1. Consider the following gas-phase reaction, at equilibrium, under conditions where the value of the equilibrium constant, $K$, is equal to 8:

$$N_2O_4(g) \rightleftharpoons 2NO_2(g), \quad K = 8$$

Which of the following diagrams represents a snapshot of a very small portion of this system at equilibrium?

2. Given the following reaction and equilibrium constant, which statement is correct for this reaction at equilibrium.

$$CO_2 \rightleftharpoons CO + \frac{1}{2}O_2, \quad K_{c1} = 9.1 \times 10^{-12}$$

a. The forward rate will be the same as the reverse rate.
b. The forward rate will be larger than the reverse rate.
c. The forward rate will be smaller than the reverse rate.
d. The concentration of CO$_2$ must be much smaller than the concentrations of both CO and O$_2$

3. Given the equilibrium constants for the first two reactions below at 1000°C, what is the equilibrium constant for the third reaction at the same temperature. (Assume that all species are in the gas phase.)

$$CO_2 \rightleftharpoons CO + \frac{1}{2}O_2, \quad K_{c1} = 9.1 \times 10^{-12} \quad (1)$$

$$H_2O \rightleftharpoons H_2 + \frac{1}{2}O_2, \quad K_{c2} = 7.1 \times 10^{-12} \quad (2)$$

$$CO_2 + H_2 \rightleftharpoons CO + H_2O, \quad K_{c3} = ? \quad (3)$$

4. If the following reaction were at equilibrium in a closed vessel at a controlled temperature, what would be the effect of adding more H$_2$ to the reaction vessel and permitting the reaction to approach equilibrium again.

$$CO + H_2O \rightleftharpoons CO_2 + H_2$$
The concentrations of CO, H₂O, and H₂ would all increase.

b. The concentrations of CO, H₂O, and H₂ would all decrease.

c. The concentrations of CO and H₂O would increase and the concentration of CO₂ would decrease.

d. The concentrations of CO and H₂O would decrease and the concentration of CO₂ would increase.

5. At 200°C, nitrogen oxide reacts with oxygen to form nitrogen dioxide as follows:

\[ 2\text{NO} + \text{O}_2 \rightleftharpoons 2\text{NO}_2, K_c = 3 \times 10^6 \]

In a mixture of the three species at equilibrium, we can accurately predict that:

a. The concentrations of both NO and O₂ will be much larger than the concentration of NO₂.

b. The concentrations of both NO and O₂ will be much smaller than the concentration of NO₂.

c. The concentrations of either NO or O₂ (and possibly both) will be much smaller than the concentration of NO₂.

d. The concentration of O₂ will be exactly one half the concentration of NO.

e. The concentration of O₂ will be exactly twice the concentration of NO.

6. At 200°C, nitrogen oxide reacts with oxygen to form nitrogen dioxide as follows:

\[ 2\text{NO} + \text{O}_2 \rightleftharpoons 2\text{NO}_2, K_c = 3 \times 10^6 \]

If a mixture of these three gases contains 0.10 M NO, 0.10 M NO₂, and 0.01 M O₂, then we can accurately predict that the reaction:

a. is at equilibrium.

b. is not at equilibrium and must proceed from left to right to reach equilibrium.

c. is not at equilibrium and must proceed from right to left to reach equilibrium.

d. is not at equilibrium but insufficient information is given to predict which direction the reaction must go to reach equilibrium.

e. the rate from right to left is greater than the rate from left to right.

7. If the following reaction were at equilibrium in a closed vessel at a controlled temperature, what would be the effect of adding more CO₂ to the reaction vessel and permitting the reaction to approach equilibrium again.

\[ \text{CO} + \text{H}_2\text{O} \rightleftharpoons \text{CO}_2 + \text{H}_2 \]

a. The concentrations of CO₂, H₂O, and H₂ would all increase.

b. The concentrations of CO₂, H₂O, and H₂ would all decrease.

c. The concentrations of CO and H₂O would decrease and the concentration of H₂ would increase.

d. The concentrations of CO and H₂O would increase and the concentration of H₂ would decrease.

8. At 300°C sulfur trioxide decomposes into sulfur dioxide and oxygen as follows:

\[ 2\text{SO}_3 \rightleftharpoons 2\text{SO}_2 + \text{O}_2, K_c = 1.6 \times 10^{-10} \]

In a mixture of the three species at equilibrium, we can accurately predict that:

a. The concentrations of both SO₂ and O₂ will be much larger than the concentration of SO₃.
b. The concentrations of either SO$_2$ or O$_2$ (and possibly both) will be much smaller than the concentration of SO$_3$.

c. The concentration of O$_2$ will be exactly one half the concentration of SO$_3$.

d. The concentration of O$_2$ will be exactly twice the concentration of SO$_3$.

9. At 300°C, gaseous sulfur trioxide decomposes into gaseous sulfur dioxide and oxygen as follows:

\[ 2 \text{SO}_3 \rightleftharpoons 2 \text{SO}_2 + \text{O}_2, K_c = 1.6 \times 10^{-10} \]

If a mixture of these three gases contains 0.10 M SO$_3$, 0.10 M SO$_2$, and 0.01 M O$_2$, then we can accurately predict that the reaction:

a. is at equilibrium.

b. is not at equilibrium and must proceed from left to right to reach equilibrium.

c. is not at equilibrium and must proceed from right to left to reach equilibrium.

d. is not at equilibrium but insufficient information is given to predict which direction the reaction must go to reach equilibrium.

