{-3} at 298 K

When changes to the amount of dissolved carbon dioxide in the ocean occur, the pH of sea water remains approximately constant between pH 7.5 and 8.5. This is due to CO_3^{2-}(aq) and HCO_3^-(aq) acting as a buffer.

(a) Approximately 200 years ago, the average pH of sea water taken from the ocean surface was 8.2. At present, this is 8.1.
Calculate the percentage increase in hydrogen ion concentration of the sea water taken from the ocean surface at present compared to 200 years ago.

(b) Using information from reactions 4.1 and 4.2, suggest how the CO_3^{2-}(aq) and HCO_3^-(aq) buffer maintains the pH in sea water as the amount of carbon dioxide gas in the atmosphere increases.

(c) Deduce the most abundant inorganic carbon-containing species present in sea water at pH 8.1. Explain your answer.

5 The K_a of lactic acid is 1.4×10^{-4} mol dm^{-3} at 298 K.

A buffer solution contains 1.5 mol dm^{-3} lactic acid and 0.5 mol dm^{-3} sodium lactate.

Which statement correctly describes the buffer solution?

A The pH of the buffer solution is 4.33.

B The pH of the buffer solution decreases upon dilution with water.

C The buffering capacity of the buffer solution increases upon dilution with water.

D The buffer solution has a greater buffering capacity against a base compared to an acid.

6 The major acidic component of soured milk is lactic acid, $CH_3CH(OH)CO_2H$. When 10.0 cm^3 of solution of lactic acid was titrated against 0.050 mol dm^{-3} sodium hydroxide the following pH readings were obtained:

Volume of NaOH added /cm^3	0	2	4	6	8	10	12	14	16	18	20
pH	2.5	3.1	3.4	3.7	3.9	4.1	4.4	4.7	9.1	11.6	11.8

(a) Plot a graph of these results with pH on the y–axis and volume of NaOH added on the x–axis.

Identify the two major organic species present in this solution at pH 3.0 − 5.0.
Explain why the slope of the graph only changes gradually in this region.

(b) (i) Suggest a suitable indicator for this titration, giving a reason for your choice.

(ii) For the indicator chosen, state the colour change at the end–point of the titration.

(c) Calculate the molar concentration of the lactic acid in the solution.

(d) Deduce from the graph the K_a value for lactic acid.

(e) Explain why, at the equivalence–point of this titration, the resulting solution is basic.

(f) Indicate clearly on your graph the region within which the mixture is acting as an acidic buffer solution, labelling the point in which the mixture has maximum buffer capacity.

7 Phenylboronic acid, $C_6H_5B(OH)_2$, and benzoic acid, $C_6H_5CO_2H$, are both monoprotic (monobasic) acids, with pK_a values of 8.86 and 4.20 respectively.

(a) Give the equation which represents the dissociation of benzoic acid.

(b) Calculate the pH of 0.010 mol dm^{-3} benzoic acid.

(c) Which is the stronger of the two acids? Explain your reasoning.

(d) A 10.0 cm^3 sample of **X**, a solution containing both of these acids, was titrated against 0.050 mol dm^{-3} NaOH using a mixture of two indicators, bromothymol blue and thymolphthalein. It was found that 8.6 cm^3 of NaOH(aq) were needed to change the colour of the first indicator and a further 7.1 cm^3 were needed to change the colour of the second indicator.

(i) Using the above information, sketch a labelled graph to show how pH changes with the addition of NaOH(aq) for this titration.

(ii) Use the data to calculate the concentration of each of the two acids in **X**.
(hint: the NaOH added will first react with the stronger acid in the titration.)