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Topic 8.10: Buffer Capacity

Worksheet · AP Chemistry

UNIT 8 · ACIDS AND BASES

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How to Use This Worksheet

Work in order. Section A checks the ideas: what capacity means, which member caps each direction, capacity as a mole count, dilution, and judging claims. Section B practises: symmetric additions at pH = pKa, an unequal buffer attacked both ways, concentration scaling, ranking by pH change, volume against concentration, and exhaustion in volumes. Section C is exam style: a design to a specification, a stepwise march of additions past the cliff edge, and a lopsided buffer judged by direction.

Conventions: 25 °C throughout, Kw = 1.0×10^{-14}, concentrations in mol L^{-1}, pH to two decimal places. The pair used most often is CH_3COOH / CH_3COO^- with Ka of $CH_3COOH = 1.8 \times 10^{-5}$ (pKa 4.74); the ammonia pair appears with pKa of $NH_4^+ = 9.26$.

One working habit ties the sheet together: capacity questions are mole questions. Convert every stock to moles (concentration × volume), identify which member the attack spends, recount after the addition, and only then take the ratio and the logarithm. If the recount drives a member to zero, the buffer is finished: the leftover, not the ratio, sets the pH. "Before the pH changes significantly" is pinned down two ways: a stated allowed move (0.20 units in C1) and outright exhaustion. Near exhaustion the key quotes the exact value.

The answer key shows every recount, ratio and logarithm step in full. Attempt every question before looking at it.

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Section A: Recall and Concepts

A1. (a) Define buffer capacity, and state the event that marks its end. (b) State which member caps the capacity against added acid and which against added base, writing the reaction for each. (c) Explain why capacity is quoted in moles of acid or base absorbed, not in pH units.

A2. Three acetate buffers all sit at pH = pKa = 4.74: (i) 1.0 L holding 0.050 mol L^{-1} of each member; (ii) 1.0 L holding 0.50 mol L^{-1} of each member; (iii) 2.0 L holding 0.10 mol L^{-1} of each member. For each, state the moles of CH_3COO^- present and the moles of HCl that exhaust it, and rank the three by capacity against acid.

A3. A 1.0 L buffer holds 0.010 mol L^{-1} HA and 0.10 mol L^{-1} A^- for a pair with pKa 4.74. (a) Calculate its pH, and the percent of the pair present as HA. (b) State which direction of attack it resists weakly, and the moles of that attack that exhaust it. (c) Calculate the pH after 0.0050 mol of NaOH is added, and comment on the size of the move relative to the addition.

A4. Two 1.0 L portions of acetate buffer: one at 0.40 mol L^{-1} of each member, one diluted tenfold to 0.040 mol L^{-1} of each member. (a) State the pH of each. (b) State the moles of HCl that exhaust each. (c) Calculate the pH of each after 0.020 mol of HCl is added to it, and state what dilution changed and what it did not.

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A5. Judge each claim, giving a reason in moles or ratio terms. (a) "Two buffers at the same pH have the same capacity." (b) "Doubling the volume at the same concentrations doubles the capacity and leaves the pH unchanged." (c) "A buffer at ratio 100 resists added base as well as a buffer at ratio 1 holding the same total moles of the pair." (d) "Once one member is exhausted, further strong acid changes the pH only slightly, because the other member is still present."

Section B: Core Practice

B1. A 1.0 L acetate buffer holds 0.25 mol of CH_3COOH and 0.25 mol of CH_3COO^-. (a) State its pH. (b) Then 0.050 mol of HCl is added (volume change negligible): recount and calculate the new pH and its change. (c) Starting again, 0.050 mol of NaOH is added instead: recount and calculate likewise. (d) State why the two moves are equal in size, and the feature of the starting buffer that guarantees it.

B2. A 1.0 L acetate buffer holds 0.40 mol of CH_3COOH and 0.20 mol of CH_3COO^-. (a) Calculate its pH. (b) State the moles of NaOH, and separately of HCl, that exhaust it. (c) Calculate the pH after 0.10 mol of NaOH is added, and after 0.10 mol of HCl is added to a fresh portion. (d) State, in one sentence tied to the stocks, which addition this buffer is built to survive.

B3. Buffers X and Y are acetate buffers at pH = pKa, each 1.0 L: X holds 0.20 mol of each member, Y 0.10 mol of each. (a) State the moles of HCl that exhaust each. (b) Add 0.040 mol of HCl to each: calculate both new pH values and both changes. (c) State the pattern: what did halving the stocks do to the exhaustion limit, and roughly to the pH move?

