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Topic 7.7: Calculating Equilibrium Concentrations

Worksheet · AP Chemistry

UNIT 7 · EQUILIBRIUM

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How to Use This Worksheet

Work in order. Section A checks the set-up skills: what x means, how the change row is built, and when x may be neglected. Section B practises each solving route in turn: the square root method, the quadratic, a valid small-x approximation, a rearrangement for one missing value, a Q comparison, and a table that starts from products only. Section C is exam style: a system with a product already present, a percent dissociation, and a student's approximation to judge and correct.

Reference facts. Kc is built from equilibrium concentrations only: write the K expression first, then substitute the equilibrium row. The change for each species is its coefficient times x. When both sides of the K expression are perfect squares, take the square root and solve a linear equation. Otherwise expand to $ax^2 + bx + c = 0$ and use the quadratic formula. The small-x approximation is valid only when x is under 5 percent of the initial concentration it was subtracted from. K depends only on temperature.

Conventions: every concentration is in mol L^{-1}, and x always refers to the change row exactly as the question defines it. Every finished problem is closed by substituting the equilibrium row back into the K expression. Where a percent dissociation is requested, the denominator is the starting concentration of the species that dissociates, never its equilibrium concentration.

Do not look at the answer key until you have attempted every question.

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Section A: Recall and Concepts

A1. Explain what x represents in an ICE table. In $N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$, the change for N_2 is written $-x$. State the change entries for H_2 and NH_3, and explain why they are not both $-x$ and $+x$ with no multipliers.

A2. Judge each statement, giving the reason. (a) "The equilibrium row is the initial row plus the change row, with reactants decreasing and products increasing when the reaction runs forward as written." (b) "If x = 0.30 mol L^{-1} in the ammonia synthesis starting from reactants only, $[H_2]$ falls by 0.30 mol L^{-1}." (c) "Of the two roots of the quadratic, the smaller root is always the physical one."

A3. For $A(g) + B(g) \rightleftharpoons C(g)$, an equilibrium mixture has [A] = 0.10, [B] = 0.40 and [C] = 0.80 mol L^{-1}. (a) Calculate Kc. (b) A student instead substitutes the initial row, [A] = 0.50, [B] = 0.50, [C] = 0, obtains 0, and concludes Kc = 0. Explain the error.

A4. For $2A(g) \rightleftharpoons B(g) + C(g)$, a vessel starts with [A] = 1.20 mol L^{-1} and no B or C. (a) Write the equilibrium row in terms of x. (b) Write the equation that x must satisfy for a given Kc. (c) State why [A] falls by 2x while [B] and [C] each rise by only x.

A5. (a) State the condition under which x may be neglected next to a starting concentration in the denominator of an equilibrium expression. (b) A student neglects x for a reactant starting at 0.020 mol L^{-1} and obtains x = 0.0016 mol L^{-1}. Decide whether the approximation was justified, and state what must happen next.

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Section B: Core Practice

B1. For $H_2(g) + I_2(g) \rightleftharpoons 2HI(g)$, Kc = 64. A vessel starts with $[H_2] = [I_2] = 0.70$ mol L^{-1} and no HI. (a) Write the ICE equilibrium row. (b) Solve for x by taking the square root of both sides. (c) Give all three equilibrium concentrations and verify them against Kc.

B2. For $PCl_5(g) \rightleftharpoons PCl_3(g) + Cl_2(g)$, Kc = 0.50, starting with $[PCl_5] = 0.20$ mol L^{-1} and no products. (a) Apply the small-x approximation and show that it returns an x larger than the starting concentration. State what that proves. (b) Solve the quadratic, select the physical root, and explain the rejection of the other. (c) Give the equilibrium concentrations and the percent dissociation, and verify by substitution.

B3. For $A(aq) \rightleftharpoons B(aq) + C(aq)$, $Kc = 2.5 \times 10^{-6}$, starting with $[A] = 0.40$ mol L^{-1} and no products. (a) Use the small-x approximation to find x. (b) Carry out the 5 percent check. (c) Give [B] and [C] at equilibrium, verify by substitution, and state the exact quadratic value of x for comparison.

B4. For $A(g) + 2B(g) \rightleftharpoons C(g)$, Kc = 8.0. At equilibrium [A] = 0.50 and [B] = 0.25 mol L^{-1}. Find [C], showing the rearrangement of the Kc expression.

