Past-paper walk-through

Weak Acid and Base Equilibria ▪ 8.3

eXercise

Questions in this set

- 2026 Q3
- 2025 Q7
- 2023 Q5
- 2021 Q1
- 2019 Q3
- 2018 Q5
- 2016 Q4
- 2014 Q2

Reading the mark scheme

- **B1** a mark that stands on its own – the point is either made or not.
- **M1** a *method* mark: the right approach, even if the number is wrong.
- **A1** an *answer* mark, and it usually needs its M mark first.
- **C1** a working mark on the way to the answer.
- // separates answers the examiner accepts equally.
- **ecf** = error carried forward: a later part is marked on your own earlier answer.
- **owtte** = "or words to that effect" – the wording need not match.

Question 3

2026 ▪ Q3

Nitrous acid, HNO_2, is a weak acid that ionizes according to Equation 1.

Equation 1: $HNO_2(aq) + H_2O(l) \rightleftharpoons NO_2^-(aq) + H_3O^+(aq)$ $\qquad K_a = 5.6 \times 10^{-4}$ at 298 K

(a) Identify a conjugate acid-base pair in the equation. Be sure to clearly label which is the acid and which is the base.

Question 3

Table 1

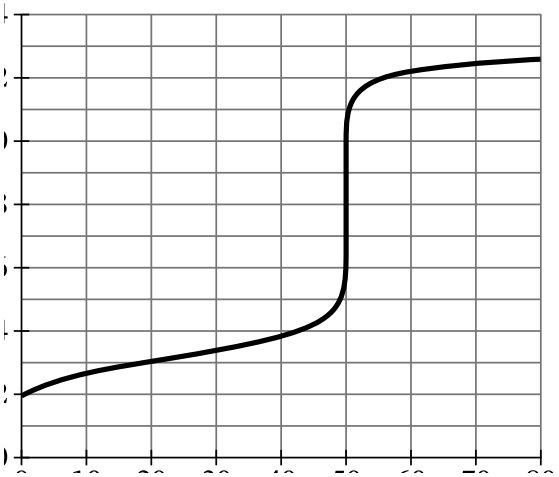
Chemical Equation	Equilibrium Constant
$HNO_2(aq) + H_2O(l) \rightleftarrows NO_2^-(aq) + H_3O^+(aq)$	$K_a = 5.6 \times 10^{-4}$
$H_2O(l) + H_2O(l) \rightleftarrows H_3O^+(aq) + OH^-(aq)$	$K_w = 1.0 \times 10^{-14}$
$HNO_2(aq) + OH^-(aq) \rightarrow NO_2^-(aq) + H_2O(l)$	$K_2 =$?

Question 3

Table 2

Indicator Name	Acid Color	pH Range of Color Change	Base Color
Methyl orange	Red	3.1–4.4	Yellow
Thymol blue	Yellow	8.0–9.6	Blue
Clayton yellow	Yellow	12.2–13.2	Orange

Question 3



Question 3

2026 ▪ Q3

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(b)(i) A solution of $HNO_2(aq)$ with an initial concentration of 0.125 M has a pH of 2.09.

Calculate the value of $[H_3O^+]$ in the solution. Show the work that leads to your answer.

(b)(ii) **Calculate** $[HNO_2]$ at equilibrium. Show the work that leads to your answer.

Question 3

2026 ▪ Q3

Nitrous acid, HNO_2, is a weak acid that ionizes according to Equation 1.

Equation 1: $HNO_2(aq) + H_2O(l) \rightleftharpoons NO_2^-(aq) + H_3O^+(aq)$ $\qquad K_a = 5.6 \times 10^{-4}$ at 298 K

(c)(i) In an experiment, the solution of 0.125 *M* $HNO_2(aq)$ is heated to 333 K. The new equilibrium concentrations are determined to be $[HNO_2] = 0.114$ *M*, $[NO_2^-] = 0.0109$ *M*, and $[H_3O^+] = 0.0109$ *M*.
Calculate the value of K_a for HNO_2 at 333 K. Show the work that leads to your answer.
(c)(ii) Is the reaction represented by Equation 1 endothermic or exothermic? **Justify** your answer by comparing K_a values at 298 K and 333 K.

Question 3

2026 ▪ Q3

Nitrous acid, HNO_2, is a weak acid that ionizes according to Equation 1.

Equation 1: $HNO_2(aq) + H_2O(l) \rightleftharpoons NO_2^-(aq) + H_3O^+(aq)$ $\qquad K_a = 5.6 \times 10^{-4}$ at 298 K

(d) The following information applies to parts D, E, and F.
In a second experiment, a student is given a bottle containing HNO_2 with an unknown molarity. To determine the concentration of the $HNO_2(aq)$ in the bottle, the student titrates 35.0 mL of the $HNO_2(aq)$ with 0.16 M $NaOH(aq)$ at 298 K, which reacts according to Equation 2.

Equation 2: $HNO_2(aq) + OH^-(aq) \rightarrow NO_2^-(aq) + H_2O(l)$

Question 3

The results of the titration are summarized in Figure 1.
[Figure 1: Titration curve, pH vs. Volume of 0.16 M NaOH Added (mL); y-axis pH 0 to 14 in increments of 2, x-axis 0 to 80 mL in increments of 10; curve starts near $(0, 2)$, rises gradually to about $(40, 4)$, then rises steeply (equivalence point) between about 45-55 mL up to about pH 12, then levels off gradually to approximately $(80, 12.7)$.]
Using Figure 1, **identify** the pH at the equivalence point.

Question 3

2026 ▪ Q3

Nitrous acid, HNO_2, is a weak acid that ionizes according to Equation 1.

Equation 1: $HNO_2(aq) + H_2O(l) \rightleftharpoons NO_2^-(aq) + H_3O^+(aq)$ $\qquad K_a = 5.6 \times 10^{-4}$ at 298 K

(e) Using Figure 1, **calculate** the molarity $HNO_2(aq)$ of in the bottle. Show the work that leads to your answer.

Question 3

2026 ▪ Q3

Nitrous acid, HNO_2, is a weak acid that ionizes according to Equation 1.

Equation 1: $HNO_2(aq) + H_2O(l) \rightleftharpoons NO_2^-(aq) + H_3O^+(aq)$ $\qquad K_a = 5.6 \times 10^{-4}$ at 298 K

(f) **Draw** an X on Figure 1 to represent a point in the titration where $[HNO_2] > [NO_2^-]$ in the reaction mixture.