10. In recitation, you constructed a microscopic representation of a gas-phase reaction at equilibrium. Consider the following gas-phase reaction, at equilibrium, under conditions where $K_c = 1$:

\[ \text{H}_2 (g) + \text{I}_2 (g) \rightleftharpoons 2 \text{HI} (g), K_c = 1 \]

Which of the following diagrams represents a snapshot of a very small portion of this system at equilibrium?

![Diagram Options]

11. Consider the following gas-phase reaction,

\[ \text{N}_2 (g) + 3 \text{H}_2 (g) \rightleftharpoons 2 \text{NH}_3 (g), K_c = 0.040 @ 650°C \]

If the concentrations of N$_2$ (g), H$_2$ (g) and NH$_3$ (g) at a particular moment in time are 0.25 M, 0.10 M and 0.15 M, respectively, we can accurately predict:

a. that the reaction is at equilibrium.

b. that the reaction is not at equilibrium, and must proceed to the left to reach equilibrium.

c. that the reaction is not at equilibrium, and must proceed to the right to reach equilibrium.

d. that the value of $K_c$ will be different when the reaction reaches equilibrium.

e. nothing.

12. The equilibrium constant for the following gas-phase reaction is equal to $5.8 \times 10^{-5}$ at 25°C,

\[ \text{N}_2 \text{O}_4 (g) \rightleftharpoons 2 \text{NO}_2 (g) \]

Calculate the value of $K_c$ at 25°C for the reaction:

\[ 4 \text{NO}_2 (g) \rightleftharpoons 2 \text{N}_2 \text{O}_4 (g) \]
13. Consider the following gas-phase reaction at equilibrium,

\[ \text{Cl}_2 (g) + 3 \text{F}_2 (g) \rightleftharpoons 2 \text{ClF}_3 (g) \]

If the concentration of \( \text{F}_2 (g) \) is suddenly doubled at constant pressure and volume, which of the following best describes what will happen?

a. The concentrations of both \( \text{F}_2 (g) \) and \( \text{ClF}_3 (g) \) will increase; \( \text{Cl}_2 (g) \) will decrease.
b. The concentrations of both \( \text{F}_2 (g) \) and \( \text{Cl}_2 (g) \) will decrease; \( \text{ClF}_3 (g) \) will increase.
c. The concentration of \( \text{ClF}_3 (g) \) will decrease; \( \text{Cl}_2 (g) \) and \( \text{F}_2 (g) \) will both increase.
d. The concentrations of all three species will be unaffected.
e. It is impossible to tell without the value of the equilibrium constant.

14. Given the equilibrium constant for the following reaction at 500 K,

\[ 2 \text{NO} (g) + \text{O}_2 (g) \rightleftharpoons 2 \text{NO}_2 (g), K_c = 6.2 \times 10^5 \]

calculate the equilibrium constant for the following reaction at the same temperature

\[ \text{NO} (g) + \frac{1}{2} \text{O}_2 (g) \rightleftharpoons \text{NO}_2 (g). \]

15. Given the equilibrium constant for the following reaction at 500 K,

\[ 2 \text{NO} (g) + \text{O}_2 (g) \rightleftharpoons 2 \text{NO}_2 (g), K_c = 6.2 \times 10^5 \]

calculate the equilibrium constant for the reaction expressed as partial pressures. (NOTE: \( R = 0.0821 \text{ L atm mol}^{-1} \text{ K}^{-1} \))

16. Given the following reaction, equilibrium constant, and molar concentrations of the three species,

\[ 2 \text{NO} (g) + \text{O}_2 (g) \rightleftharpoons 2 \text{NO}_2 (g), \ K_c = 6.2 \times 10^5 \]

0.0513 0.112 0.000212

we can accurately predict:

a. that the reaction is at equilibrium.
b. that the reaction is not at equilibrium and must proceed left to right to reach equilibrium.
c. that the reaction is not at equilibrium and must proceed right to left to reach equilibrium.
d. that the reaction is not at equilibrium but insufficient information is given to predict the direction it must go to reach equilibrium.
e. nothing regarding the equilibrium condition for the reaction from the information given.

17. Given the following reaction and equilibrium constant:

\[ \text{CO} (g) + \frac{1}{2} \text{O}_2 (g) \rightleftharpoons \text{CO}_2 (g), K_c = 1.1 \times 10^{11} \]

select the correct response from below.

a. The net driving force for the reaction will always be left to right because the equilibrium constant is very large.
b. The rate of the forward reaction will always be greater than the rate of the reverse reaction because the equilibrium constant is so large.
c. For a reaction mixture containing equilibrium concentrations of the three components, the forward and reverse rates will both go to zero.
d. All responses above are correct.
e. All responses above are incorrect.
18. Assuming that the following reaction is at equilibrium:

\[ 2 \text{SO}_3 (g) + \text{Cl}_2 (g) \rightleftharpoons 2 \text{SO}_2 \text{Cl}_2 (g) + \text{O}_2 (g) \]

select the correct response below.

a. Addition of Cl\textsubscript{2} to the reaction mixture would cause the concentrations of SO\textsubscript{2}Cl\textsubscript{2} and O\textsubscript{2} to increase.
b. Addition of O\textsubscript{2} to the reaction mixture would cause both the SO\textsubscript{2}Cl\textsubscript{2} and the SO\textsubscript{3} concentrations to increase.
c. Increasing the pressure of the system would cause the reaction to shift from left to right.
d. All responses above are correct.
e. No response above is correct.

19. At 1000°C, the equilibrium constant for the reaction of hydrogen and oxygen to produce water is very large (K\textsubscript{c} = 2 \times 10^{22}). When the reaction is at equilibrium:

a. the rate of the forward reaction will be much larger than the rate of the reverse reaction.
b. the rate of the reverse reaction will be much larger than the rate of the forward reaction.
c. the rates of the forward and reverse reactions will be the same.
d. there will not be any direct relationship between the rates of the forward and reverse reactions.