B5. For $2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)$, $Kc = 4.0 \times 10^{2}$. A mixture at one instant has $[SO_2] = 0.20$, $[O_2] = 0.10$ and $[SO_3] = 0.40$ mol L^{-1}. (a) Calculate Q and state the direction of net change. (b) State how $[SO_2]$ and $[SO_3]$ change as equilibrium is approached. (c) Later the same system is sampled again with $[SO_3] = 4.0$ mol L^{-1} and the other two concentrations momentarily unchanged. Calculate Q and state the direction of net change now.

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B6. For $2HI(g) \rightleftharpoons H_2(g) + I_2(g)$, Kc = 0.0156. A vessel starts with [HI] = 0.50 mol L^{-1} and no products. (a) Write the ICE equilibrium row, taking x as the equilibrium concentration of H_2 formed. (b) Solve by taking the square root of both sides, keeping both signs, and select the physical root with the reason. (c) Give the equilibrium concentrations and verify them against Kc.

Section C: Exam Style

C1. For $A(g) + B(g) \rightleftharpoons C(g) + D(g)$, Kc = 9.0. A vessel starts with [A] = [B] = 0.60, [C] = 0 and [D] = 0.20 mol L^{-1}. (a) Write the ICE equilibrium row in terms of x. (b) Set up the equation for x and solve it, giving both roots. (c) Select the physical root, with the reason. (d) Give all four equilibrium concentrations and verify them by substitution into the Kc expression.

C2. For $N_2O_4(g) \rightleftharpoons 2NO_2(g)$, Kc = 0.15. A vessel starts with $[N_2O_4]$ = 0.25 mol L^{-1} and no NO_2. (a) Try the small-x approximation and show that it fails the 5 percent check. (b) Solve the quadratic and select the physical root, explaining the rejection. (c) Give $[NO_2]$ at equilibrium and the percent dissociation of N_2O_4. (d) Verify by substitution.

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C3. A student works $HA(aq) \rightleftharpoons H^+(aq) + A^-(aq)$ with $K_a = 4.0 \times 10^{-4}$ and $[HA] = 0.050$ mol L^{-1} initially. Neglecting x, the student reports $[H^+] = 4.5 \times 10^{-3}$ mol L^{-1}. (a) Reproduce the student's calculation, then run the check the student skipped and state the verdict. (b) Solve the quadratic and give the correct $[H^+]$. (c) State the percent by which the student's value overshoots the correct value, and the percent dissociation of the acid.

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Answer Key

A1. x is the change in concentration tied to the extent of reaction: the amount by which the concentration of a species with coefficient 1 changes. Every other species changes by its coefficient times x, so the changes stay in the mole ratio of the equation. For H_2 the entry is $-3x$ and for NH_3 it is $+2x$. Writing $-x$ for H_2 would consume hydrogen and nitrogen in a 1 to 1 ratio that the equation does not allow, and the ICE row would no longer conserve atoms.

A2. (a) True. The equilibrium row is built by adding the signed change row to the initial row; for a reaction running forward as written, reactants carry negative changes and products positive ones. (b) False. $[H_2]$ falls by $3x = 3 \times 0.30 = 0.90$ mol L^{-1}, because three moles of H_2 are consumed for every one mole of N_2. (c) False. The physical root is the one that leaves every equilibrium concentration positive and reachable from the starting amounts. A larger root can be the physical one, a smaller root can still overshoot a starting concentration, and when both roots fail the set-up, not the algebra, is at fault.

A3. (a) $K_c = [C] / ([A][B]) = 0.80 / (0.10 \times 0.40) = 0.80 / 0.040 = 20$. (b) K is defined by equilibrium concentrations only. Substituting the initial row calculates Q at the first instant, not K; with no product present that value is 0 whatever K is, and it tells you only that the reaction must run forward from that mixture. The student's 0 is a value of Q, and the conclusion $K_c = 0$ does not follow.

A4. (a) $[A] = 1.20 - 2x$, $[B] = x$, $[C] = x$. (b) $K_c = [B][C] / [A]^2 = x^2 / (1.20 - 2x)^2$. (c) Two moles of A are consumed for each mole of B and each mole of C formed, so the concentration of A falls at twice the rate x at which B and C rise; the change entries are the coefficients multiplied by x.

