Guide to Chapter 15. Aqueous Equilibria: Acids and Bases

We will spend five lecture days on this chapter. During the first two class meetings we will introduce acids and bases and some of the theories that have been developed to describe them, especially the Bronsted-Lowry Theory. We will review the strong acids and weak acids (from Chapter 4) and go into a lot more detail about acid dissociation in water, the pH scale, calculating pH of strong acids and bases, weak acid equilibria, calculating pH of weak acids in solution. We will also cover the dissociation of water itself. We will review percent dissociation. On about the third class meeting, we will discuss polyprotic acids, weak base equilibria and the relationship between weak acids and their weak bases. Towards the end of the chapter, we will learn how to predict the pH of salts. We may get to the last few sections: Factors affecting acid-base strength and Lewis acids and bases.

Review Chapter 4, Section 2 on how ionic substances dissociate in water.

Read the introductory paragraph to Chapter 15.

Read Section 15.1 Acid-Base Concepts: The Bronsted-Lowry Theory.

Learning Objective 1: Know the terms *acid* and *base* using the Arrhenius and Lowry-Bronsted,.

Learning Objective 2: Given a formula of an acid, write the formula of its conjugate base. Given a formula of a base, write the formula of its conjugate acid.

Do Problems 1 - 3 at the end of the section.

Do the following end-of-chapter problems: 42, 44

Problem Club Question A. (ACS Style) Answer: B

Problem Club Question B. (ACS Style) Answer:*?*

Read Section 15.2 Acid Strength and Base Strength.

Learning Objective 3: Memorize the strong acids and bases and write the equilibrium equations showing how they break apart in water.

Learning Objective 4: If the concentration of a strong acid is known, calculate the concentration of the hydronium ion.

Learning Objective 5: If the concentration of a strong base is known, calculate the concentration of the hydroxide ion.

Learning Objective 6: From the formula, identify a compound as a weak or strong acid or strong or weak base. Identify a compound as a weak or strong electrolyte

Learning Objective 7: Given the formula of a salt, identify it as a weak or strong electrolyte.

Do Problems 4 and 5 at the end of the section.

Do the following end-of-chapter problems: 46, 48,

Read Sections 15.3. Hydrated protons and hydronium ions; and 15.4. Dissociation of water.

Learning Objective 8: Know the definition of the hydronium ion.

Learning Objective 9: Water is amphoteric. Write the dissociation reaction of water and the equilibrium equation, K_W. Know the value of K_W

Do Problems 6 and 7 at the end of the section.

Do the following end-of-chapter problems: 50

Problem Club Question C. (ACS Style) Answer: E?

Problem Club Question D. (ACS Style) Answer: E

Read Section 15.5. The pH Scale; and Section 15.6. Measuring pH; and Section 15.7. The pH in Solutions of Strong Acids and Strong Bases.

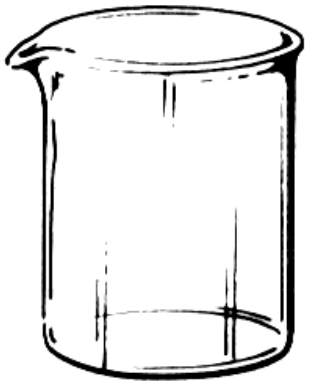
Learning Objective 10: Given the $[H_3O^+]$ determine the $[OH^-]$ in mol/L, or given the $[OH^-]$ determine the $[H_3O^+]$.

Learning Objective 11: Given the concentration of H_3O^+ or OH^- in mol/L, determine the pH and pOH.

Learning Objective 12: Given the pOH or pH, determine the concentration of the hydronium ion or hydroxide ion.

Learning Objective 13: Given the concentration of a strong acid or strong base determine the $[H_3O^+]$, $[OH^-]$, pH, and pOH.

Learning Objective 14: Given the pH, pOH, $[H_3O^+]$, or $[OH^-]$ of a solution, determine if the solution is acidic, basic, or neutral.