20. At 1000°C, the equilibrium constant for the reaction of carbon monoxide and oxygen to produce carbon dioxide is very large (K\textsubscript{c} = 1.2 \times 10^{22}). When the reaction is at equilibrium:

a. concentration of carbon dioxide will be much larger than one or both reactants.
b. concentration of carbon dioxide will be much smaller than concentrations of both reactants.
c. concentration of carbon monoxide will be much larger than the concentration of carbon dioxide.
d. concentrations of both reactants must be much smaller than the concentration of carbon dioxide.
e. None of the above responses is correct.

21. For which of the following reactions would the equilibrium concentrations NOT be affected by a change in the total pressure?

a. N\textsubscript{2}(g) + 3 H\textsubscript{2}(g) \rightleftharpoons 2 NH\textsubscript{3}(g)
b. PCl\textsubscript{3}(g) + Cl\textsubscript{2}(g) \rightleftharpoons PCl\textsubscript{5}(g)
c. 2 NO\textsubscript{2}(g) \rightleftharpoons N\textsubscript{2}(g) + 2 O\textsubscript{2}(g)
d. CO(g) + 1/2 O\textsubscript{2}(g) \rightleftharpoons CO\textsubscript{2}(g)
e. CO(g) + H\textsubscript{2}O(g) \rightleftharpoons CO\textsubscript{2}(g) + H\textsubscript{2}(g)

22. Given the following reactions and associated equilibrium constants, select the correct expression for the third equilibrium constant in terms of the first two. (Be careful.)

(1) \[ 2 \text{CO}(g) + \text{O}_2(g) \rightleftharpoons 2\text{CO}_2(g) \quad K_{c1} \]
(2) \[ \text{H}_2(g) + 1/2\text{O}_2(g) \rightleftharpoons \text{H}_2\text{O}(g) \quad K_{c2} \]
(3) \[ \text{CO}(g) + \text{H}_2\text{O}(g) \rightleftharpoons \text{CO}_2(g) + \text{H}_2(g) \quad K_{c3} \]

a. \( K_{c3} = K_{c1} \times K_{c2} \)
b. \( K_{c3} = K_{c1} / K_{c2} \)
c. \( K_{c3} = (K_{c1})^{1/2} / K_{c2} \)
d. \( K_{c3} = K_{c1} \times (K_{c2})^{1/2} \)
e. \( K_{c3} = (K_{c1})^{1/2} \times (K_{c2})^{1/2} \)
23. The equilibrium constant for the following reaction is \( K_c = 1.5 \times 10^4 \).

\[
\text{CO(g)} + \text{Cl}_2(g) \rightleftharpoons \text{COCl}_2(g)
\]

Given a reaction vessel containing 0.050 M COCl\(_2\), 0.0010 M CO and 0.0001 M Cl\(_2\), we can accurately predict that the reaction:

a. is at equilibrium.
b. must shift from right to left to reach equilibrium.
c. must shift left to right to reach equilibrium.
d. is not at equilibrium but insufficient information is given to predict which direction the reaction must go to reach equilibrium.

24. Commercially, ammonia (NH\(_3\)) is produced from nitrogen (N\(_2\)) and hydrogen (H\(_2\)) using the Haber process:

\[
\text{N}_2(g) + 3 \text{H}_2(g) \rightleftharpoons 2 \text{NH}_3(g)
\]

This reaction is exothermic. Which of the following would INCREASE the amount of NH\(_3\) obtained (i.e., maximize the yield of NH\(_3\)) at equilibrium?

i. Decrease the pressure.
ii. Increase the temperature.
iii. Increase the concentration of N\(_2\).
iv. Increase the concentration of NH\(_3\).
v. Decrease the concentration of H\(_2\).

a. i, ii, iv and v.  
b. i and iii.
c. ii and iii.
d. iii only  
e. iii, iv and v.

25. Laughing gas, N\(_2\)O, can be prepared from H\(_2\) and NO:

\[
\text{H}_2(g) + 2 \text{NO(g)} \rightleftharpoons \text{N}_2\text{O(g)} + \text{H}_2\text{O(g)}, K_c = 1.4 \times 10^{52} @ 25^\circ C
\]

If the reaction mixture contains 0.05 M H\(_2\), 0.02 M NO (g), 5.4 M N\(_2\)O (g) and 8.7 M H\(_2\)O (g) at some particular moment in time, then we can accurately predict that:

a. the reaction is very close to equilibrium.
b. the reaction is very far from equilibrium.
c. the reaction is at equilibrium.
d. both the H\(_2\) (g) and NO (g) concentrations must increase significantly to reach equilibrium.
e. there will be no N\(_2\)O (g) at equilibrium.

