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Topic 8.1: Introduction to Acids and Bases

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: the Brønsted-Lowry definitions, writing conjugate partners, and spotting pairs that fail the one-proton test. Section B practices the working skills: labelling full reactions, using Kw to move between [H_3O^+] and [OH^-], and reading an equilibrium constant out of weak acid data. Section C is exam style: a polyprotic ladder, a temperature where neutral is not pH 7, and an acidity ranking that must be earned through Kw rather than guessed.

Reference facts. Every temperature is 25 °C unless a question says otherwise, Kw = 1.0×10^{-14} at 25 °C, and concentrations are in mol L^{-1}. In every labelling question, decide the roles from the reaction as written: the species that loses H^+ is the acid, the one that gains it is the base.

Two checks run through the whole sheet. The pair check: a claimed conjugate partner must differ from its starting species by exactly one proton and exactly one unit of charge. The Kw check: at 25 °C, any [H_3O^+] and [OH^-] quoted for the same solution must multiply together to give 1.0×10^{-14}. If either check fails, the error is in the working, never in the check.

The answer key checks every conjugate pair by the one-proton difference and every Kw answer by multiplying the pair of concentrations back to 1.0×10^{-14}. Do not look at the answer key until you have attempted every question in Sections A, B and C.

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Section A: Recall and Concepts

A1. State, in one sentence each, what a Brønsted-Lowry acid does and what a Brønsted-Lowry base does. Then explain why NH_3 counts as a base in water even though its formula contains no OH^- group.

A2. Write the conjugate base of each acid: (a) HNO_3, (b) H_2CO_3, (c) NH_4^+, (d) HSO_4^-, (e) H_3O^+. Then write the conjugate acid of each base: (f) OH^-, (g) CO_3^{2-}, (h) F^-.

A3. Judge each claimed conjugate pair, and correct the ones that fail. (a) HCl and Cl^-. (b) H_2SO_4 and SO_4^{2-}. (c) HCO_3^- and CO_3^{2-}. (d) H_3PO_4 and PO_4^{3-}. (e) NH_4^+ and NH_2^-.

A4. (a) Define amphiprotic in one sentence. (b) From this list, pick out every amphiprotic species: Cl^-, H_2O, HCO_3^-, NH_4^+, $H_2PO_4^-$, SO_4^{2-}. (c) For one of the species you picked, write the product when it acts as an acid and the product when it acts as a base.

A5. (a) Write the equation for the autoionization of water. (b) Write the expression for Kw and state its value at 25 °C. (c) State $[H_3O^+]$ and $[OH^-]$ in pure water at 25 °C, and the condition that makes any solution neutral, whatever its temperature.

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Section B: Core Practice

B1. $CH_3COOH + H_2O \rightleftharpoons CH_3COO^- + H_3O^+$. (a) Identify the acid and the base. (b) Identify the conjugate base of the acid and the conjugate acid of the base. (c) State whether the position of equilibrium suggests CH_3COOH is strong or weak, and what that means for the fraction of molecules ionized.

B2. $CO_3^{2-} + H_2O \rightleftharpoons HCO_3^- + OH^-$. (a) Identify the acid and the base in this reaction, taking care with water's role. (b) Name the two conjugate pairs. (c) In the reaction $HCO_3^- + H_2O \rightleftharpoons CO_3^{2-} + H_3O^+$, water plays the opposite role. State water's role in each reaction, and the property of water that allows both.

B3. A solution at 25 °C has $[OH^-] = 4.0 \times 10^{-6}$ mol L^{-1}. (a) Calculate $[H_3O^+]$. (b) Check your answer against Kw. (c) State whether the solution is acidic, neutral or basic, and the feature of the two concentrations that decides it.

B4. A solution at 25 °C has $[H_3O^+] = 1.0 \times 10^{-4}$ mol L^{-1}. (a) Calculate $[OH^-]$. (b) Calculate the pH. (c) Tenfold dilution lowers $[H_3O^+]$ to 1.0×10^{-5} mol L^{-1}. State the new pH and the general rule connecting a tenfold change in $[H_3O^+]$ to the pH change.

