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Topic 7.10: Reaction Quotient and Le Chatelier's Principle

Worksheet · AP Chemistry

UNIT 7 · EQUILIBRIUM

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How to Use This Worksheet

Work in order. Section A checks the routine itself: the three Q comparisons, what each kind of disturbance does to Q and to K, and the volume and temperature rules. Section B practises the routine disturbance by disturbance, with Q calculated from numbers every time. Section C is exam style: judging claims, one system disturbed two ways, and a five-change comparison.

Reference facts. Q has the same form as K but uses the concentrations or partial pressures present right now. For the general reaction aA + bB ⇌ cC + dD, the reaction quotient is

$Qc = [C]^c[D]^d \div [A]^a[B]^b$

Pure solids and pure liquids are left out. Q less than K means shift right toward products; Q greater than K means shift left toward reactants; Q equal to K means equilibrium. Concentration, pressure, and volume stresses change Q; only temperature changes K. For an exothermic reaction, raising the temperature lowers K; for an endothermic reaction, raising the temperature raises K. Increasing pressure shifts equilibrium toward fewer gas moles; decreasing pressure shifts it toward more gas moles. A catalyst, an inert gas at constant volume, and added solid or liquid never shift an equilibrium. Useful values: $H_2 + I_2 \rightleftharpoons 2HI$ has Kc = 54; $N_2O_4 \rightleftharpoons 2NO_2$ has Kc = 0.21; $PCl_5 \rightleftharpoons PCl_3 + Cl_2$ has Kc = 0.042; $CO + Cl_2 \rightleftharpoons COCl_2$ has Kc = 255; $2A \rightleftharpoons B + C$ has Kc = 1.6.

Three habits protect every answer. Write the Q expression with correct exponents and no solids or liquids before you touch a number. Plug in the current concentrations, not

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equilibrium ones, and compare the number with K. If the stress is temperature, adjust K first, then compare.

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

Section A: Recall and Concepts

A1. (a) Write the expression for Qc for $N_2O_4(g) \rightleftharpoons 2NO_2(g)$. (b) For each comparison, Q less than Kc, Q greater than Kc, and Q equal to Kc, state which net reaction runs, if any, and what happens to Q while it runs. (c) State which single stress changes K, and which stresses change Q only. (d) State what happens to Q when a reaction at equilibrium is left undisturbed.

A2. Judge each statement, giving the correction. (a) "Adding a reactant increases Kc, so the equilibrium shifts right." (b) "Heating an equilibrium mixture changes Q at once, before any reaction happens." (c) "A catalyst shifts the equilibrium right by speeding up the forward reaction." (d) "Adding more solid $CaCO_3$ to $CaCO_3(s) \rightleftharpoons CaO(s) + CO_2(g)$ at equilibrium shifts the reaction right."

A3. $N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$ is exothermic and sits at equilibrium. (a) State what raising the temperature does to K. (b) State how Q compares with the new K just after heating, and state the direction of the shift. (c) State what lowering the temperature does to K, and state the direction of the shift. (d) State whether the equilibrium amount of NH_3 is higher or lower at the higher temperature than it was before heating.

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A4. For each reaction, state the gas moles on each side, the factor by which Q is multiplied when the volume of an equilibrium mixture is halved at constant temperature, and the direction of the shift. (a) $2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)$. (b) $H_2(g) + I_2(g) \rightleftharpoons 2HI(g)$. (c) $PCl_5(g) \rightleftharpoons PCl_3(g) + Cl_2(g)$, with the volume doubled instead of halved.

A5. $Fe^{3+}(aq) + SCN^-(aq) \rightleftharpoons FeSCN^{2+}(aq)$ is at equilibrium. The product is deep red. (a) A few drops of KSCN(aq) are added. State what happens to Q, the direction of the shift, and the color. (b) A little $Fe(NO_3)_3(aq)$ is added. State what happens to Q, the direction of the shift, and the color. (c) Some Fe^{3+} is removed from the mixture. State what happens to Q, the direction of the shift, and the color. (d) A catalyst is added. State the effect on Q, on K, and on the color.

Section B: Core Practice

B1. $N_2O_4(g) \rightleftharpoons 2NO_2(g)$ has Kc = 0.21 at 100 °C. A mixture contains $[N_2O_4]$ = 0.10 M and $[NO_2]$ = 0.20 M. (a) Calculate Q. (b) Compare Q with Kc and state the direction of the shift. (c) State what happens to $[NO_2]$ as the shift proceeds. (d) State the value Q reaches when the shift stops. (e) If $[NO_2]$ were 0.10 M instead, with $[N_2O_4]$ still 0.10 M, calculate Q and state the shift.