Question 3

2026 ▪ Q3

Nitrous acid, HNO_2, is a weak acid that ionizes according to Equation 1.

Equation 1: $HNO_2(aq) + H_2O(l) \rightleftharpoons NO_2^-(aq) + H_3O^+(aq)$ $\quad K_a = 5.6 \times 10^{-4}$ at 298 K

(g) Equilibrium constants at 298 K are shown in Table 1 for the acid ionization reaction represented by Equation 1, K_a; the autoionization of water, K_w; and the neutralization reaction represented by Equation 2, K_2.

| Chemical Equation | Equilibrium Constant | |—|—| |
$HNO_2(aq) + H_2O(l) \rightleftharpoons NO_2^-(aq) + H_3O^+(aq)$ | $K_a = 5.6 \times 10^{-4}$ | |
$H_2O(l) + H_2O(l) \rightleftharpoons H_3O^+(aq) + OH^-(aq)$ | $K_w = 1.0 \times 10^{-14}$ | |
$HNO_2(aq) + OH^-(aq) \rightarrow NO_2^-(aq) + H_2O(l)$ | $K_2 = ?$ |

Question 3

Calculate the value of K_2 for Equation 2 at 298 K. Show the work that leads to your answer.

Question 3

2026 ▪ Q3

Nitrous acid, HNO_2, is a weak acid that ionizes according to Equation 1.

Equation 1: $HNO_2(aq) + H_2O(l) \rightleftharpoons NO_2^-(aq) + H_3O^+(aq)$ $\qquad K_a = 5.6 \times 10^{-4}$ at 298 K

(h) The student decides to repeat the experiment, this time using an indicator, and has access to the indicators in Table 2.

Indicator Name	Acid Color	pH Range of Color Change	Base Color
Methyl orange	Red	3.1–4.4	Yellow
Thymol blue	Yellow	8.0–9.6	Blue
Clayton yellow	Yellow	12.2–13.2	Orange

Question 3

The student conducts a second titration by adding two drops of methyl orange indicator to 35.0 mL of the $HNO_2(aq)$ solution and titrating the solution with 0.16 M NaOH(aq) until a color change from red to yellow occurs.
The student claims that methyl orange was the best choice for the indicator. Do you agree or disagree? **Justify** your answer.

Question 7

2025 ▪ Q7

Answer the following questions about the glycolate ion, $C_2H_3O_3^-$, which acts as a base in aqueous solution. A Lewis diagram for the ion is provided.

[Lewis structure of the glycolate ion in brackets with an overall negative charge: H—O—C(—H)(—H)—C(=O)—O:, i.e., an H atom bonded to an O atom (with two lone pairs) which is bonded to a C atom; that C atom is bonded to two H atoms and to a second C atom; the second C atom is double-bonded to an O atom (with two lone pairs) above it and singly bonded to another O atom (with three lone pairs) on the right.]

(a) On the Lewis diagram in part A, circle the atom that accepts the proton when the glycolate ion reacts with water.

When the glycolate ion reacts with water, it forms glycolic acid, $HC_2H_3O_3$, according to the following equation. The K_b expression for the reaction is provided.

Question 7

$$C_2H_3O_3^-(aq) + H_2O(l) \rightleftharpoons HC_2H_3O_3(aq) + OH^-(aq) \qquad K_b = \frac{[HC_2H_3O_3][OH^-]}{[C_2H_3O_3^-]}$$

Question 7

2025 ▪ Q7

Answer the following questions about the glycolate ion, $C_2H_3O_3^-$, which acts as a base in aqueous solution. A Lewis diagram for the ion is provided.

[Lewis structure of the glycolate ion in brackets with an overall negative charge: H—O—C(—H)(—H)—C(=O)—O:, i.e., an H atom bonded to an O atom (with two lone pairs) which is bonded to a C atom; that C atom is bonded to two H atoms and to a second C atom; the second C atom is double-bonded to an O atom (with two lone pairs) above it and singly bonded to another O atom (with three lone pairs) on the right.]

(b) At $25°C$, a 2.5 *M* solution of glycolate is found to have $[OH^-] = 1.3 \times 10^{-5}$ *M*.

(b)(i) Calculate the value of K_b for the glycolate ion.

(b)(ii) Using your answer to part B (i), calculate the value of K_a for glycolic acid at $25°C$.

Question 7

Glycolic acid can be produced from the hydrolysis of methyl glycolate, $C_3H_6O_3$. A proposed mechanism for the reaction is given.

Step 1: $C_3H_6O_3 + H_3O^+ \rightleftharpoons C_2H_5O_3^+ + CH_3OH$

Step 2: $C_2H_5O_3^+ + H_2O \rightleftharpoons HC_2H_3O_3 + H_3O^+$

Overall: $C_3H_6O_3 + H_2O \rightleftharpoons HC_2H_3O_3 + CH_3OH$

Question 7

2025 ▪ Q7

Answer the following questions about the glycolate ion, $C_2H_3O_3^-$, which acts as a base in aqueous solution. A Lewis diagram for the ion is provided.

[Lewis structure of the glycolate ion in brackets with an overall negative charge: H—O—C(—H)(—H)—C(=O)—O:, i.e., an H atom bonded to an O atom (with two lone pairs) which is bonded to a C atom; that C atom is bonded to two H atoms and to a second C atom; the second C atom is double-bonded to an O atom (with two lone pairs) above it and singly bonded to another O atom (with three lone pairs) on the right.]

(c) A student claims that H_3O^+ is a catalyst for the reaction. Do you agree or disagree? Justify your answer based on the mechanism given.

Solution 7

(a)

Mark scheme

- Circle one of the two equivalent terminal oxygen atoms on the carboxylate ($-COO^-$) group of the glycolate ion — the atom that accepts the proton (H^+) from water to form glycolic acid. Because of resonance, the two C–O bonds on the carboxylate group are equivalent, so circling either one is acceptable.

Solution 7

(b)

Mark scheme

- No separate response required — this is the context/stem giving $[OH^-] = 1.3 \times 10^{-5}$ *M* for a 2.5 M glycolate solution at 25°C that parts (i) and (ii) below use.