Do Problems 8 – 11 embedded throughout these sections.

Do the following end-of-chapter problems: 34, 52, 54, 56, 58, 60, 62

Problem Club Question E. Hydrochloric acid is a strong acid in water. Write its chemical equilibrium. Sketch a beaker like the one shown here on your page. Inside the beaker, sketch a total of ten hydrochloric acid molecules and draw them in such a way as to be consistent with the equilibrium.

Answer: $HCl + H_2O \rightleftharpoons H_3O^+ + Cl^-$

Problem Club Question F. Complete the following table

pH	$[H_3O^+]$	pOH	$[OH^-]$
3.45			
		2.78	
	2.88×10^{-3}		
			8.8×10^{-4}

Answer:

pH	$[H_3O^+]$	pOH	$[OH^-]$
3.45	3.55×10^{-4}	10.55	2.82×10^{-11}
11.22	6.03×10^{-12}	2.78	1.66×10^{-3}
2.54	2.88×10^{-3}	11.46	3.47×10^{-12}
10.94	1.14×10^{-11}	3.06	8.8×10^{-4}

Problem Club Question G. Which of the species in the previous question is the most acidic? Most basic?

Answer: (a) the third one is most acidic; (b) the second one is most basic

Problem Club Question H. An acid solution is prepared by dissolving 0.0433 moles HCl in water to make 500.0 mL. Calculate the $[H_3O^+]$, $[OH^-]$, pH and pOH of the solution.

Answer: pH = 1.06 (strong acid calc)

Problem Club Question I. (ACS Style) Answer: B

Problem Club Question J. (ACS Style) Answer: E

Problem Club Question K. (ACS Style) Answer: B

Problem Club Question L. (ACS Style) Answer: C

Problem Club Question M. (ACS Style) Answer: B

Problem Club Question N. (ACS Style) Answer: A

Read Section 15.8 Equilibria in Solutions of Weak Acids; Section 15.9. Calculating Equilibrium Concentrations in Solutions of Weak Acids; and 15.10. Percent Dissociation in Solutions of weak acids.

Learning Objective 15: Write chemical equations showing how water and a *weak* Bronsted acid react with each other. (The dissociation equation of an acid in water.)

Learning Objective 16: After correctly writing this equilibrium equation, identify the acid, base, the conjugate acid, and the conjugate base.

Learning Objective 17: Write the equilibrium constant expression, K_a, for these equilibria.

Learning Objective 18: Given the concentration of a weak acid expressed in mol/L, determine the pH, pOH, $[H_3O^+]$, and $[OH^-]$. Determine the concentrations of each species in the aqueous weak acid solution.

Learning Objective 19: Given the value of K_a, determine the pK_a

Learning Objective 20: Given a list of acids and the K_a or pK_a, rank them in order of strength.

Learning Objective 21: Rank the conjugate base of an acid in order of base strength

Learning Objective 22: Determine the K_a and pK_a of a weak acid given the molarity of acid and pH.

Learning Objective 23: Determine the pH of a weak acid given the molarity of acid and K_a or pK_a .

Learning Objective 24: Know when using the approximation is OK and when you must use the quadratic equation. Be able to do both.

Learning Objective 25: Determine the percent dissociation of the acid.

Do Problems 12 – 16 embedded throughout these sections.

Do the following end-of-chapter problems: 32, 64, 68, 70, 72

Problem Club Question O. HF is a weak acid in water. Write its chemical equilibrium. Sketch a beaker as you did for HCl above. Inside this beaker, sketch a total of ten HF molecules and draw them in such a way as to be consistent with the equilibrium.

Answer: $HF + H_2O \rightleftharpoons H_3O^+ + F^-$

Problem Club Question P. Would you expect butanoic acid to conduct electricity very well? Explain.
Answer: No, butanoic acid is not one of the 6 strong acids. Therefore it must be a weak acid.