B5. A 0.50 mol L^{-1} solution of a weak acid HA reaches equilibrium with $[H_3O^+] = 3.0 \times 10^{-3}$ mol L^{-1}. (a) State $[A^-]$ at equilibrium and why it equals $[H_3O^+]$. (b) Calculate the approximate Ka of HA. (c) Calculate the percentage of the acid that has ionized, and comment on whether neglecting the ionized amount beside 0.50 in part (b) was safe.

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B6. (a) Rank these acids from strongest to weakest using only the conjugate information given: the conjugate base of acid P is a noticeably stronger base than the conjugate base of acid Q, and the conjugate base of acid R barely accepts protons at all. (b) HCl is a strong acid and HF is a weak acid. State which of Cl^- and F^- is the stronger base, and justify the answer with the seesaw rule. (c) Explain why Cl^- can be treated as a spectator when HCl dissolves, while CH_3COO^- cannot be treated as a spectator in a solution of CH_3COOH.

Section C: Exam Style

C1. Phosphoric acid loses its protons one at a time: $H_3PO_4 \rightleftharpoons H_2PO_4^- \rightleftharpoons HPO_4^{2-} \rightleftharpoons PO_4^{3-}$, each step releasing one H^+. (a) Write the conjugate base of $H_2PO_4^-$ and the conjugate acid of HPO_4^{2-}. (b) Identify every amphiprotic species on the ladder and justify the choice. (c) A student claims H_3PO_4 and HPO_4^{2-} form a conjugate pair. Test the claim by counting protons, and give the verdict. (d) In the reaction $H_2PO_4^- + OH^- \rightarrow HPO_4^{2-} + H_2O$, identify the acid, the base, and the two conjugate pairs.

C2. At 37 °C, the temperature of the human body, $K_w = 2.4 \times 10^{-14}$. (a) Calculate $[H_3O^+]$ in a neutral solution at 37 °C. (b) Calculate the pH of that neutral solution. (c) A blood sample at 37 °C has pH 7.4. Using your part (b) result, state whether the sample is acidic, neutral or basic relative to neutral at this temperature, and explain why comparing it with 7.0 would mislead.

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C3. Four solutions at 25 °C: W has $[OH^-] = 1.0 \times 10^{-9}$ mol L^{-1}; X has $[H_3O^+] = 1.0 \times 10^{-4}$ mol L^{-1}; Y has $[OH^-] = 1.0 \times 10^{-12}$ mol L^{-1}; Z has pH 6. (a) Convert every solution to $[H_3O^+]$, showing the Kw step wherever the given value is $[OH^-]$. (b) Rank the four from most acidic to least acidic. (c) State which single comparison in the list is the trap for a student who ranks by the size of the given number alone, and why.

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Answer Key

A1. A Brønsted-Lowry acid donates a proton to another species. A Brønsted-Lowry base accepts a proton from another species. NH_3 is a base because, in water, it does the accepting: $NH_3 + H_2O \rightleftharpoons NH_4^+ + OH^-$. The OH^- in that equation is a product formed from water, not something NH_3 contained or released directly; the role comes from the proton transfer, not from the formula.

A2. Conjugate bases, each with one fewer proton and one more unit of negative charge: (a) NO_3^-. (b) HCO_3^-. (c) NH_3. (d) SO_4^{2-}. (e) H_2O. Conjugate acids, each with one more proton and one less unit of negative charge: (f) H_2O. (g) HCO_3^-. (h) HF. Every answer differs from its starting species by exactly one H and exactly one unit of charge; that double check catches both a miscounted proton and a miswritten charge.

A3. (a) Passes: HCl and Cl^- differ by one proton and one unit of charge. (b) Fails: H_2SO_4 and SO_4^{2-} differ by two protons. The conjugate base of H_2SO_4 is HSO_4^-. (c) Passes: HCO_3^- loses one proton to give CO_3^{2-}, and the charge moves from 1− to 2−. (d) Fails: H_3PO_4 and PO_4^{3-} differ by three protons. They sit at opposite ends of a ladder, H_3PO_4 with $H_2PO_4^-$, then $H_2PO_4^-$ with HPO_4^{2-}, then HPO_4^{2-} with PO_4^{3-}. (e) Fails: NH_4^+ and NH_2^- differ by two protons. The conjugate base of NH_4^+ is NH_3.