26. Consider the following reaction and equilibrium constant,

\[
\text{CO(g)} + \text{H}_2\text{O(g)} \rightleftharpoons \text{CO}_2(g) + \text{H}_2(g), K_{c1} = 0.72 @ 800^\circ C
\]

Which of the following is the correct expression for the equilibrium constant at 800°C for:

\[
2 \text{CO}_2(g) + 2 \text{H}_2(g) \rightleftharpoons 2 \text{CO(g)} + 2 \text{H}_2\text{O(g)}, K_{c2} = ??
\]

a. \( K_{c2} = 0.72 \)
b. \( K_{c2} = (0.72)^2 \)
c. \( K_{c2} = 1/0.72 \)
d. \( K_{c2} = (1/0.72)^2 \)
e. \( K_{c2} = (1/0.72)^{1/2} \)
Use the following information to answer the next 5 questions, assuming the same temperature for all questions.

\[ 3 \text{H}_2 (g) + \text{N}_2 (g) \rightleftharpoons 2 \text{NH}_3 (g), \quad K_c = 60 \]

27. If the reaction above were at equilibrium, then addition of some nitrogen would cause:
   a. both the \( \text{H}_2 \) and \( \text{NH}_3 \) concentrations to increase.
   b. both the \( \text{H}_2 \) and \( \text{NH}_3 \) concentrations to decrease.
   c. the \( \text{H}_2 \) concentration to increase and the \( \text{NH}_3 \) concentration to decrease.
   d. the \( \text{H}_2 \) concentration to decrease and the \( \text{NH}_3 \) concentration to increase.

28. The equilibrium constant expressed as partial pressure would be:
   a. \( K_p = 60(\text{RT}) \)
   b. \( K_p = 60/(\text{RT}) \)
   c. \( K_p = 60/(\text{RT})^2 \)
   d. \( K_p = (\text{RT})^{-1}/60 \)
   e. \( K_p = (\text{RT})^{-2}/60 \)

29. If the reaction quotient for the above reaction were \( Q_c = 73 \), then we can accurately predict that the following concentration changes must take place for the reaction to reach equilibrium.
   a. \( \text{H}_2 \), \( \text{N}_2 \) increase; \( \text{NH}_3 \) decrease
   b. \( \text{H}_2 \), \( \text{N}_2 \) decrease; \( \text{NH}_3 \) increase
   c. \( \text{H}_2 \), \( \text{NH}_3 \) decrease; \( \text{N}_2 \) increase
   d. all concentrations increase
   e. all concentrations decrease

30. Based on information given above, what is the equilibrium constant for the reaction:
   \[ \frac{3}{2} \text{H}_2 (g) + \frac{1}{2} \text{N}_2 (g) \rightleftharpoons \text{NH}_3 (g) \]
   a. \( K_c = 60 \)
   b. \( K_c = (60)^2 \)
   c. \( K_c = 1/60 \)
   d. \( K_c = (1/60)^2 \)
   e. \( K_c = (60)^{1/2} \)

31. If a reaction mixture contains 0.15 M hydrogen, 1.1 M \( \text{N}_2 \) and 0.472 M ammonia, then we can accurately predict that:
   a. the reaction is very close to equilibrium.
   b. the reaction is very far from equilibrium.
   c. the ammonia concentration must more than double to reach equilibrium.
   d. both \( \text{H}_2 \) and \( \text{N}_2 \) concentrations must increase significantly to reach equilibrium.

32. Consider the following exothermic gas-phase reaction, at equilibrium,
   \[ 4 \text{HCl (g)} + \text{O}_2 (g) \rightleftharpoons 2 \text{Cl}_2 (g) + 2 \text{H}_2 \text{O (g)} \]
   If the concentration of \( \text{HCl (g)} \) were suddenly increased, describe what would happen to:
   a. the concentration of \( \text{O}_2 (g) \).
   b. the concentration of \( \text{Cl}_2 (g) \).
   c. the concentration of \( \text{H}_2 \text{O (g)} \).
   d. the value of the equilibrium constant

33. Nitrogen dioxide (\( \text{NO}_2 \)) is involved in the formation of smog and acid rain. A reaction that is important in the formation of \( \text{NO}_2 \) is:
   \[ \text{O}_3 (g) + \text{NO (g)} \rightleftharpoons \text{O}_2 (g) + \text{NO}_2 (g), \quad K_c = 6.0 \times 10^{34} \]
   If the air over a section of Indianapolis contained \( 1.0 \times 10^{-6} \) M \( \text{O}_3 \), \( 1.0 \times 10^{-5} \) M \( \text{NO} \), \( 2.5 \times 10^{-4} \) M \( \text{NO}_2 \) and \( 8.2 \times 10^{-3} \) M \( \text{O}_2 \), what can we conclude?
a. There will be a tendency to form more NO and $O_3$.
b. There will be a tendency to form more $NO_2$ and $O_2$.
c. There will be a tendency to form more $NO_2$ and $O_3$.
d. There will be a tendency to form more NO and $O_2$.
e. There will be no tendency for change because the reaction is at equilibrium.

34. At 1800 K, molecular oxygen dissociates slightly to give small amounts of atomic oxygen as follows:

$$O_2 (g) \rightleftharpoons 2 O (g), \quad K_c = 1.7 \times 10^{-8}$$

What is the value of the equilibrium constant, $K'_c$, for the reaction,

$$\frac{1}{2} O (g) \rightleftharpoons \frac{1}{4} O_2 (g)$$
at 1800 K?

a. $K'_c = 4.3 \times 10^{-9}$  
b. $K'_c = 1.1 \times 10^{-2}$  
c. $K'_c = 8.8 \times 10^{1}$  
d. $K'_c = 7.7 \times 10^{3}$  
e. $K'_c = 5.9 \times 10^{7}$

35. What is the equilibrium constant for the reaction,

$$2 H_2 (g) + S_2 (g) \rightleftharpoons 2 H_2 S (g)$$

if a mixture of gaseous $H_2$, $S_2$ and $H_2 S$ which has been allowed to react to equilibrium at 700°C in a 12.0 L flask, contains 0.208 M $H_2 (g)$, 1.12 x $10^{-6}$ M $S_2 (g)$ and 0.725 M $H_2 S (g)$?

a. $9.22 \times 10^{-8}$  
b. $2.26 \times 10^{6}$  
c. $3.11 \times 10^{6}$  
d. $1.08 \times 10^{7}$  
e. $4.56 \times 10^{8}$

36. If the volume of the container in the previous question were reduced from 12.0 L to 6.0 L (pressure doubled), it is expected that:

a. the amount of $H_2 S (g)$ would increase and the amounts of $H_2 (g)$ and $S_2 (g)$ would decrease.
b. the amounts of $H_2 (g)$ and $S_2 (g)$ would increase and the amount of $H_2 S (g)$ would decrease.
c. the magnitude of the equilibrium constant would change.
d. the concentrations of all species would increase.
e. the concentrations of $H_2 (g)$ and $S_2 (g)$ would decrease, but the concentration of $H_2 S (g)$ would remain unchanged.