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B4. The same addition, 0.010 mol of HCl, is made to 1.0 L of each of three acetate buffers at pH = pKa: (i) 0.010 mol of each member; (ii) 0.10 mol of each; (iii) 0.50 mol of each. (a) For (ii) and (iii), calculate the new pH by the ratio route. (b) For (i), state what the addition does to the pair, and give the resulting pH (exact solve: 3.23). (c) Rank the three by capacity, justifying the ranking by the pH changes.

B5. Three acetate buffers, all with equal members: P is 2.0 L at 0.10 mol L^{-1} of each member; Q is 0.50 L at 0.40 mol L^{-1} of each; R is 1.0 L at 0.15 mol L^{-1} of each. (a) Calculate the moles of each member in each buffer. (b) Rank the three by capacity against added HCl, and calculate the volume of 1.0 mol L^{-1} HCl that exhausts each. (c) State the pH of each, and name the trap this question is built around.

B6. A student has 0.50 L of an acetate buffer, 0.20 mol L^{-1} of each member. (a) Calculate the moles of each member. (b) Calculate the volumes of 1.0 mol L^{-1} HCl and of 0.50 mol L^{-1} NaOH that exhaust the CH_3COO^- and the CH_3COOH respectively. (c) The student adds 60 mL of the 1.0 mol L^{-1} HCl: calculate the pH, and state whether the new total volume enters it. (d) The student instead adds 120 mL: state what has happened to the pair, and give the pH (exact solve at the new volume, 0.620 L: 1.49).

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Section C: Exam Style

C1. A 1.0 L acetate buffer is to sit at pH = pKa and absorb 0.050 mol of added NaOH with a pH rise of no more than 0.20 units. (a) With equal members of n mol each, write the post-addition ratio and find the minimum n meeting the specification. (b) A design uses 0.25 mol of each member: state its concentrations, and verify the specification by calculating the rise. (c) A cheaper proposal uses 0.125 mol of each member: calculate its rise and state the verdict. (d) State the moles of HCl, and separately of NaOH, that exhaust the 0.25 mol design.

C2. One litre of acetate buffer, 0.20 mol of each member, receives HCl in stages, each stage adding to the last. (a) State the starting pH. (b) Calculate the pH after cumulative additions of 0.050, 0.100 and 0.150 mol of HCl. (c) After a cumulative 0.190 mol, the ratio route gives pH 3.15 while an exact equilibrium solve gives 3.18: state the reason for the gap. (d) Give the pH at a cumulative 0.200 mol and at 0.210 mol (exact solves), and say in one sentence what the sequence shows about capacity. (e) Calculate the moles of HCl that lower the pH by exactly 1.00 unit, and compare it with the exhaustion amount.

C3. A 1.0 L acetate buffer holds 0.60 mol of CH_3COOH and 0.060 mol of CH_3COO^-. (a) Calculate its pH. (b) Calculate the pH after 0.050 mol of NaOH is added, and the size of the move. (c) Calculate the pH after 0.050 mol of HCl is added to a fresh portion (ratio route; exact solve 2.98), and the size of the move. (d) State the moles of HCl, and separately of NaOH, that exhaust this buffer; compare them with the caps of an equal-member buffer holding the same 0.66 mol total; and give a one-sentence verdict on what it is for.

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Answer Key

A1. (a) Buffer capacity is the amount of strong acid or strong base a buffer can absorb before its pH changes significantly. It ends at exhaustion, when the addition has consumed the defending member's stock and the pH swings. (b) Against acid the cap is A^-, through $A^- + H_3O^+ \rightarrow HA + H_2O$; against base the cap is HA, through $HA + OH^- \rightarrow A^- + H_2O$. (c) A pH unit is a log-scale ratio step, so equal pH moves can hide very different amounts of chemistry. Capacity is counted in moles.

A2. (i) CH_3COO^- = 0.050 mol L^{-1} × 1.0 L = 0.050 mol; exhausted by 0.050 mol of HCl. (ii) 0.50 × 1.0 = 0.50 mol; exhausted by 0.50 mol. (iii) 0.10 × 2.0 = 0.20 mol; exhausted by 0.20 mol. Ranking against acid: (ii), then (iii), then (i). The ranking is set by moles of A^-, concentration × volume.

A3. (a) pH = 4.74 + log(0.10 ÷ 0.010) = 4.74 + 1.00 = 5.74. HA's share of the pair is 0.010 ÷ 0.11 = 9%. (b) Weak against base: OH^- spends HA, only 0.010 mol of HA stands in the litre, and 0.010 mol of NaOH exhausts that direction; against acid it holds 0.10 mol. (c) HA falls to 0.0050 mol and A^- rises to 0.105 mol, so pH = 4.74 + log(0.105 ÷ 0.0050) = 4.74 + log(21) = 6.06. A rise of 0.32 from an addition consuming half the entire base-direction stock.