Problem Club Question Q. Write a chemical equation that shows what happens to each substance in water. Identify the strong acids (SA), strong bases (SB), and weak acids (WA) from this list. Identify soluble salts with the word 'SALT' Note: Some species may be more than one (SA, SB, SALT) One of these is a weak acid (WA). The first on has been done for you.

(a) $HCl + H_2O$ ⟹ $H_3O^+ + Cl^-$ strong acid

(b) NaOH; (c) H_2CO_3; (d) $HClO_4$; (e) NaBr; (f) $NaNO_3$; (g) HNO_3; (h) KOH; (i) HBr; (j) $HClO_2$; (k) LiOH; (l) HNO_2; (m) HI

Answer:

(a) $HCl + H_2O$ ⟹ $H_3O^+ + Cl^-$ strong acid

(b) $NaOH$ ⟹ $Na^+ + OH^-$ strong base

(c) H_2CO_3 ⇌ $H_3O^+ + HCO_3^-$ weak acid

(d) $HClO_4 + H_2O$ ⟹ $H_3O^+ + ClO_4^-$ strong acid

(e) NaBr ⟹ $Na^+ + Br^-$ salt

(f) $NaNO_3$ ⟹ $Na^+ + NO_3^-$ salt

(g) $HNO_3 + H_2O$ ⟹ $H_3O^+ + NO_3^-$ strong acid

(h) KOH ⟹ $K^+ + OH^-$ strong base

(i) $HBr + H_2O$ ⟹ $H_3O^+ + Br^-$ strong acid

(j) $HClO_2$ ⇌ $H_3O^+ + ClO_2^-$ weak acid

(k) LiOH ⟹ $Li^+ + OH^-$ strong base

(l) $HNO_2 + H_2O$ ⇌ $H_3O^+ + NO_2^-$ (weak acid)

(m) $HI + H_2O$ ⟹ $H_3O^+ + I^-$ strong acid

Problem Club Question R. Each of the following is either a strong acid or weak acid. Write the equilibrium reaction using the appropriate arrows (long or long/short) for each. The first one has been done for you.

(a) $HF(aq) + H_2O$ ⇌ $H_3O^+ + F^-$

(b) $H_2SO_4(aq)$; (c) $HCl(aq)$; (d) $HNO_3(aq)$; (e) $H_3PO_4(aq)$; (f) $HC_2H_3O_2(aq)$; (g) $HCN(aq)$

Answer:

(a) $HF + H_2O$ ⇌ $H_3O^+ + F^-$ weak acid

(b) $H_2SO_4 + H_2O$ ⟹ $H_3O^+ + HSO_4^-$ strong acid

(c) $HCl + H_2O$ ⟹ $H_3O^+ + Cl^-$ strong acid

(d) $HNO_3 + H_2O$ ⟹ $H_3O^+ + NO_3^-$ strong acid

(e) $H_3PO_4 + H_2O$ ⇌ $H_3O^+ + H_2PO_4^-$ (weak acid)

(f) $HC_2H_3O_2 + H_2O$ ⇌ $H_3O^+ + C_2H_3O_2^-$ (weak acid)

(g) $HCN + H_2O$ ⇌ $H_3O^+ + CN^-$ (weak acid)

Problem Club Question S. An acid solution is prepared by dissolving 0.847 moles HF in water to make 500.0 mL. Calculate the $[H_3O^+]$, $[OH^-]$, pH and pOH of the solution. ($Ka = 3.5 \times 10^{-4}$)

Answer: pH = 1.61 (weak acid calc)

Problem Club Question T. A weak acid, HA, is prepared as a 0.089 M solution. The resulting pH is 4.93. What is the Ka and the percent dissociation?

Answer: Ka = 1.55 x 10-9 (b) % dissociation = 0.013%

Problem Club Question U. A weak acid, HD, is prepared as a 0.875 M solution. The pKa for HD is 4.44. (a) What is the pH and the % dissociation? (b)Are you able to use the '400 Rule'?