Solution 7

(b)(i)

Mark scheme

- $K_b = \dfrac{[HC_2H_3O_3][OH^-]}{[C_2H_3O_3^-]} = \dfrac{(1.3 \times 10^{-5})(1.3 \times 10^{-5})}{2.5 - 1.3 \times 10^{-5}} \approx \dfrac{(1.3 \times 10^{-5})^2}{2.5} = 6.8 \times 10^{-11}$.

Solution 7

(b)(ii)

Mark scheme

- $K_a = \dfrac{K_w}{K_b} = \dfrac{1.0 \times 10^{-14}}{6.8 \times 10^{-11}} = 1.5 \times 10^{-4}$ (using the K_b value from part B(i)).

Solution 7

(c)

Mark scheme

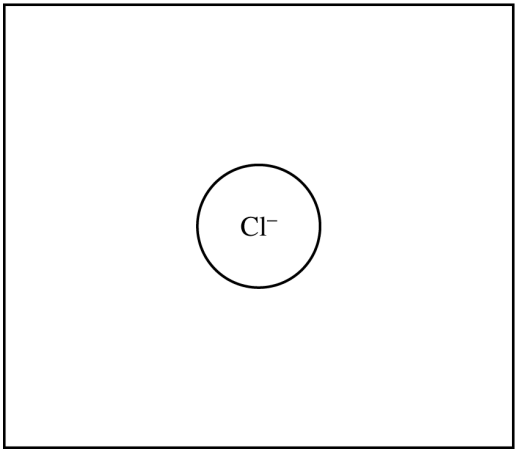
- Agree. H_3O^+ is consumed in step 1 of the mechanism and regenerated in step 2, which is consistent with the behavior of a catalyst — it is used up and then reformed, so it is not permanently consumed by the overall reaction.

Question 5

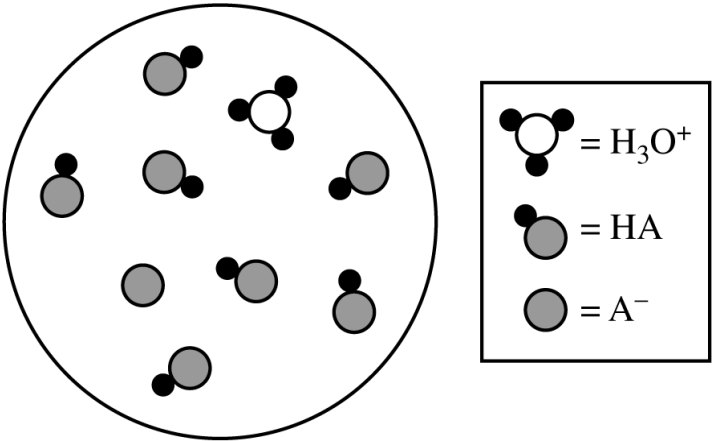
2023 ▪ Q5

HCl is a molecular gas as a pure substance but acts as an acid in aqueous solution.
(a)(i) A sample of HCl(g) is stored in a rigid 6.00 L container at 7.45 atm and 296 K. Calculate the number of moles of HCl(g) in the container.
(a)(ii) The rigid 6.00 L container of HCl(g) is cooled to a temperature of 271 K. Calculate the new pressure, in atm, of the HCl(g).

Question 5



Question 5



Question 5

2023 ▪ Q5

HCl is a molecular gas as a pure substance but acts as an acid in aqueous solution.

(b) When HCl ionizes in aqueous solution, $Cl^-(aq)$ ions are formed. In the following box, draw three water molecules with proper orientation around the Cl^- ion. Use [a water-molecule symbol: a large circle (O) with two small circles (H) attached] to represent water molecules.

[Empty square box with a small circle labeled Cl^- at its center, for the student to draw three water molecules around.]

Question 5

2023 ▪ Q5

HCl is a molecular gas as a pure substance but acts as an acid in aqueous solution.

(c) | Acid (HA) | Anion (A^-) | K_a Value | |—|—|—| | HNO_2 | NO_2^- | 5.6×10^{-4} | | HCl | Cl^- | 2.0×10^7 | | $HClO_4$ | ClO_4^- | 1.6×10^{15} |

The K_a values for three acids are shown in the preceding table.

The following particulate diagram represents the ionization of one of the acids in the data table. Water molecules have been omitted for clarity. Which acid (HNO_2, HCl, or $HClO_4$) is represented in the diagram? Justify your answer using the information in the table.

[Particle diagram: a large circle containing several small particle pairs; legend shows three symbols: a three-circle cluster (two small white circles bonded to one larger white circle) = H_3O^+; a gray circle with a small black dot attached = HA; a plain gray circle = A^-. Inside the large circle: two H_3O^+-like clusters, several HA (gray-with-dot)

Question 5

particles, and several bare A^- (plain gray) particles scattered about — roughly equal numbers of HA and A^- particles with two H_3O^+ clusters, suggesting near-complete/extensive ionization.]

Solution 5

(a)(i)

Mark scheme

- Ideal gas law: $n = \dfrac{PV}{RT} = \dfrac{(7.45\ \text{atm})(6.00\ \text{L})}{\left(0.08206\ \frac{\text{L}\cdot\text{atm}}{\text{mol}\cdot\text{K}}\right)(296\ \text{K})} = 1.84\ \text{mol}.$

Solution 5

(a)(ii)

Mark scheme

- At constant volume and moles, $\frac{P_1}{T_1} = \frac{P_2}{T_2} \Rightarrow P_2 = \frac{P_1 T_2}{T_1} = \frac{(7.45\ \text{atm})(271\ \text{K})}{296\ \text{K}} = 6.82\ \text{atm}$ (equivalently via $P = nRT/V$ using $n = 1.84$ mol).

Solution 5

(b)

Mark scheme

- Draw three water molecules arranged around the central Cl^- ion with the partially-positive hydrogen (H) atom of each water molecule pointed inward, toward the Cl^- ion — reflecting the ion-dipole attraction between the negative Cl^- and the $\delta+$ H atoms of water.

Solution 5

(c)

Mark scheme

- HNO_2. The particulate diagram shows most of the acid molecules still in un-ionized (molecular) form, indicating a weak acid with a K_a value less than 1 — much less than the fully-dissociated strong acids HCl or $HClO_4$ in the table — which is consistent with HNO_2.