37. Consider the following reaction initially at equilibrium:

$$4 NO_2 (g) + 6 H_2 O (g) \rightleftharpoons 4 NH_3 (g) + 7 O_2 (g)$$

If the concentration of $NH_3 (g)$ were suddenly INCREASED, which of the following best describes what would happen to the concentrations of the other species?

a. $NO_2 (g)$, $H_2 O (g)$ and $O_2 (g)$ would all increase.
b. $NO_2 (g)$, $H_2 O (g)$ and $O_2 (g)$ would all decrease.
c. $NO_2 (g)$ and $H_2 O (g)$ would decrease and $O_2 (g)$ would increase.
d. $NO_2 (g)$ and $H_2 O (g)$ would increase and $O_2 (g)$ would decrease.
e. $NO_2 (g)$ and $O_2 (g)$ would increase and $H_2 O (g)$ would decrease.
38. What is the correct equilibrium constant expression for the reaction:
\[ 2 \text{NOCl(g)} \rightleftharpoons 2 \text{NO(g)} + \text{Cl}_2(g) \]

a. \( K_c = [\text{NO}][\text{Cl}_2]/[\text{NOCl}] \)
b. \( K_c = ([\text{NO}] + [\text{NO}] + [\text{Cl}_2])/([\text{NOCl}] + [\text{NOCl}]) \)
c. \( K_c = [\text{NO}]^2[\text{Cl}_2]/[\text{NOCl}]^2 \)
d. \( K_c = ([\text{NOCl}] + [\text{NOCl}])/([\text{NO}] + [\text{NO}] + [\text{Cl}_2]) \)
e. \( K_c = [\text{NOCl}]^2/[\text{NO}]^2[\text{Cl}_2] \)

39. Assume the equilibrium constant for the following reaction is known:
\[ 2 \text{NO}_2(g) \rightleftharpoons 2 \text{NO(g)} + \text{O}_2(g), K_1 = 7.4 \times 10^{-16} \text{ (at 25°C)} \]
What is the correct value of the equilibrium constant, \( K_2 \), for the opposite reaction:
\[ 2 \text{NO(g)} + \text{O}_2(g) \rightleftharpoons 2 \text{NO}_2(g) \]

a. impossible to determine from this information. b. \( K_2 = K_1 = 7.4 \times 10^{-16} \)
c. \( K_2 = 1/K_1 = 1.4 \times 10^{15} \) d. \( K_2 = K_1(RT) = 1.8 \times 10^{-14} \)
e. \( K_2 = K_1(RT)^{-1} = 3.0 \times 10^{-17} \)

40. Assume that the equilibrium constants for the following reactions are known:
\[ 2 \text{SO}_2(g) + \text{O}_2(g) \rightleftharpoons 2 \text{SO}_3(g), K_1 \]
\[ 2 \text{CO(g)} + \text{O}_2(g) \rightleftharpoons 2 \text{CO}_2(g), K_2 \]
What is the equilibrium constant for the following reaction?
\[ 2 \text{SO}_2(g) + 2 \text{CO}_2(g) \rightleftharpoons 2 \text{SO}_3(g) + 2 \text{CO(g)} \]

a. \( K = K_1 \times K_2 \) b. \( K = K_1/K_2 \)
c. \( K = K_2/K_1 \) d. \( K = K_1 + K_2 \)
e. \( K = K_1 - K_2 \)

41. The correct value for the equilibrium constant, \( K_p \), for the reaction:
\[ 2 \text{NO}_2(g) \rightleftharpoons 2 \text{NO(g)} + \text{O}_2, K_c = 7.4 \times 10^{-16} \]
would be:

a. \( K_p = K_c = 7.4 \times 10^{-16} \) b. \( K_p = 1/K_c = 1.4 \times 10^{15} \)
c. \( K_p = K_c(RT) = 1.8 \times 10^{14} \) d. \( K_p = K_c(RT)^{-1} = 3.0 \times 10^{-17} \)
e. none of the above

42. Assume that the reaction quotient, \( Q_c \), for the following reaction at 25°C is \( 1.0 \times 10^{-8} \):
\[ 2 \text{NO}_2(g) \rightleftharpoons 2 \text{NO(g)} + \text{O}_2(g), K_c = 7.4 \times 10^{-16} \text{ (at 25°C)} \]
From this we can conclude:

a. the reaction is at equilibrium.
b. without any reaction taking place, equilibrium could be reached by adding enough NO or \( \text{O}_2 \) to the system.
c. the reaction must proceed from left to right to reach equilibrium.
d. the reaction must proceed from right to left to reach equilibrium.
e. the reaction can never reach equilibrium.
Physic chemistry

43. Farmers use ammonia, NH₃, extensively as a fertilizer because: (1) it is a highly concentrated source of nitrogen, (2) it is easy to apply to the soil and (3) it is relatively inexpensive. Ammonia is produced commercially using the Haber process:

\[ N_2 (g) + 3 \text{H}_2 (g) \rightleftharpoons 2 \text{NH}_3 (g), K_c = 0.040 \text{ @ } 25^\circ C \]

Calculate the equilibrium constant, \( K'_c \), for the following reaction at 25°C:

\[ 6 \text{NH}_3 (g) \rightleftharpoons 3 \text{N}_2 (g) + 9 \text{H}_2 (g) \]

44. Which of the following statements correctly describe(s) chemical equilibrium? Circle all of the correct answers.

a. A state in which the concentrations of the reactants and products are always equal.

b. A state in which the concentrations of all the reactants and products remain constant with time.

c. A state in which the rates of the forward and reverse reactions are not equal.

d. A state in which all chemical reactions no longer occur.

e. A state that is affected by changes in concentration, temperature or pressure.