B2. $A(g) + B(g) \rightleftharpoons C(g)$ has Kc = 5.0. A flask holds [A] = 0.50 M, [B] = 0.50 M, and [C] = 0.50 M. (a) Calculate Q. (b) Compare Q with Kc and state the direction of the shift. (c) Extra C is added until [C] = 1.50 M, with [A] and [B] unchanged. Calculate the new Q and state the direction of the shift. (d) State what happens to [A] during the shift in part (c). (e) State the value of Kc after the shift in part (c).

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B3. $H_2(g) + I_2(g) \rightleftharpoons 2HI(g)$ has Kp = 54. Partial pressures in a vessel are PH_2 = 1.0 atm, PI_2 = 1.0 atm, and PHI = 3.0 atm. (a) Calculate Qp. (b) Compare Qp with Kp and state the direction of the reaction. (c) Extra H_2 is injected until PH_2 = 2.0 atm, with the other pressures unchanged. Calculate the new Qp and state the direction of the reaction. (d) State the value of Kp after the change in part (c). (e) At equilibrium with PH_2 = 1.0 atm and PI_2 = 1.0 atm, calculate the equilibrium partial pressure of HI.

B4. $PCl_5(g) \rightleftharpoons PCl_3(g) + Cl_2(g)$ has Kc = 0.042 at a certain temperature. A vessel holds $[PCl_5]$ = 0.080 M, $[PCl_3]$ = 0.060 M, and $[Cl_2]$ = 0.120 M. (a) Calculate Q. (b) Compare Q with Kc and state the direction of the shift. (c) Starting again from the same mixture, $[Cl_2]$ is doubled to 0.240 M with the other concentrations unchanged. Calculate Q and state the direction of the shift. (d) State the value of Kc after the change in part (c). (e) Starting again from the original mixture, the volume is halved. State the three concentrations immediately afterwards, calculate Q, and state the direction of the shift.

B5. $CO(g) + Cl_2(g) \rightleftharpoons COCl_2(g)$ has Kc = 255. A vessel contains [CO] = 0.10 M, $[Cl_2]$ = 0.10 M, and $[COCl_2]$ = 2.0 M. (a) Calculate Q and state the direction of the reaction. (b) Extra CO is injected until [CO] = 0.20 M, with the other concentrations unchanged. Calculate Q and state the direction of the reaction. (c) State the value of Kc after the change in part (b). (d) The reaction is exothermic. State what raising the temperature does to K. (e) Starting again from the original mixture, the temperature is raised until K falls to 100. Compare Q with the new K at the instant after heating and state the direction of the shift.

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B6. A(aq) ⇌ 2B(aq) has Kc = 4.0. An equilibrium mixture has [A] = 0.25 M and [B] = 1.0 M. (a) Verify that the mixture is at equilibrium by calculating Q. (b) The mixture is diluted to twice its volume at constant temperature. State the two concentrations immediately afterwards, calculate Q, and state the direction of the shift. (c) State what happens to [B] as the shift in part (b) proceeds. (d) Starting again from the original equilibrium mixture, B is added until [B] = 1.50 M, with [A] unchanged. Calculate Q and state the direction of the shift. (e) A catalyst is added to the original equilibrium mixture. State the effect on Q, on Kc, and on the position of equilibrium.

Section C: Exam Style

C1. Judge each claim, supporting each verdict with the Q comparison or the rule it depends on. (a) "Q less than K means the reaction shifts left." (b) "Halving the volume always doubles Q." (c) "Heating an exothermic reaction increases K." (d) "Adding helium at constant volume to $N_2O_4(g)$ ⇌ $2NO_2(g)$ at equilibrium shifts the reaction right, because the total pressure rises." (e) "After a shift, Q returns to K and the concentrations are the same as they were before the disturbance."

C2. $2SO_2(g) + O_2(g)$ ⇌ $2SO_3(g)$ has Kc = 16. An equilibrium mixture has $[SO_2]$ = 0.50 M, $[O_2]$ = 0.25 M, and $[SO_3]$ = 1.00 M. (a) Verify that the mixture is at equilibrium by calculating Q. (b) The volume is halved at constant temperature. State the three concentrations immediately afterwards, calculate Q, and state the direction of the shift, giving the gas mole counts on each side. (c) Starting again from the original equilibrium mixture, argon is added at constant volume. State the value of Q and whether the system shifts, with the reason. (d) Starting again from the original equilibrium mixture, a catalyst is added. State the effect on Q, on Kc, and on the position of equilibrium. (e) The reaction is exothermic. Starting again from the original equilibrium mixture, the temperature is raised. State what happens to K, compare Q with the new K, and state the direction of the shift.