Question 1

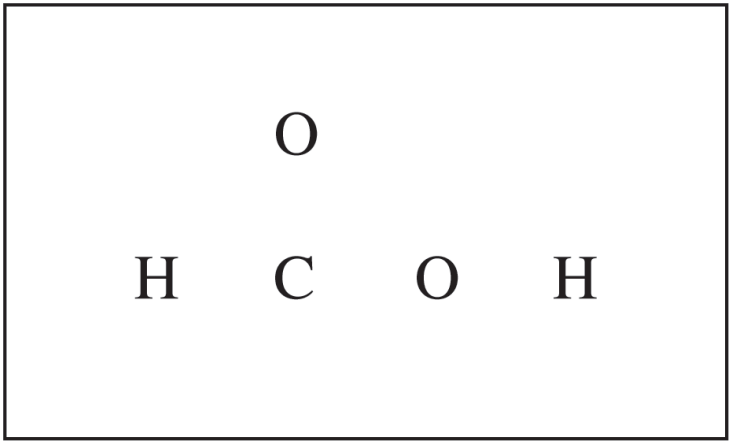
2021 ▪ Q1

$$HCOOH(aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + HCOO^-(aq) \qquad K_a = 1.8 \times 10^{-4}$$

Methanoic acid, HCOOH, ionizes according to the equation above.

(a) Write the expression for the equilibrium constant, K_a, for the reaction.

Question 1



Question 1

2021 ▪ Q1

$$HCOOH(aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + HCOO^-(aq) \qquad K_a = 1.8 \times 10^{-4}$$

Methanoic acid, HCOOH, ionizes according to the equation above.

(b) Calculate the pH of a 0.25 *M* solution of HCOOH.

Question 1

2021 ▪ Q1

$$HCOOH(aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + HCOO^-(aq) \qquad K_a = 1.8 \times 10^{-4}$$

Methanoic acid, HCOOH, ionizes according to the equation above.

(c) In the box below, complete the Lewis electron-dot diagram for HCOOH. Show all bonding and nonbonding valence electrons.

[Box containing the skeletal atom arrangement of HCOOH (no bonds or lone pairs drawn), laid out as:

```
        O
        |
H - C - O - H
```

Question 1

i.e. a central C bonded to: an O atom above it (drawn separated, no bond line shown), an H atom to its left, and an O atom to its right which is in turn bonded to a further H atom on the far right. The student must add all bonding and nonbonding valence electrons to complete the Lewis structure.]

Question 1

2021 ▪ Q1

$$HCOOH(aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + HCOO^-(aq) \qquad K_a = 1.8 \times 10^{-4}$$

Methanoic acid, HCOOH, ionizes according to the equation above.

(d)(i)

$$H_2NNH_2(aq) + H_2O(l) \rightleftharpoons H_2NNH_3^+(aq) + OH^-(aq) \qquad K_b = 1.3 \times 10^{-6}$$

In aqueous solution, the compound H_2NNH_2 reacts according to the equation above. A 50.0 mL sample of 0.25 *M* $H_2NNH_2(aq)$ is combined with a 50.0 mL sample of 0.25 *M* $HCOOH(aq)$.

Write the balanced net ionic equation for the reaction that occurs when H_2NNH_2 is combined with HCOOH.

(d)(ii) Is the resulting solution acidic, basic, or neutral? Justify your answer.

Question 1

2021 ▪ Q1

$$HCOOH(aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + HCOO^-(aq) \qquad K_a = 1.8 \times 10^{-4}$$

Methanoic acid, HCOOH, ionizes according to the equation above.

(e) When a catalyst is added to a solution of $HCOOH(aq)$, the reaction represented by the following equation occurs.

$$HCOOH(aq) \rightarrow H_2(g) + CO_2(g)$$

Is the reaction a redox reaction? Justify your answer.

Question 1

2021 ▪ Q1

$$HCOOH(aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + HCOO^-(aq) \qquad K_a = 1.8 \times 10^{-4}$$

Methanoic acid, HCOOH, ionizes according to the equation above.

(f) [Graph: Total Pressure (atm) on the y-axis (from 0 to above 24, with a dashed horizontal line at 24) vs. Time (hours) on the x-axis. The curve rises steeply from the origin, curving and leveling off asymptotically to a plateau at a total pressure of 24 atm.]

The reaction occurs in a rigid 4.3 L vessel at 25°C, and the total pressure is monitored, as shown in the graph above. The vessel originally did not contain any gas. Calculate the number of moles of $CO_2(g)$ produced in the reaction. (Assume that the amount of $CO_2(g)$ dissolved in the solution is negligible.)

Question 1

2021 ▪ Q1

$$HCOOH(aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + HCOO^-(aq) \qquad K_a = 1.8 \times 10^{-4}$$

Methanoic acid, HCOOH, ionizes according to the equation above.

(g) After the reaction has proceeded for several minutes, does the amount of catalyst increase, decrease, or remain the same? Justify your answer.

Solution 1

(a)

Mark scheme

- $K_a = \dfrac{[H_3O^+][HCOO^-]}{[HCOOH]}$ — the correct equilibrium-constant expression for the dissociation of HCOOH (products over reactant; water omitted as pure liquid).

Solution 1

(b)

Mark scheme

- ICE table for HCOOH + H2O H3O+ + HCOO-, initial [HCOOH]=0.25 M: $K_a = 1.8 \times 10^{-4} = \dfrac{x^2}{0.25 - x}$. Assuming $x \ll 0.25$: $x^2 = (1.8 \times 10^{-4})(0.25) \Rightarrow x = [\mathrm{H_3O^+}] = 0.0067$ *M* (1 pt). Then $\mathrm{pH} = -\log[\mathrm{H_3O^+}] = -\log(0.0067) = 2.17$ (1 pt, consistent with the calculated concentration).

Solution 1

(c)

Mark scheme

- Correct complete Lewis structure of HCOOH (formic acid): H–C(=O)–O–H. The central C is bonded to: an H atom (single bond), a terminal O by a double bond (that terminal O carries 2 lone pairs), and a second O by a single bond (that O carries 2 lone pairs and is also single-bonded to the second H). All bonding pairs and all nonbonding (lone) pairs of valence electrons must be shown explicitly.

Solution 1

(d)(i)

Mark scheme

- $H_2NNH_2(aq) + HCOOH(aq) \rightarrow H_2NNH_3^+(aq) + HCOO^-(aq)$ — the weak base H2NNH2 accepts a proton from the weak acid HCOOH; already balanced as written (state symbols not required).