A5. (a) x may be neglected only when, after solving, x is less than 5 percent of the starting concentration it was subtracted from. (b) x as a percentage of the starting concentration is $0.0016 / 0.020 = 8.0$ percent, which exceeds 5 percent, so the approximation was not justified. The problem must be solved again with the full quadratic, keeping the $(0.020 - x)$ term intact.

B1. (a) $[H_2] = 0.70 - x$, $[I_2] = 0.70 - x$, $[HI] = 2x$. (b) $K_c = (2x)^2 / (0.70 - x)^2 = 64$. Taking square roots: $2x / (0.70 - x) = 8$, so $2x = 5.6 - 8x$, $10x = 5.6$ and $x = 0.56$. (c) $[H_2] = [I_2] = 0.70 - 0.56 = 0.14$ mol L^{-1} and $[HI] = 2 \times 0.56 = 1.12$ mol L^{-1}. Check: $(1.12)^2 / (0.14 \times 0.14) = 1.2544 / 0.0196 = 64$, as required.

B2. (a) Neglecting x gives $x^2 \approx K_c \times 0.20 = 0.50 \times 0.20 = 0.10$, so $x \approx \sqrt{0.10} = 0.32$ mol L^{-1}. That exceeds the starting concentration of 0.20 mol L^{-1}: the vessel cannot lose more PCl_5 than it holds, so the approximation is invalid before any percent check is run. (b) Keeping the full term: $x^2 / (0.20 - x) = 0.50$, which expands to $x^2 + 0.50x - 0.10 = 0$. The roots are $x = 0.153$ and $x = -0.653$. The negative root sets $[PCl_3] = [Cl_2] = -0.653$ mol L^{-1}, which is impossible, so $x = 0.153$. (c) $[PCl_5] = 0.20 - 0.153 = 0.047$ mol L^{-1} and $[PCl_3] = [Cl_2] = 0.153$ mol L^{-1}. Percent dissociation $= 0.153 / 0.20 \times 100 = 77$ percent. Check: $(0.153 \times 0.153) / 0.047 = 0.50$, as required.

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B3. (a) Neglecting x next to 0.40: $x^2 / 0.40 = 2.5 \times 10^{-6}$, so $x = \sqrt{(2.5 \times 10^{-6} \times 0.40)} = \sqrt{(1.0 \times 10^{-6})} = 1.0 \times 10^{-3}$ mol L^{-1}. (b) The check: $1.0 \times 10^{-3} / 0.40 = 0.25$ percent, well under 5 percent, so the approximation is valid. (c) [B] = [C] = 1.0×10^{-3} mol L^{-1} and [A] = 0.40 mol L^{-1} to the precision used. Check: $(1.0 \times 10^{-3})^2 / 0.40 = 2.5 \times 10^{-6}$, as required. The exact quadratic root is 9.99×10^{-4} mol L^{-1}, only 0.13 percent below the approximation.

B4. $K_c = [C] / ([A][B]^2)$, so $[C] = K_c \times [A] \times [B]^2 = 8.0 \times 0.50 \times (0.25)^2 = 8.0 \times 0.50 \times 0.0625 = 0.25$ mol L^{-1}. The coefficient of B appears as the power on [B] in the rearrangement, exactly as it did in the original expression. Check: $0.25 / (0.50 \times 0.0625) = 8.0$, returning K_c.

B5. The expression is $Q = [SO_3]^2 / ([SO_2]^2[O_2])$. (a) $Q = (0.40)^2 / ((0.20)^2 \times 0.10) = 0.16 / 0.0040 = 40$. Since $Q = 40$ is less than $K_c = 4.0 \times 10^2$, the net change is forward, toward products. (b) $[SO_2]$ falls and $[SO_3]$ rises, and $[O_2]$ falls at half the rate of $[SO_2]$, following the coefficients: for every 2 mol of SO_2 consumed, 1 mol of O_2 is consumed and 2 mol of SO_3 is formed, until Q rises to meet K_c. (c) $Q = (4.0)^2 / ((0.20)^2 \times 0.10) = 16 / 0.0040 = 4.0 \times 10^3$, which exceeds K_c, so the net change is now in reverse, toward reactants. Nothing about K_c changed between the two samples; only the mixture did.