A4. (a) Both read pH = pKa = 4.74: dilution divides both members by one factor, leaving the ratio unchanged. (b) Exhausted by 0.40 mol of HCl (concentrated) and 0.040 mol (diluted), their A^- stocks. (c) Concentrated: recount 0.42 ÷ 0.38 mol, pH = 4.74 + log(0.38 ÷ 0.42) = 4.70, a fall of 0.04. Diluted: recount 0.060 ÷ 0.020 mol, pH = 4.74 + log(0.020 ÷ 0.060) = 4.27, a fall of 0.48. Exact solves agree with both. Dilution divided the capacity per litre by ten.

A5. (a) False. pH reads the ratio only: buffers at 0.50 ÷ 0.50 and 0.0050 ÷ 0.0050 mol L^{-1} share a pH while their acid caps differ a hundredfold, 0.50 against 0.0050 mol a litre. (b) True: doubling the volume at fixed concentrations doubles both stocks and caps; the ratio, hence the pH, is untouched. (c) False. At ratio 100 the acid member is 1/101, about 1%, of the pair: 0.0065 mol of a 0.66 mol total, so 0.0065 mol of base exhausts that direction, against 0.33 mol at ratio 1. (d) False. With A^- gone, no pair remains: further H_3O^+ accumulates and the pH falls as in unbuffered water. The surviving HA is the product of the defence, not a reserve.

B1. (a) Equal members, so pH = pKa = 4.74. (b) $CH_3COO^- + H_3O^+ \rightarrow CH_3COOH + H_2O$: CH_3COOH rises to 0.30 mol and CH_3COO^- falls to 0.20 mol. pH = 4.74 + log(0.20 ÷ 0.30) = 4.57, a fall of 0.18 (exact 4.57). (c) $CH_3COOH + OH^- \rightarrow CH_3COO^- + H_2O$: the stocks become 0.20 and 0.30 mol. pH = 4.74 + log(0.30 ÷ 0.20) = 4.92, a rise of 0.18 (exact 4.92). (d) The two recounts are reciprocals, 0.20 ÷ 0.30 and 0.30 ÷ 0.20, so their log terms are equal and opposite; the guarantee is the equal split at pH = pKa.

B2. (a) pH = 4.74 + log(0.20 ÷ 0.40) = 4.74 − 0.30 = 4.44 (exact 4.44). (b) NaOH spends HA, so 0.40 mol exhausts the buffer; HCl spends A^-, so 0.20 mol exhausts it. (c) After 0.10 mol of NaOH the stocks are 0.30 ÷ 0.30 mol, so pH = 4.74, a rise of 0.30. After 0.10 mol of HCl in a fresh portion they

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are 0.50 ÷ 0.10 mol, so pH = 4.74 + log(0.10 ÷ 0.50) = 4.04, a fall of 0.40 (exact 4.05). (d) Built to survive base: it holds twice the HA stock of the A^- stock, twice the cap that way.

B3. (a) X is exhausted by 0.20 mol of HCl, Y by 0.10 mol, their A^- stocks. (b) X: recount 0.24 ÷ 0.16 mol, pH = 4.74 + log(0.16 ÷ 0.24) = 4.57, a fall of 0.18 (exact 4.57). Y: recount 0.14 and 0.060 mol, pH = 4.74 + log(0.060 ÷ 0.14) = 4.38, a fall of 0.37 (exact 4.38). (c) Halving the stocks halved the exhaustion limit exactly and roughly doubled the pH move from the same addition.

B4. (a) Buffer (ii): recount 0.11 ÷ 0.090 mol, pH = 4.74 + log(0.090 ÷ 0.11) = 4.66, a fall of 0.09 (exact 4.66). Buffer (iii): recount 0.51 and 0.49 mol, pH = 4.74 + log(0.49 ÷ 0.51) = 4.73, a fall of 0.02 (exact 4.73). (b) In (i) the addition is exactly the whole A^- stock: the pair is destroyed, leaving 0.020 mol L^{-1} CH_3COOH alone, a lone weak acid of pH 3.23, a fall of 1.52. (c) (iii) > (ii) > (i): the ranking of the moves, 0.02, 0.09 and destruction, is the ranking of the defending stocks, 0.50, 0.10 and 0.010 mol.

B5. (a) P: 0.10 × 2.0 = 0.20 mol of each member. Q: 0.40 × 0.50 = 0.20 mol of each. R: 0.15 × 1.0 = 0.15 mol of each. (b) Capacity against HCl is the A^- stock, so P and Q tie, R last. Exhaustion volumes of 1.0 mol L^{-1} HCl: P, 0.20 mol = 200 mL; Q, 200 mL; R, 0.15 mol = 150 mL. (c) All three read pH = pKa = 4.74. The trap is concentration: capacity counts moles, and P's volume compensates.