Solution 1

(d)(ii)

Mark scheme

- Acidic. The resulting solution is a mixture of the conjugate acid H2NNH3+ and the conjugate base HCOO-. Because the K_a of $H_2NNH_3^+$ is greater than the K_b of $HCOO^-$, production of $H_3O^+(aq)$ occurs to a greater extent than production of $OH^-(aq)$, so the solution is acidic.

Solution 1

(e)

Mark scheme

- Yes, it is a redox reaction. Accept either valid justification: the oxidation number of hydrogen changes from $+1$ in HCOOH to 0 in H2 (reduction); or the oxidation number of carbon changes from $+2$ in HCOOH to $+4$ in CO2 (oxidation).

Solution 1

(f) Mark scheme

- Reaction HCOOH(aq) $\rightarrow$ H2(g) + CO2(g) produces H2 and CO2 in a 1:1 mole ratio, so each contributes half the total pressure: $P_{CO_2} = 24 \text{ atm} \times \frac{1 \text{ atm } CO_2}{2 \text{ atm product}} = 12 \text{ atm}$ (1 pt, may be implicit). Then using the ideal gas law $PV = nRT$ with V=4.3 L, T=298 K: $n = \frac{PV}{RT} = \frac{(12 \text{ atm})(4.3 \text{ L})}{(0.08206 \text{ L} \cdot \text{atm} \cdot \text{mol}^{-1}\text{K}^{-1})(298 \text{ K})} = 2.1 \text{ mol } CO_2$ (1 pt).

Solution 1

(g)

Mark scheme

- It would remain the same. In a catalyzed reaction the catalyst is not consumed — it participates in the mechanism but is regenerated — so the net amount of catalyst present stays constant over time.

Question 3

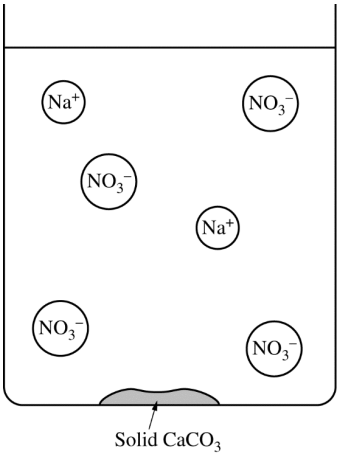
2019 ▪ Q3

A student is given 50.0 mL of a solution of Na_2CO_3 of unknown concentration. To determine the concentration of the solution, the student mixes the solution with excess 1.0 *M* $Ca(NO_3)_2(aq)$, causing a precipitate to form. The balanced equation for the reaction is shown below.

$$Na_2CO_3(aq) + Ca(NO_3)_2(aq) \rightarrow 2\,NaNO_3(aq) + CaCO_3(s)$$

(a) Write the net ionic equation for the reaction that occurs when the solutions of Na_2CO_3 and $Ca(NO_3)_2$ are mixed.

Question 3



Question 3

Volume of Na_2CO_3 solution	50.0 mL
Volume of 1.0 *M* $Ca(NO_3)_2$ added	100.0 mL
Mass of $CaCO_3$ precipitate collected	0.93 g

Question 3

2019 ▪ Q3

A student is given 50.0 mL of a solution of Na_2CO_3 of unknown concentration. To determine the concentration of the solution, the student mixes the solution with excess 1.0 *M* $Ca(NO_3)_2(aq)$, causing a precipitate to form. The balanced equation for the reaction is shown below.

$$Na_2CO_3(aq) + Ca(NO_3)_2(aq) \rightarrow 2\,NaNO_3(aq) + CaCO_3(s)$$

(b) The diagram below is incomplete. Draw in the species needed to accurately represent the major ionic species remaining in the solution after the reaction has been completed.

Question 3

[Diagram of a beaker of solution after reaction: floating ion labels Na^+, NO_3^-, NO_3^-, Na^+, NO_3^-, NO_3^- scattered above a layer of gray solid labelled "Solid $CaCO_3$" at the bottom of the beaker]

The student filters and dries the precipitate of $CaCO_3$ (molar mass 100.1 g/mol) and records the data in the table below.

Volume of Na_2CO_3 solution	50.0 mL
Volume of 1.0 *M* $Ca(NO_3)_2$ added	100.0 mL
Mass of $CaCO_3$ precipitate collected	0.93 g

Question 3

2019 ▪ Q3

A student is given 50.0 mL of a solution of Na_2CO_3 of unknown concentration. To determine the concentration of the solution, the student mixes the solution with excess 1.0 *M* $Ca(NO_3)_2(aq)$, causing a precipitate to form. The balanced equation for the reaction is shown below.

$$Na_2CO_3(aq) + Ca(NO_3)_2(aq) \rightarrow 2\,NaNO_3(aq) + CaCO_3(s)$$

(c) Determine the number of moles of Na_2CO_3 in the original 50.0 mL of solution.

Question 3

2019 ▪ Q3

A student is given 50.0 mL of a solution of Na_2CO_3 of unknown concentration. To determine the concentration of the solution, the student mixes the solution with excess 1.0 *M* $Ca(NO_3)_2(aq)$, causing a precipitate to form. The balanced equation for the reaction is shown below.

$$Na_2CO_3(aq) + Ca(NO_3)_2(aq) \rightarrow 2\,NaNO_3(aq) + CaCO_3(s)$$

(d) The student realizes that the precipitate was not completely dried and claims that as a result, the calculated Na_2CO_3 molarity is too low. Do you agree with the student's claim? Justify your answer.

Question 3

2019 ▪ Q3

A student is given 50.0 mL of a solution of Na_2CO_3 of unknown concentration. To determine the concentration of the solution, the student mixes the solution with excess 1.0 *M* $Ca(NO_3)_2(aq)$, causing a precipitate to form. The balanced equation for the reaction is shown below.

$$Na_2CO_3(aq) + Ca(NO_3)_2(aq) \rightarrow 2\,NaNO_3(aq) + CaCO_3(s)$$

(e) After the precipitate forms and is filtered, the liquid that passed through the filter is tested to see if it can conduct electricity. What would be observed? Justify your answer.