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C3. $N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$ is exothermic. Five changes are made, each separately, to a mixture at equilibrium. For each change state the shift direction, the effect on Kc, and the effect on the equilibrium concentration of NH_3 compared with the original equilibrium. (a) The vessel is compressed at constant temperature. (b) Some NH_3 is removed at constant temperature and volume. (c) The temperature is raised. (d) A catalyst is added. (e) Argon is added at constant volume.

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Answer Key

A1. (a) Qc = $[NO_2]^2 \div [N_2O_4]$. (b) Q less than Kc: the forward reaction runs net and Q climbs toward Kc. Q greater than Kc: the reverse reaction runs net and Q falls toward Kc. Q equal to Kc: the mixture is at equilibrium and Q stays at Kc. (c) Only temperature changes K; concentration, pressure, and volume stresses change Q only. (d) Nothing: Q stays equal to K.

A2. (a) False. Adding a reactant changes Q, never Kc. It lowers Q below Kc, and the shift right is the system restoring Q to the unchanged Kc. (b) False. Heating changes K at once; the concentrations, and so Q, are momentarily unchanged. The shift follows from comparing the unchanged Q with the new K. (c) False. A catalyst speeds the forward and reverse reactions equally, so concentrations, Q, and K are unchanged and there is no shift. (d) False. $CaCO_3$ is a pure solid and does not appear in Q, which equals $[CO_2]$. Adding more solid changes nothing.

A3. (a) Raising the temperature lowers K for an exothermic reaction. (b) At the instant after heating Q is unchanged, so Q now exceeds the new, smaller K, and the system shifts left toward reactants. (c) Lowering the temperature raises K for an exothermic reaction, so Q falls below the new K and the system shifts right toward products. (d) Lower: at the higher temperature the equilibrium holds less NH_3 than before heating.

A4. (a) 3 gas moles of reactants against 2 of products. Halving the volume multiplies Q by 2^{-1}, so Q becomes Kc ÷ 2, below Kc, and the shift is right. (b) 2 gas moles on each side. Halving the volume multiplies Q by $2^0 = 1$, so Q still equals Kc and there is no shift. (c) 1 gas mole of reactant against 2 of products. Doubling the volume multiplies Q by $(1 \div 2)^1$, so Q becomes Kc ÷ 2, below Kc, and the shift is right toward more gas moles.

A5. (a) Added SCN^- enlarges the denominator of Q, so Q falls below K. The reaction shifts right, more $FeSCN^{2+}$ forms, and the color deepens. (b) Added Fe^{3+} also enlarges the denominator of Q, so Q falls below K. The reaction shifts right and the color deepens. (c) Removing Fe^{3+} shrinks the denominator of Q, so Q rises above K. The reaction shifts left, $FeSCN^{2+}$ is consumed, and the color fades. (d) No effect on Q, on K, or on the color: a catalyst changes only how fast equilibrium is reached.

B1. (a) $Q = (0.20)^2 \div 0.10 = 0.040 \div 0.10 = 0.40$. (b) 0.40 exceeds Kc = 0.21, so the system shifts left toward N_2O_4. (c) $[NO_2]$ falls as the reverse reaction consumes it. (d) Q falls until it reaches Kc = 0.21. (e) $Q = (0.10)^2 \div 0.10 = 0.010 \div 0.10 = 0.10$, below Kc = 0.21, so the forward reaction runs and the mixture shifts right.

B2. (a) $Q = 0.50 \div (0.50 \times 0.50) = 0.50 \div 0.25 = 2.0$. (b) 2.0 is below Kc = 5.0, so the forward reaction runs and the mixture shifts right. (c) $Q = 1.50 \div (0.50 \times 0.50) = 1.50 \div 0.25 = 6.0$, above Kc = 5.0, so the reverse reaction runs and the mixture shifts left. (d) [A] rises as the reverse reaction forms A and B from C. (e) Kc is still 5.0: only temperature changes K, and the temperature did not change.

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B3. (a) Qp = $(3.0)^2 \div (1.0 \times 1.0) = 9.0 \div 1.0 = 9.0$. (b) 9.0 is below Kp = 54, so the reaction proceeds forward toward products. (c) Qp = $(3.0)^2 \div (2.0 \times 1.0) = 9.0 \div 2.0 = 4.5$, below Kp = 54, so the reaction proceeds forward. (d) Kp is still 54: only temperature changes K. (e) At equilibrium Qp = Kp, so $(PHI)^2 \div (1.0 \times 1.0) = 54$, giving PHI = $\sqrt{54} = 7.3$ atm.