45. Consider the following exothermic gas-phase reaction,

\[ 4 \text{HCl} (g) + \text{O}_2 (g) \rightleftharpoons 2 \text{Cl}_2 (g) + 2 \text{H}_2 \text{O} (g), \Delta H = -113 \text{ kJ} \]

Assuming that the system is initially at equilibrium, describe what will happen to the number of moles of HCl (g) in a container of fixed volume if:

a. \( \text{O}_2 (g) \) is added to the system

b. \( \text{Cl}_2 (g) \) is added to the system

c. some of the \( \text{H}_2 \text{O} (g) \) is removed from the system

d. the temperature is increased.

e. the pressure is increased.

46. Consider the following gas-phase reaction and equilibrium constant at 25°C,

\[ 4\text{HCl}(g) + \text{O}_2(g) \rightleftharpoons 2\text{Cl}_2(g) + 2\text{H}_2\text{O}(g), K = 2.1 \times 10^{13} \]

The concentrations of all species were measured at a particular moment in time and the following data were obtained:

\[ [\text{HCl}] = 0.00050 \text{ M} \quad [\text{O}_2] = 0.0010 \text{ M} \]
\[ [\text{Cl}_2] = 2.30 \text{ M} \quad [\text{H}_2\text{O}] = 1.22 \text{ M} \]

Which of the following statements is TRUE at this moment in time?

a. The reaction is at equilibrium.

b. The reaction is not at equilibrium; the reaction must proceed left to right to reach equilibrium.

c. The reaction is not at equilibrium; the reaction must proceed right to left to reach equilibrium.

d. The reaction is not at equilibrium, but the concentrations of all species will no longer change with time.

e. It is impossible to tell.

47. At 450 K, phosphorus pentachloride (PCl₅) decomposes to produce phosphorus trichloride (PCl₃) and chlorine (Cl₂):

\[ \text{PCl}_5(g) \rightleftharpoons \text{PCl}_3(g) + \text{Cl}_2(g), K = 1.3 \times 10^{-3} \text{ @ } 450 \text{ K} \]
At a particular moment in time, the following concentrations are determined:

\[ [\text{PCl}_5] = 0.80 \text{ M}; \ [\text{PCl}_3] = 0.0064 \text{ M}; \ [\text{Cl}_2] = 0.55 \text{ M} \]

Which of the following statements is TRUE?

a. The reaction is not at equilibrium; the concentration of PCl\(_5\) will increase as the reaction proceeds toward equilibrium.

b. The reaction is not at equilibrium; the concentration of PCl\(_5\) will decrease as the reaction proceeds toward equilibrium.

c. The reaction is not at equilibrium; the concentration of PCl\(_5\) will not change as the reaction proceeds toward equilibrium.

d. The reaction is at equilibrium.

e. There is insufficient information provided to answer the question.

48. Given the following reaction and equilibrium constant, which statement is correct for this reaction at equilibrium?

\[ \text{CO(g)} + \frac{1}{2}\text{O}_2(g) \rightleftharpoons \text{CO}_2(g), K_c = 1.1 \times 10^{11} \]

a. The forward rate will be much larger than the reverse rate.

b. The forward rate will be much smaller than the reverse rate.

c. The forward rate will be the same as the reverse rate.

d. The value of the equilibrium constant will be equal to 1.

e. None of the responses above are correct.

49. Given the equilibrium constants for the first two reactions below at 1000°C, what is the equilibrium constant for the third reaction at the same temperature? (Assume that all species are in the gas phase.)

\[ \text{CO(g)} + \frac{1}{2}\text{O}_2(g) \rightleftharpoons \text{CO}_2(g), K_{c1} = 1.1 \times 10^{11} \tag{1} \]

\[ \text{H}_2(g) + \frac{1}{2}\text{O}_2(g) \rightleftharpoons \text{H}_2\text{O}(g), K_{c2} = 1.4 \times 10^{11} \tag{2} \]

\[ \text{CO(g)} + \text{H}_2\text{O}(g) \rightleftharpoons \text{CO}_2(g) + \text{H}_2(g), K_{c3} = ? \tag{3} \]

50. If the following reaction were at equilibrium in a closed vessel at a controlled temperature, what would be the effect of adding more CO\(_2\) to the reaction vessel and permitting the reaction to approach equilibrium again?

\[ \text{CO(g)} + \text{H}_2\text{O(g)} \rightleftharpoons \text{CO}_2(g) + \text{H}_2(g) \]

a. The concentrations of CO, H\(_2\)O, and H\(_2\) would all increase.

b. The concentrations of CO, H\(_2\)O, and H\(_2\) would all decrease.

c. The concentrations of CO and H\(_2\)O would decrease and the concentration of H\(_2\) would increase.

d. The concentrations of CO and H\(_2\)O would increase and the concentration of H\(_2\) would decrease.

e. There would be no change.