Question 3

The student decides to determine the molarity of the same Na_2CO_3 solution using a second method. When Na_2CO_3 is dissolved in water, $CO_3^{2-}(aq)$ hydrolyzes to form $HCO_3^-(aq)$, as shown by the following equation.

$$CO_3^{2-}(aq) + H_2O(l) \rightleftharpoons HCO_3^-(aq) + OH^-(aq) \qquad K_b = \frac{[HCO_3^-][OH^-]}{[CO_3^{2-}]} = 2.1 \times 10^{-4}$$

Question 3

2019 ▪ Q3

A student is given 50.0 mL of a solution of Na_2CO_3 of unknown concentration. To determine the concentration of the solution, the student mixes the solution with excess 1.0 *M* $Ca(NO_3)_2(aq)$, causing a precipitate to form. The balanced equation for the reaction is shown below.

$$Na_2CO_3(aq) + Ca(NO_3)_2(aq) \rightarrow 2\,NaNO_3(aq) + CaCO_3(s)$$

(f)(i) The student decides to first determine $[OH^-]$ in the solution, then use that result to calculate the initial concentration of $CO_3^{2-}(aq)$.
Identify a laboratory method (not titration) that the student could use to collect data to determine $[OH^-]$ in the solution.

Question 3

(f)(ii) Explain how the student could use the measured value in part (f)(i) to calculate the initial concentration of $CO_3^{2-}(aq)$. (Do not do any numerical calculations.)

Question 3

2019 ▪ Q3

A student is given 50.0 mL of a solution of Na_2CO_3 of unknown concentration. To determine the concentration of the solution, the student mixes the solution with excess 1.0 M $Ca(NO_3)_2(aq)$, causing a precipitate to form. The balanced equation for the reaction is shown below.

$$Na_2CO_3(aq) + Ca(NO_3)_2(aq) \rightarrow 2\,NaNO_3(aq) + CaCO_3(s)$$

(g) In the original Na_2CO_3 solution at equilibrium, is the concentration of $HCO_3^-(aq)$ greater than, less than, or equal to the concentration of $CO_3^{2-}(aq)$? Justify your answer.

Question 3

2019 ▪ Q3

A student is given 50.0 mL of a solution of Na_2CO_3 of unknown concentration. To determine the concentration of the solution, the student mixes the solution with excess 1.0 *M* $Ca(NO_3)_2(aq)$, causing a precipitate to form. The balanced equation for the reaction is shown below.

$$Na_2CO_3(aq) + Ca(NO_3)_2(aq) \rightarrow 2\,NaNO_3(aq) + CaCO_3(s)$$

(h) The student needs to make a CO_3^{2-}/HCO_3^- buffer. Is the Na_2CO_3 solution suitable for making a buffer with a pH of 6? Explain why or why not.

Solution 3

(a)

Mark scheme

- Ca^2 (aq) + $CO3^2$ (aq) $\rightarrow$ CaCO3(s). 1 point for the correct net ionic equation (spectator ions Na and NO3 omitted).

Solution 3

(b)

Mark scheme

- The completed diagram should show one Ca^2 ion added among the floating Na and NO3 ions: Ca(NO3)2 was added in excess (100.0 mL of 1.0 M vs. only 50.0 mL of dilute Na2CO3), so some unreacted Ca^2 remains in solution along with the spectator Na and NO3 ions. 1 point for drawing a Ca^2 ion in the solution.

Solution 3

(c)

Mark scheme

- 0.93 g CaCO3 × (1 mol CaCO3 / 100.1 g) = 0.0093 mol CaCO3. Since the reaction is 1:1 (Na2CO3 : CaCO3), 0.0093 mol CaCO3 × (1 mol Na2CO3 / 1 mol CaCO3) = 0.0093 mol Na2CO3. 1 point for the correct answer (0.0093 mol).

Solution 3

(d)

Mark scheme

- Disagree. If the precipitate was not completely dried, residual water increases the measured mass of the 'CaCO3' precipitate above its true mass. This makes the calculated moles of CaCO3 (and therefore of Na2CO3) too high, not too low — so the calculated Na2CO3 molarity would actually be too HIGH, contrary to the student's claim. 1 point for disagreeing with valid justification.

Solution 3

(e)

Mark scheme

- The filtrate would conduct electricity, because dissolved ions remain in solution — specifically Na (aq), the excess Ca^2 (aq) (from the excess Ca(NO3)2 added), and NO3 (aq). 1 point for the correct answer (conducts) with valid justification listing the ions present.

Solution 3

(f)(i)

Mark scheme

- Measure the pH of the solution using a pH meter (a non-titration laboratory method for determining [OH]). 1 point for identifying a valid method.

Solution 3

(f)(ii)

Mark scheme

- From the measured pH: $pOH = 14 - pH$, then $[OH^-] = 10^{\wedge}(-pOH)$. 1 point for this valid method of determining $[OH^-]$ from the measured value. Then, using the Kb expression $Kb = [HCO3^-][OH^-]/[CO3^{2-}]$ with an ICE table (I: ci, 0, 0; C: $-x$, $+x$, $+x$; E: ci$-x$, x, x, where $x = [OH^-] = [HCO3^-]$ at equilibrium since they form in a 1:1 ratio from water), solve $ci = (x^2/Kb) + x$ for the initial concentration ci of $CO3^{2-}$ (equal to the sum of the equilibrium $[CO3^{2-}]$ and $[HCO3^-]$). 1 point for this valid method of determining the initial concentration of $CO3^{2-}$ from $[OH^-]$.

Solution 3

(g)

Mark scheme

HCO3 is less than [CO3^{2}]. The small value of Kb (2.1×10 , much less than 1) indicates that the reactants (H2O and CO3^{2}) are favored at equilibrium over the products, so only a small fraction of CO3^{2} hydrolyzes to HCO3 . 1 point for the correct answer (less than) with valid justification.

Solution 3

(h)

Mark scheme

- No, the Na2CO3 solution is not suitable for making a pH-6 buffer. The pKa of HCO3 (the conjugate acid in this $CO3^2$ /HCO3 system) is 10.32. A buffer is most effective when the desired pH is close to the pKa of its weak-acid component; pH 6 is far from pKa 10.32, so this system cannot buffer effectively at pH 6. 1 point for the correct answer (no) with a valid explanation referencing pKa.

Question 5

2018 ▪ Q5

$$HF(aq) + H_2O(l) \rightleftharpoons F^-(aq) + H_3O^+(aq)$$

The ionization of $HF(aq)$ in water is represented by the equation above. In a 0.0350 M $HF(aq)$ solution, the percent ionization of HF is 13.0 percent.