A4. (a) An amphiprotic species is one that can either donate a proton or accept one, acting as an acid in one reaction and as a base in another. (b) H_2O, HCO_3^- and $H_2PO_4^-$. Cl^- has no proton to give; NH_4^+ can only donate, since accepting another proton is not available to it; SO_4^{2-} can only accept. (c) For HCO_3^-: acting as an acid it loses H^+ to become CO_3^{2-}; acting as a base it gains H^+ to become H_2CO_3. Both products differ from HCO_3^- by exactly one proton, in opposite directions.

A5. (a) $2H_2O(l) \rightleftharpoons H_3O^+(aq) + OH^-(aq)$: one water molecule donates a proton to the other. (b) $K_w = [H_3O^+][OH^-] = 1.0 \times 10^{-14}$ at 25 °C. (c) $[H_3O^+] = [OH^-] = 1.0 \times 10^{-7}$ mol L^{-1}, each the square root of K_w. A solution is neutral whenever $[H_3O^+] = [OH^-]$, at any temperature; the value 1.0×10^{-7} belongs to 25 °C only, because K_w changes with temperature. Note the division of labour: K_w fixes the product of the two concentrations, and the neutrality condition fixes their ratio at 1:1; together they fix both values.

B1. (a) CH_3COOH is the acid: it loses H^+. H_2O is the base: it gains H^+ to become H_3O^+. (b) The conjugate base of CH_3COOH is CH_3COO^-; the conjugate acid of H_2O is H_3O^+. (c) The equilibrium lies to the left, with far more CH_3COOH molecules than ions present, so CH_3COOH is weak: only a small fraction of its molecules ionize. A strong acid would show the opposite picture, ionization effectively complete and the equilibrium arrow pointing one way. The arrow itself carries the verdict: the double arrow here and the single arrow written for $HCl + H_2O \rightarrow Cl^- + H_3O^+$ are the same fact in written form.

B2. (a) H_2O is the acid: it donates a proton to CO_3^{2-} and ends as OH^-. CO_3^{2-} is the base: it accepts the proton to become HCO_3^-. Water's position on the reactant side tempts a base label, but the

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proton flow decides, and here the flow is out of water. (b) The pairs are H_2O/OH^- and HCO_3^-/CO_3^{2-}. (c) With CO_3^{2-}, water donates a proton and is the acid. With HCO_3^-, water accepts a proton to become H_3O^+ and is the base. Water can take either role because it is amphiprotic: it carries a proton it can give and a lone pair that can take one, so the partner decides which role it plays.

B3. (a) $[H_3O^+] = Kw \div [OH^-] = (1.0 \times 10^{-14}) \div (4.0 \times 10^{-6}) = 2.5 \times 10^{-9}$ mol L^{-1}. (b) Check: $(2.5 \times 10^{-9})(4.0 \times 10^{-6}) = 1.0 \times 10^{-14}$, which is Kw, so the pair is consistent. (c) Basic: $[OH^-]$ exceeds $[H_3O^+]$ by more than a factor of a thousand. The comparison of the two concentrations, not either value alone, is what decides the label.

B4. (a) $[OH^-] = (1.0 \times 10^{-14}) \div (1.0 \times 10^{-4}) = 1.0 \times 10^{-10}$ mol L^{-1}. (b) pH = $-\log(1.0 \times 10^{-4}) = 4.00$. (c) The new pH is 5.00: each tenfold fall in $[H_3O^+]$ raises the pH by exactly one unit, because the scale is logarithmic in base ten. A hundredfold fall would raise it by two units.