51. If the following reaction were at equilibrium,

\[ 3 \text{H}_2(g) + \text{N}_2(g) \rightleftharpoons 2 \text{NH}_3(g), K_c = 60 \]

then removal of ammonia by condensation would cause:
a. the concentrations of H₂ and N₂ to increase.
b. the concentrations of H₂ and N₂ to decrease.
c. the concentration of H₂ to increase and the concentration of N₂ to decrease.
d. the concentration of H₂ to decrease and the concentration of N₂ to increase.
e. no change in the concentrations of H₂ and N₂.

52. Given the following reaction and equilibrium constant,
\[ 3 \text{H}_2(\text{g}) + \text{N}_2(\text{g}) \rightleftharpoons 2 \text{NH}_3(\text{g}), K_c = 60 \]
the value of the equilibrium constant for the reaction,
\[ \text{NH}_3(\text{g}) \rightleftharpoons 3/2 \text{H}_2(\text{g}) + 1/2 \text{N}_2(\text{g}) \]
would be:

53. If the reaction, 3 H₂ + N₂ \rightleftharpoons 2 NH₃, is at equilibrium, an increase in pressure in the reaction vessel will cause:
   a. the amount of ammonia to increase.
   b. the amount of ammonia to decrease.
   c. the concentrations of all species to decrease.
   d. the amounts of hydrogen and nitrogen to increase.
   e. no change in the amounts of any reactants or products.

54. The equilibrium constant for the reaction, 2 NO + O₂ \rightleftharpoons 2 NO₂, at 500 K is \( K_c = 7.7 \times 10^7 \). For a reaction mixture containing 1.0 x 10⁻³ mol/L of each of the three components:
   a. the reaction is an equilibrium.
   b. the concentration of NO₂ must decrease, and the concentration of NO must increase to reach equilibrium.
   c. the concentration of NO must decrease, and the concentration of NO₂ must increase to reach equilibrium.
   d. the reaction is not at equilibrium, but it is not possible to predict which direction the reaction must go to reach equilibrium without calculating equilibrium concentrations.

55. Consider the following gas-phase reaction at 500 K,
\[ 2 \text{SO}_2(\text{g}) + \text{O}_2(\text{g}) \rightleftharpoons 2 \text{SO}_3(\text{g}), K_c = 2.8 \times 10^{12} \]
Which of the following statements best describes how a system that initially contains 0.90 M SO₂ (g), 0.20 M O₂ (g), and 0.10 M SO₃ (g) will approach equilibrium?
   a. The reaction must proceed from left to right to reach equilibrium.
   b. The reaction must proceed from right to left to reach equilibrium.
   c. The reaction is at equilibrium for the conditions given.
   d. Insufficient information is given to make a valid prediction.

56. For the reaction, CH₄ (g) + 2 O₂ (g) \rightleftharpoons CO₂ (g) + 2 H₂O (g), which of the following is the correct expression for the equilibrium constant?

(a) \[ K_c = \frac{[\text{CO}_2]^2 [\text{H}_2\text{O}]^2}{[\text{CH}_4][\text{O}_2]^2} \]

(b) \[ K_c = \frac{[\text{CH}_4][\text{O}_2]^2}{[\text{CO}_2]^2 [\text{H}_2\text{O}]^2} \]
57. If the reaction quotient for a reaction is larger than the equilibrium constant (i.e., $Q_c > K_c$) then the reaction:
   a. will always proceed to equilibrium very rapidly
   b. must shift from right to left to reach equilibrium
   c. must shift from left to right to reach equilibrium
   d. is at equilibrium
   e. will shift in an unpredictable direction.

58. If a reaction with equilibrium constant, $K_1$, is subtracted from a reaction with equilibrium constant, $K_2$, then the equilibrium constant for the resulting reaction, $K_3$, is:
   a. $K_2 - K_1$
   b. $K_2 \times K_1$
   c. $K_2 / K_1$
   d. $K_1 / K_2$
   e. different from any combination given here.

59. For two reactions with the same stoichiometry (e.g., $2A + B \rightleftharpoons 2D$) and the same initial concentrations of all reactants, then AT EQUILIBRIUM, the reaction with the smallest equilibrium constant will:
   a. have the largest reaction quotient
   b. have a reaction quotient the same as the other reaction
   c. have the highest concentration of species D
   d. have the highest concentration of species A
   e. have the smallest concentration of species B

60. Which of the following statements is TRUE?
   a. Equilibrium is a static state in which both the forward and reverse reactions no longer occur.
   b. Equilibrium is a state in which the net reactant and product concentrations remain constant with time.
   c. Equilibrium is a state in which the rates of the forward and reverse reactions are equal.
   d. (b) and (c) are true.
   e. (a), (b) and (c) are true.

61. Given the following gas-phase reaction,
   \[ 2 \text{NO (g)} \rightleftharpoons \text{O}_2 (g) + \text{N}_2 (g) \]
   If the concentrations of NO (g), O$_2$ (g) and N$_2$ (g) are 0.05 M, 0.50 M and 0.50 M, respectively, in what direction must the reaction shift to reach equilibrium if $K_c = 3.1 \times 10^9$?
   a. No shift will occur since the reaction is at equilibrium.
   b. The reaction will shift toward products to reach equilibrium.
   c. The reaction will shift toward reactants to reach equilibrium.
d. The reaction cannot reach equilibrium because there is not enough O\(_2\) (g) to react with all of the N\(_2\) (g).

e. It is impossible to tell from this information.