B6. (a) $[HI] = 0.50 - 2x$, $[H_2] = x$, $[I_2] = x$. (b) $K_c = x^2 / (0.50 - 2x)^2 = 0.0156$. Taking square roots with both signs: $x / (0.50 - 2x) = \pm\sqrt{0.0156} = \pm 0.125$. The positive sign gives $x = 0.050$. The negative sign gives $x = -0.083$, which would set $[H_2] = [I_2] = -0.083$ mol L^{-1}, so it is rejected. (c) $[HI] = 0.50 - 2 \times 0.050 = 0.40$ mol L^{-1} and $[H_2] = [I_2] = 0.050$ mol L^{-1}. Check: $(0.050 \times 0.050) / (0.40)^2 = 0.0156$, as required. This K_c is 1 / 64, the reciprocal of the forward constant in the notes Example 1, as the reversing rule requires.

C1. (a) $[A] = 0.60 - x$, $[B] = 0.60 - x$, $[C] = x$, $[D] = 0.20 + x$. The D row starts at 0.20 because product is already present; its change is still +x. Because every coefficient in this equation is 1, all four change entries use plain x with no multipliers. (b) $K_c = [C][D] / ([A][B]) = x(0.20 + x) / (0.60 - x)^2 = 9.0$. Expanding: $x^2 + 0.20x = 9.0(x^2 - 1.2x + 0.36)$, which rearranges to $8x^2 - 11x + 3.24 = 0$. The roots are $x = 0.427$ and $x = 0.948$. (c) $x = 0.948$ sets $[A] = [B] = 0.60 - 0.948 = -0.35$ mol L^{-1}, which is impossible, so $x = 0.427$. (d) $[A] = [B] = 0.60 - 0.427 = 0.173$ mol L^{-1}, $[C] = 0.427$ mol L^{-1} and $[D] = 0.20 + 0.427 = 0.627$ mol L^{-1}. Check: $(0.427 \times 0.627) / (0.173 \times 0.173) = 9.0$, as required, using unrounded values.

C2. (a) Neglecting x: $(2x)^2 \approx K_c \times 0.25 = 0.15 \times 0.25$, so $4x^2 = 0.0375$ and $x \approx \sqrt{0.009375} = 0.097$. The check: $0.097 / 0.25 = 39$ percent, far over 5 percent, so the approximation fails and the quadratic is required. (b) $(2x)^2 / (0.25 - x) = 0.15$ expands to $4x^2 + 0.15x - 0.0375 = 0$, with roots $x = 0.0799$ and $x = -0.117$. The negative root sets $[NO_2] = 2x = -0.23$ mol L^{-1}, so it is rejected and $x = 0.0799$. (c) $[NO_2] = 2 \times 0.0799 = 0.160$ mol L^{-1}. Percent dissociation $= 0.0799 / 0.25 \times 100 = 32$ percent. (d) Check: $(0.160)^2 / (0.25 - 0.0799) = 0.0256 / 0.170 = 0.15$, as required.

C3. (a) The student set $x^2 / 0.050 = 4.0 \times 10^{-4}$, giving $x = \sqrt{(4.0 \times 10^{-4} \times 0.050)} = \sqrt{(2.0 \times 10^{-5})} = 4.5 \times 10^{-3}$ mol L^{-1}. The skipped check: $4.5 \times 10^{-3} / 0.050 = 8.9$ percent, which exceeds 5 percent, so

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neglecting x was not justified and the reported value is not reliable. (b) Keeping the full term: x^2 / (0.050 − x) = 4.0×10^{-4}, which expands to $x^2 + 4.0 \times 10^{-4}x - 2.0 \times 10^{-5} = 0$. The positive root is x = 4.3×10^{-3} mol L^{-1}, so $[H^+] = 4.3 \times 10^{-3}$ mol L^{-1}. (c) The overshoot is (4.472 − 4.277) / 4.277 × 100 = 4.6 percent, using the unrounded values. The percent dissociation is 4.28×10^{-3} / 0.050 × 100 = 8.6 percent: nearly one acid molecule in eleven is dissociated, which is exactly why x could not be treated as negligible next to 0.050.

Continue Revising

Topic 7.7 Revision Notes

Topic 7.7 Quiz: Calculating Equilibrium Concentrations

Previous Worksheet: Topic 7.6 Properties of the Equilibrium Constant

Next Worksheet: Topic 7.8 Representations of Equilibrium

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