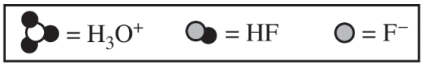
(a) Two particulate representations of the ionization of HF molecules in the 0.0350 M $HF(aq)$ solution are shown below in Figure 1 and Figure 2. Water molecules are not shown. Explain why the representation of the ionization of HF molecules in water in Figure 1 is more accurate than the representation in Figure 2. (The key below identifies the particles in the representations.)

[Key: filled black triple-particle cluster = H_3O^+; two-particle black-and-gray cluster = HF; single gray circle = F^-.]

Question 5

[Figure 1: a circle containing a mixture of particles — approximately 2 H_3O^+ clusters, 2 F^- single circles, and 6 HF two-particle clusters, scattered with mostly HF molecules present and few ionized species, consistent with a small (13
[Figure 2: a circle containing a denser mixture of particles — approximately 6 H_3O^+ clusters, 6 F^- single circles, and 8 HF two-particle clusters, scattered with a much higher proportion of ionized species than Figure 1, inconsistent with only 13

Question 5



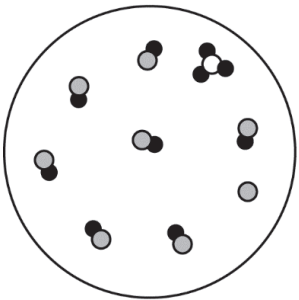


Figure 1

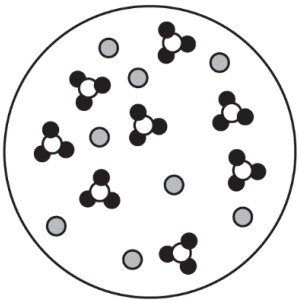


Figure 2

Question 5

2018 ▪ Q5

$$HF(aq) + H_2O(l) \rightleftharpoons F^-(aq) + H_3O^+(aq)$$

The ionization of $HF(aq)$ in water is represented by the equation above. In a 0.0350 M $HF(aq)$ solution, the percent ionization of HF is 13.0 percent.

(b) Use the percent ionization data above to calculate the value of K_a for HF.

Question 5

2018 ▪ Q5

$$HF(aq) + H_2O(l) \rightleftharpoons F^-(aq) + H_3O^+(aq)$$

The ionization of $HF(aq)$ in water is represented by the equation above. In a 0.0350 M $HF(aq)$ solution, the percent ionization of HF is 13.0 percent.

(c) If 50.0 mL of distilled water is added to 50.0 mL of 0.035 M $HF(aq)$, will the percent ionization of $HF(aq)$ in the solution increase, decrease, or remain the same? Justify your answer with an explanation or calculation.

Solution 5

(a)

Mark scheme

- HF is a weak acid and is only partially ionized. This is consistent with Figure 1, which shows only one out of eight (~13%) HF particles ionized (forming one H3O+ and one F-), matching the given 13.0% ionization. Figure 2, showing complete (100%) ionization of every HF molecule, cannot represent a weak acid like HF. 1 point is earned for a valid explanation.

Solution 5

(b)

Mark scheme

- Assume [H3O+] = [F-] in HF(aq). Since percent ionization is 13.0%: [H3O+]/0.0350 M = 0.130, so [H3O+] = 0.00455 M. ICE table: initial [HF]=0.0350, change -0.00455/+0.00455/+0.00455, equilibrium [HF]=0.0304 M, [H3O+]=[F-]=0.00455 M. Ka = [H3O+][F-]/[HF] = (0.00455)^2/(0.0304) = 6.81x10^-4. 1 point is earned for the correct calculation of [H3O+]; 1 point is earned for a value of Ka consistent with the calculated [H3O+].

Solution 5

(c) Mark scheme

- The percent ionization would increase. Doubling the volume (adding an equal volume of water) halves the initial concentration of each species, so Q = [(1/2[H3O+]i)(1/2[F-]i)]/(1/2[HF]i) = 1/2 Ka, i.e. Q < Ka, so the equilibrium shifts toward products, increasing percent ionization. (Confirmed by calculation: new [HF]i = 0.035/2 = 0.0175 M; solving 6.81x10^-4 = x^2/(0.0175-x) approximately x^2/0.0175 gives x approximately 0.00345 M; percent ionization = 0.00345/0.0175 x 100 = 20.%, which is greater than the original 13.0%.) 1 point is earned for a correct answer (increase) AND a valid explanation or calculation.

Question 4

2016 ▪ Q4

$$C_6H_5OH(aq) + H_2O(l) \rightleftharpoons C_6H_5O^-(aq) + H_3O^+(aq) \qquad K_a = 1.12 \times 10^{-10}$$

Phenol is a weak acid that partially dissociates in water according to the equation above.

(a) What is the pH of a 0.75 *M* $C_6H_5OH(aq)$ solution?

(b) For a certain reaction involving $C_6H_5OH(aq)$ to proceed at a significant rate, the phenol must be primarily in its deprotonated form, $C_6H_5O^-(aq)$. In order to ensure that the $C_6H_5OH(aq)$ is deprotonated, the reaction must be conducted in a buffered solution. On the number scale below, circle each pH for which more than 50 percent of the phenol molecules are in the deprotonated form ($C_6H_5O^-(aq)$). Justify your answer.

[Number scale from 1 to 14, in increments of 1: 1 2 3 4 5 6 7 8 9 10 11 12 13 14]

Solution 4

(a)

Mark scheme

- Ka = [C6H5O−][H3O+]/[C6H5OH]; 1.12×10^−10 = $x^2/(0.75 - x)$, assuming x << 0.75. x^2 = 8.4×10^−11, so x = $\sqrt{(8.4\times10^{-11})}$ = 9.2×10^−6 M = [H3O+]. pH = −log(9.2×10^−6) = 5.04. 1 point for a correct setup and calculation of [H+], 1 point for the correct pH value based on a correctly-set-up [H+] calculation.

Solution 4

(b)

Mark scheme

- Numbers 10 through 14 should be circled. When pH $>$ pKa, the deprotonated form predominates; pKa $= -\log(1.12\times10\hat{}-10) = 9.95$, so at pH 10 and above [C6H5O$-$] $>$ [C6H5OH]. 1 point for circling pH values 10–14, 1 point for the justification referencing pKa ≈ 9.95 and the condition pH $>$ pKa.