62. The reaction of nitrogen, N\(_2\)(g), with hydrogen, H\(_2\)(g), to produce ammonia, NH\(_3\)(g), is a commercially important gas-phase reaction because huge amounts of ammonia are used for fertilization:

\[ \text{N}_2(g) + 3\text{H}_2(g) \rightleftharpoons 2\text{NH}_3(g) \]

This reaction is generally performed at high pressure and high temperature. Which of the following statements best explains why high pressure is used?

a. Increasing the pressure will lead to the production of more N\(_2\)(g) and NH\(_3\)(g).

b. Increasing the pressure will lead to the production of more N\(_2\)(g) and H\(_2\)(g).

c. Increasing the pressure will lead to the production of more NH\(_3\)(g).

d. Increasing the pressure will lead to the production of more H\(_2\)(g) and NH\(_3\)(g).

e. Increasing the pressure will have no effect on this reaction.

63. If the reaction, 3H\(_2\) + N\(_2\) \rightleftharpoons 2\text{NH}_3, is at equilibrium, DECREASING the volume of the reaction vessel by a factor of two, at constant temperature, will cause:

a. the amount of ammonia to increase.

b. the amount of ammonia to decrease.

c. the concentrations of all species to decrease.

d. the amounts of hydrogen and nitrogen to increase.

e. no change in the amounts of any reactants or products.

64. Consider the following reaction,

\[ \text{A}(g) \rightleftharpoons \text{B}(g) \]

One mole of A(g) is placed in a 1.0-L flask and the reaction is allowed to reach equilibrium. A graph of the mole percent of A(g) and B(g) versus time is shown below.

![Graph showing mole percent of A and B over time](image)

Calculate the value for the equilibrium constant for this reaction.

65. Consider the following gas-phase reaction, at equilibrium, at 298 K,

\[ 2\text{SO}_2(g) + \text{O}_2(g) \rightleftharpoons 2\text{SO}_3(g), \Delta H = -196.6 \text{ kJ} \]

Which one of the following, when applied to this system initially at equilibrium, would increase the equilibrium concentration of SO\(_3\)(g)?
a. decreasing the pressure by increasing the volume of the reaction vessel
b. increasing the temperature
c. increasing the pressure by adding Ar(g)
d. decreasing the concentration of O$_2$(g)
e. decreasing the temperature

66. The Haber-Bosch process is used to prepare ammonia,

\[
\text{N}_2(g) + 3\text{H}_2(g) \rightleftharpoons 2\text{NH}_3(g), \Delta H = -92.4 \text{ kJ}
\]

Industrially, this reaction is performed at temperatures ranging from 400°C to 650°C. The high temperatures used in the process cause:
a. the value for $K_c$ to increase, and the rate of the reaction to decrease.
b. the value for $K_c$ to increase, and the rate of the reaction to increase.
c. the value for $K_c$ to decrease, and the rate of the reaction to decrease.
d. the value for $K_c$ to decrease, and the rate of the reaction to increase.
e. no change in either the value for $K_c$ or the rate of the reaction.

67. Consider the following gas-phase reaction, under conditions where $K_c = 4.0$,

\[
\text{H}_2(g) + \text{I}_2(g) \rightleftharpoons 2\text{HI}(g)
\]

Which of the following diagrams represents a snapshot of the system that must proceed to the left (reactants) to achieve equilibrium?

68. In the lab, you used visible spectroscopy to determine the concentrations of the [Fe(phen)$_3$]$^{2+}$ ion in solutions containing the following equilibrium,

\[
\text{Fe}^{2+}(\text{aq, colorless}) + 3\text{phen}(\text{aq, colorless}) \rightleftharpoons [\text{Fe(phen)}_3]^{2+}(\text{aq, red-orange})
\]

where “phen” stands for 1,10-phenanthroline. In order to calculate the concentration of Fe$^{2+}$ in the original unknown solution using the concentrations of [Fe(phen)$_3$]$^{2+}$ determined in the experiment, which of the following assumptions must be made? Choose the best answer.
a. large equilibrium constant; large excess of “phen”
b. large equilibrium constant; large excess of Fe$^{2+}$
c. small equilibrium constant; large excess of “phen”
d. small equilibrium constant; large excess of Fe$^{2+}$
e. No assumptions are necessary.
### ANSWERS

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32. (i) Reaction will shift to the right, \( O_2 \) (g) will decrease.

(ii) Reaction will shift to the right, \( Cl_2 \) (g) will increase.

(iii) Reaction will shift to the right, \( H_2O \) (g) will increase.

(iv) Changes in concentration do not affect the magnitude of the equilibrium constant. \( K_c \) will not be changed.

33. b

37. d

41. c

45. (i) When the concentration of \( O_2 \) is increased, the reaction will shift to the right to reach equilibrium. Therefore, [HCl] decreases.

(ii) When the concentration of \( Cl_2 \) is increased, the reaction will shift to the left to reach equilibrium. Therefore, [HCl] increases.

(iii) When the concentration of water is decreased, the reaction will shift to the right to reach equilibrium. Therefore, [HCl] decreases.

(iv) The reaction is exothermic. Therefore, heat can be considered to be a product. If the temperature is increased, the reaction will shift to the left to reach equilibrium. Therefore, [HCl] increases.

(v) This depends on the value of \( K_c \) and the initial conditions.

46. c

50. d

54. c

58. c

62. c

66. d

47. a

51. b

55. a

59. d

63. a

67. a

48. c

52. 0.13

56. d

60. d

64. 0.49

68. a

49. 0.79

53. a

57. b

61. b

65. e

1. Opp. Khuda Baksh Library, Ashok Rajpath, Patna - 4

2. House no. 5A/65, Opp. Mahual Kothi, Alpana Market, Patna