B6. (a) Each member: 0.20 mol L^{-1} × 0.50 L = 0.10 mol. (b) Exhausting CH_3COO^- takes 0.10 mol of HCl: 100 mL at 1.0 mol L^{-1}. Exhausting CH_3COOH takes 0.10 mol of NaOH: 200 mL at 0.50 mol L^{-1}. (c) The 60 mL delivers 0.060 mol of HCl: recount 0.16 ÷ 0.040 mol, so pH = 4.74 + log(0.040 ÷ 0.16) = 4.14 (exact 4.14). The new volume does not enter: both members share it, so it cancels in the ratio. (d) The 120 mL delivers 0.120 mol against a 0.10 mol A^- stock: the pair is exhausted with 0.020 mol of strong acid left over, and that leftover, in the new 0.620 L with the 0.20 mol of CH_3COOH now present, sets pH 1.49.

C1. (a) After 0.050 mol of NaOH the members are $n - 0.050$ of HA and $n + 0.050$ of A^-, and the specification is $\log((n + 0.050) \div (n - 0.050)) \leq 0.20$, so $(n + 0.050) \div (n - 0.050) \leq 10^{0.20} = 1.585$. Then $n + 0.050 \leq 1.585n - 0.0793$, giving $n \geq 0.221$ mol of each member. (b) Concentrations of 0.25 mol L^{-1} each. Check: recount 0.20 ÷ 0.30 mol, rise = log(0.30 ÷ 0.20) = log(1.5) = 0.18, inside the 0.20 allowed (exact solve the same). (c) At 0.125 mol each the recount is 0.075 ÷ 0.175 mol and the rise is log(0.175 ÷ 0.075) = log(2.33) = 0.37: the specification fails outright. (d) Exhaustion takes 0.25 mol of HCl or of NaOH, five times the specified load.

C2. (a) Equal members, so the starting pH is pKa = 4.74. (b) After 0.050 mol: recount 0.25 ÷ 0.15 mol (CH_3COOH / CH_3COO^-), pH = 4.74 + log(0.15 ÷ 0.25) = 4.52. After 0.100 mol: 0.30 ÷ 0.10 mol, pH = 4.74 + log(0.10 ÷ 0.30) = 4.27. After 0.150 mol: 0.35 ÷ 0.050 mol, pH = 4.74 + log(0.050 ÷ 0.35) = 3.90. Exact solves agree throughout. (c) At 0.190 mol the A^- stock is 0.010 mol, no longer large beside the acid's own ionization shift, so the stocks the ratio route reads are not the equilibrium concentrations; trust the exact solve. (d) At 0.200 mol the pair is exactly consumed, leaving 0.40 mol L^{-1} CH_3COOH alone: pH 2.57. At 0.210 mol the extra 0.010 mol of strong acid stands in the litre: pH 1.97. The falls per stage grow (0.22, 0.25, 0.37), and the final 0.020 mol of additions moves the

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pH further than the first 0.150 mol did: a long resistance ending in a cliff. (e) A fall of 1.00 unit needs the ratio at 0.10: (0.20 − x) ÷ (0.20 + x) = 0.10 gives x = 0.180 ÷ 1.10 = 0.164 mol, about four fifths of the 0.20 mol exhaustion amount.

C3. (a) pH = 4.74 + log(0.060 ÷ 0.60) = 4.74 − 1.00 = 3.74. (b) The OH^- converts CH_3COOH into CH_3COO^-: stocks 0.55 ÷ 0.11 mol, so pH = 4.74 + log(0.11 ÷ 0.55) = 4.74 + log(0.20) = 4.04, a rise of 0.30 (exact 4.05). (c) The H_3O^+ converts CH_3COO^- into CH_3COOH: stocks 0.65 and 0.010 mol, so pH = 4.74 + log(0.010 ÷ 0.65) = 2.93 by the ratio route and 2.98 exactly, a fall of about 0.8; the routes part because the 0.010 mol A^- stock is no longer large beside the ionization shift. (d) Exhaustion: 0.060 mol of HCl, the A^- stock, and 0.60 mol of NaOH, the HA stock. An equal split of the same 0.66 mol total would cap both directions at 0.33 mol. This buffer has traded nearly all its acid-side defence for base-side defence: built to absorb base, and only there.

Continue Revising

Topic 8.10 Revision Notes

Topic 8.10 Quiz: Buffer Capacity

Previous Worksheet: Topic 8.9 Henderson-Hasselbalch Equation

Next Quiz: Topic 9.1 Introduction to Entropy

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