B4. (a) Q = $(0.060)(0.120) \div 0.080 = 0.0072 \div 0.080 = 0.090$. (b) 0.090 exceeds Kc = 0.042, so the reverse reaction runs and the mixture shifts left. (c) Q = $(0.060)(0.240) \div 0.080 = 0.0144 \div 0.080 = 0.18$, above Kc = 0.042, so the shift is left. (d) Kc is still 0.042: only temperature changes K. (e) Halving the volume doubles every concentration: $[PCl_5]$ = 0.16 M, $[PCl_3]$ = 0.12 M, $[Cl_2]$ = 0.24 M. Q = $(0.12)(0.24) \div 0.16 = 0.0288 \div 0.16 = 0.18$, above Kc = 0.042, so the shift is left toward fewer gas moles.

B5. (a) Q = $2.0 \div (0.10 \times 0.10) = 2.0 \div 0.010 = 200$, below Kc = 255, so the forward reaction proceeds. (b) Q = $2.0 \div (0.20 \times 0.10) = 2.0 \div 0.020 = 100$, below Kc = 255, so the forward reaction proceeds. (c) Kc is still 255: only temperature changes K. (d) Raising the temperature lowers K for an exothermic reaction. (e) At the instant after heating Q is still 200, from the original mixture, while the new K is 100. Q exceeds the new K, so the system shifts left toward reactants.

B6. (a) Q = $(1.0)^2 \div 0.25 = 1.0 \div 0.25 = 4.0$, equal to Kc, so the mixture is at equilibrium. (b) Dilution halves both concentrations: [A] = 0.125 M and [B] = 0.50 M. Q = $(0.50)^2 \div 0.125 = 0.25 \div 0.125 = 2.0$, below Kc = 4.0, so the reaction shifts right toward products. (c) [B] rises as the forward reaction converts A into B. (d) Q = $(1.50)^2 \div 0.25 = 2.25 \div 0.25 = 9.0$, above Kc = 4.0, so the reverse reaction runs and the mixture shifts left. (e) No effect on Q, on Kc, or on the position of equilibrium: a catalyst speeds both directions equally.

C1. (a) False. Q less than K means the mixture is short on products, so the forward reaction runs and the mixture shifts right. (b) False. Halving the volume multiplies Q by 2 raised to the power Δn: it halves Q when Δn = −1, leaves Q unchanged when Δn = 0, and doubles Q only when Δn = +1. (c) False. Heating an exothermic reaction lowers K; heating raises K only for an endothermic reaction. (d) False. At constant volume the helium changes no concentration, so Q is unchanged and nothing shifts, however much the total pressure rises. (e) False. Q returns to K, but the concentrations settle at new values: the disturbed species ends between its disturbed value and its original equilibrium value, never back at the original value.

C2. (a) Q = $(1.00)^2 \div ((0.50)^2 \times 0.25) = 1.00 \div 0.0625 = 16$, equal to Kc, so the mixture is at equilibrium. (b) Halving the volume doubles every concentration: $[SO_2]$ = 1.00 M, $[O_2]$ = 0.50 M, $[SO_3]$ = 2.00 M. Q = $(2.00)^2 \div ((1.00)^2 \times 0.50) = 4.00 \div 0.50 = 8.0$, below Kc = 16, so the shift is right toward the side with fewer gas moles: 2 ($2\ SO_3$) against 3 ($2\ SO_2$ and $1\ O_2$). (c) Q is still 16, equal to Kc, so there is no shift. At constant volume the argon changes no concentration and no partial pressure. (d) No effect on Q, on Kc, or on the position of equilibrium: a catalyst speeds both directions equally. (e) Heating an exothermic reaction lowers K. Q is still 16 at the instant after heating, so Q exceeds the new, smaller K and the system shifts left toward reactants.

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C3. (a) Compression: shift right, toward 2 gas moles of NH_3 against 4 of reactants; Kc unchanged; the equilibrium $[NH_3]$ rises. (b) NH_3 removed: removing a product drops Q below Kc, so the shift is right; Kc unchanged; the new equilibrium $[NH_3]$ is higher than the disturbed value but lower than the original: a partial replacement. (c) Temperature raised: the reaction is exothermic, so heating lowers Kc; the shift is left; the equilibrium $[NH_3]$ falls. (d) Catalyst added: no shift; Kc unchanged; $[NH_3]$ unchanged. (e) Argon at constant volume: no shift; Kc unchanged; $[NH_3]$ unchanged, because no concentration or partial pressure changes.

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Topic 7.10 Revision Notes

Topic 7.10 Quiz: Reaction Quotient and Le Chatelier's Principle

Previous Worksheet: Topic 7.9 Introduction to Le Chatelier's Principle

Next Worksheet: Topic 7.11 Introduction to Solubility Equilibria

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