B5. (a) $[A^-] = 3.0 \times 10^{-3}$ mol L^{-1}. The ionization $HA + H_2O \rightleftharpoons H_3O^+ + A^-$ produces the two ions in a 1:1 ratio from zero, so their equilibrium concentrations match. (b) $Ka \approx [H_3O^+][A^-] \div [HA] = (3.0 \times 10^{-3})^2 \div 0.50 = (9.0 \times 10^{-6}) \div 0.50 = 1.8 \times 10^{-5}$. (c) Percentage ionized: $(3.0 \times 10^{-3} \div 0.50) \times 100 = 0.60$ percent. The amount ionized is well under 5 percent of the starting concentration, so writing [HA] as 0.50 rather than 0.497 changes nothing at the figures quoted; the neglect was safe.

B6. (a) Strongest first: R, then Q, then P. The seesaw runs the ranking backwards through the pairs: the weakest conjugate base belongs to the strongest acid. R's conjugate base barely accepts protons at all, so R parts with its own proton most readily and is the strongest acid; P's conjugate base is the keenest proton acceptor of the three, so P holds its proton tightest and is the weakest acid. (b) F^- is the stronger base. HF is the weaker acid, so its conjugate base is the stronger of the two; Cl^-, from the strong acid HCl, has almost no tendency to accept a proton in water. (c) Cl^- never pulls a proton back from water to any measurable extent, so once HCl has ionized the chloride simply stays in solution unchanged, a spectator. CH_3COO^- does accept protons back from H_3O^+ and from water, which is exactly why the CH_3COOH equilibrium sits part-way: the reverse transfer runs at a real rate, so the acetate is a participant, not a bystander.

C1. (a) The conjugate base of $H_2PO_4^-$ is HPO_4^{2-}. The conjugate acid of HPO_4^{2-} is $H_2PO_4^-$: the same step read in the two directions. (b) $H_2PO_4^-$ and HPO_4^{2-} are amphiprotic. Each still carries at least one proton it can lose, and each can gain one more: $H_2PO_4^-$ sits between H_3PO_4 and HPO_4^{2-}, and HPO_4^{2-} sits between $H_2PO_4^-$ and PO_4^{3-}. H_3PO_4 can only donate and PO_4^{3-} can only accept, so the ends of the ladder are excluded. (c) The claim fails: H_3PO_4 and HPO_4^{2-} differ by two protons, and a conjugate pair must differ by exactly one. The correct partner for H_3PO_4 is $H_2PO_4^-$. (d) $H_2PO_4^-$ is the acid, since it loses a proton; OH^- is the base, since it gains one to become H_2O. The pairs are $H_2PO_4^-/HPO_4^{2-}$ and H_2O/OH^-.

C2. (a) Neutral means $[H_3O^+] = [OH^-]$, so $[H_3O^+] = \sqrt{(2.4 \times 10^{-14})} = 1.55 \times 10^{-7}$ mol L^{-1}, about 1.5×10^{-7}. (b) pH = $-\log(1.55 \times 10^{-7}) = 6.81$. (c) The sample, pH 7.4, is basic relative to neutral at 37 °C, because 7.4 lies above the neutral value of 6.81 at this temperature: its $[H_3O^+]$ is lower than the

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neutral concentration. Comparing with 7.0 would mislead because 7.0 is the neutral point only at 25 °C; at body temperature the whole scale's midpoint has moved, dragged by the larger Kw.

C3. (a) W: $[H_3O^+] = (1.0 \times 10^{-14}) \div (1.0 \times 10^{-9}) = 1.0 \times 10^{-5}$ mol L^{-1}. X: given directly, 1.0×10^{-4} mol L^{-1}. Y: $[H_3O^+] = (1.0 \times 10^{-14}) \div (1.0 \times 10^{-12}) = 1.0 \times 10^{-2}$ mol L^{-1}. Z: pH 6 means $[H_3O^+] = 1.0 \times 10^{-6}$ mol L^{-1}. (b) Most acidic to least: Y (1.0×10^{-2}), X (1.0×10^{-4}), W (1.0×10^{-5}), Z (1.0×10^{-6}). (c) The trap is W against X. W's given number, 1.0×10^{-9}, looks smaller than X's 1.0×10^{-4} by five powers of ten, but W's number is a hydroxide concentration: a small $[OH^-]$ forces a large $[H_3O^+]$ through Kw, landing W at 1.0×10^{-5}, only one power of ten below X. Ranking given numbers without converting them to the same ion compares two different quantities.

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