Question 2

2014 ▪ Q2

$$CH_3CH_2COOH(aq) + H_2O(l) \rightleftharpoons CH_3CH_2COO^-(aq) + H_3O^+(aq)$$

Propanoic acid, CH_3CH_2COOH, is a carboxylic acid that reacts with water according to the equation above. At 25°C the pH of a 50.0 mL sample of 0.20 *M* CH_3CH_2COOH is 2.79.

(a) Identify a Brønsted-Lowry conjugate acid-base pair in the reaction. Clearly label which is the acid and which is the base.

Question 2

2014 ▪ Q2

$$CH_3CH_2COOH(aq) + H_2O(l) \rightleftharpoons CH_3CH_2COO^-(aq) + H_3O^+(aq)$$

Propanoic acid, CH_3CH_2COOH, is a carboxylic acid that reacts with water according to the equation above. At 25°C the pH of a 50.0 mL sample of 0.20 *M* CH_3CH_2COOH is 2.79.

(b) Determine the value of K_a for propanoic acid at 25°C.

Question 2

2014 ▪ Q2

$$CH_3CH_2COOH(aq) + H_2O(l) \rightleftharpoons CH_3CH_2COO^-(aq) + H_3O^+(aq)$$

Propanoic acid, CH_3CH_2COOH, is a carboxylic acid that reacts with water according to the equation above. At 25°C the pH of a 50.0 mL sample of 0.20 *M* CH_3CH_2COOH is 2.79.

(c)(i) For each of the following statements, determine whether the statement is true or false. In each case, explain the reasoning that supports your answer.

The pH of a solution prepared by mixing the 50.0 mL sample of 0.20 *M* CH_3CH_2COOH with a 50.0 mL sample of 0.20 *M* NaOH is 7.00.

(c)(ii) For each of the following statements, determine whether the statement is true or false. In each case, explain the reasoning that supports your answer.

Question 2

If the pH of a hydrochloric acid solution is the same as the pH of a propanoic acid solution, then the molar concentration of the hydrochloric acid solution must be less than the molar concentration of the propanoic acid solution.

Question 2

2014 ▪ Q2

$$CH_3CH_2COOH(aq) + H_2O(l) \rightleftharpoons CH_3CH_2COO^-(aq) + H_3O^+(aq)$$

Propanoic acid, CH_3CH_2COOH, is a carboxylic acid that reacts with water according to the equation above. At 25°C the pH of a 50.0 mL sample of 0.20 *M* CH_3CH_2COOH is 2.79.

(d) A student is given the task of determining the concentration of a propanoic acid solution of unknown concentration. A 0.173 *M* NaOH solution is available to use as the titrant. The student uses a 25.00 mL volumetric pipet to deliver the propanoic acid solution to a clean, dry flask. After adding an appropriate indicator to the flask, the student titrates the solution with the 0.173 *M* NaOH, reaching the end point after 20.52 mL of the base solution has been added.

Calculate the molarity of the propanoic acid solution.

Question 2

2014 ▪ Q2

$$CH_3CH_2COOH(aq) + H_2O(l) \rightleftharpoons CH_3CH_2COO^-(aq) + H_3O^+(aq)$$

Propanoic acid, CH_3CH_2COOH, is a carboxylic acid that reacts with water according to the equation above. At 25°C the pH of a 50.0 mL sample of 0.20 M CH_3CH_2COOH is 2.79.

(e) The student is asked to redesign the experiment to determine the concentration of a butanoic acid solution instead of a propanoic acid solution. For butanoic acid the value of pK_a is 4.83. The student claims that a different indicator will be required to determine the equivalence point of the titration accurately. Based on your response to part (b), do you agree with the student's claim? Justify your answer.

Solution 2

(a)

Mark scheme

- A valid Brønsted-Lowry conjugate acid-base pair: CH_3CH_2COOH (acid) and $CH_3CH_2COO^-$ (base); OR equivalently H_3O^+ (acid) and H_2O (base). Credit requires clearly labeling which species is the acid and which is the base.

Solution 2

(b) Mark scheme

- $[H_3O^+] = 10^{-pH} = 10^{-2.79} = 1.6 \times 10^{-3}$ *M* (1 point for solving for [H3O+]). Set up the Ka expression with $[CH_3CH_2COO^-] = [H_3O^+]$ and $[CH_3CH_2COOH] = 0.20 - [H_3O^+] \approx 0.20$ *M*: $K_a = \frac{[CH_3CH_2COO^-][H_3O^+]}{[CH_3CH_2COOH]}$ (1 point for the correct Ka expression or correct substitution). Solving: $K_a = \frac{(1.6 \times 10^{-3})^2}{0.20} = 1.3 \times 10^{-5}$ (1 point for the correct numeric Ka value).

Solution 2

(c)(i)

Mark scheme

- False. The conjugate base CH3CH2COO- formed at equivalence undergoes hydrolysis, $CH_3CH_2COO^- + H_2O \rightleftharpoons CH_3CH_2COOH + OH^-$, giving a solution with pH > 7, not exactly 7.00.

Solution 2

(c)(ii)

Mark scheme

- True. HCl is a strong acid that ionizes completely, so fewer moles of HCl are needed to produce the same [H3O+] (and hence the same pH) as the propanoic acid solution, which only partially ionizes; therefore the HCl solution's molar concentration must be less than the propanoic acid solution's.

Solution 2

(d)

Mark scheme

- At the equivalence point, moles acid = moles base delivered. Moles NaOH = 0.02052 L $\times$ 0.173 mol/L $= 3.55 \times 10^{-3}$ mol = moles propanoic acid (1 point for correctly finding moles of acid that reacted). Molarity of acid = 3.55×10^{-3} mol / 0.02500 L = 0.142 M (1 point for the correct molarity). Equivalent method: since the acid is monoprotic, $M_A V_A = M_B V_B \Rightarrow M_A = (0.173\ M)(20.52\ \text{mL})/(25.00\ \text{mL}) = 0.142\ M$.

Solution 2

(e)

Mark scheme

- Disagree with the student's claim (1 point for disagreeing with a valid justification). From part (b), pKa for propanoic acid $= -\log(1.3 \times 10^{-5}) = 4.89$. Because butanoic acid's pKa (4.83) is so close to propanoic acid's pKa (4.89), the pH at the equivalence point of the butanoic acid titration should be close enough to that of the propanoic acid titration that the original indicator remains appropriate (1 point for numerically comparing the two pKa, Ka, or equivalence-point pH values).