Answer: (a) pH = 2.25 and % dissociation = 0.64% (b) Yes

Problem Club Question V. Which of the two acids in the previous two questions is the strongest?

Answer: HD is a stronger weak acid than HA

Problem Club Question W. The following chemical equations need equilibria arrows! Write in one of the following arrows for each: ⇌ or → or ⇀↽

(a) $HCl(aq) + H_2O$	*$H_3O^+(aq) + Cl^-(aq)$*
(b) $HF(aq) + H_2O$	*$H_3O^+(aq) + F^-(aq)$*
(c) $H_3O^+(aq) + Cl^-(aq)$	*$HCl(aq) + H_2O$*
(d) $H_3O^+(aq) + Cl^-(aq)$	*$HCl(aq) + H_2O(l)$*
(e) $H_3O^+(aq) + C_2H_3O_2^-(aq)$	*$HC_2H_3O_2(aq) + H_2O$*
(f) $K^+(aq) + OH^-(aq)$	*$KOH(aq)$*
(g) $NH_3(aq) + H_2O(l)$	*$OH^-(aq) + NH_4^+(aq)$*
(h) $NaOH(aq)$	*$OH^-(aq) + Na^+(aq)$*

Answer:

(a) ⇀↽

(b) ⇌

(c) ||

(d) ||

(e) ⇌

(f) ||

(g) ⇌

(h) ⇀↽

Problem Club Question X. Formic acid, HCOOH, (abbreviated as 'HFm') is a weak acid. Write the equilibrium expression that shows how HFm dissociates in water. What is the conjugate base?

Answer: HFm + H_2O ⇌ $H_3O^+ + Fm^-$ (b) Fm^- is conjugate base

Problem Club Question Y. Write the chemical equilibrium and the corresponding Ka expression for each of the following substances behaving as acids in solution: (a) HCN (b) $H_2PO_4^-$ (c) HSO_4^-

Answer:

(a) HCN + H_2O ⇌ $H_3O^+ + CN^-$ Ka = $[H_3O^+][CN^-]/[HCN]$

(b) $H_2PO_4^-$ + H_2O ⇌ $H_3O^+ + HPO_4^{-2}$ Ka = $[H_3O^+][HPO_4^{-2}]/[H_2PO_4^-]$

(c) HSO_4^- + H_2O ⇌ $H_3O^+ + SO_4^{-2}$ Ka = $[H_3O^+][SO_4^{-2}]/[HSO_4^-]$

Problem Club Question Z. A weak acid, HD, is prepared as a 0.0995 M solution. The pK_a for HD is 2.79. (a) What is the pH and the percent dissociation? (b) Are you able to use the '400 Rule'?

Answer: Need to use quadratic: x = 1.19×10^{-2}; (b) pH = 1.92; (c) 12%

Problem Club Question AA. (ACS Style) Answer: B

Problem Club Question BB. (ACS Style) Answer: B

Problem Club Question CC. (ACS Style) Answer: A

Problem Club Question DD. (ACS Style) Answer: B

Problem Club Question EE. (ACS Style) Answer: B

Problem Club Question FF. (ACS Style) Answer: C

Problem Club Question GG. (ACS Style) Answer: B

Read Section 15.11 Polyprotic acids

Learning Objective 26: Be able to write each dissociation reaction and equilibrium constant equation, K_a, for each dissociation of a given polyprotic acid with water:

$$H_nA_{(aq)} + H_2O \rightleftharpoons H_3O^+_{(aq)} + H_{(n-1)}A^-_{(aq)}$$

Learning Objective 27: Determine the concentration of the H_3O^+, OH^-, A^-, etc., and the pH of a known mol/L concentration of a polyprotic acid, H_nA.

Do Problems 17 and 18 at the end of the section.

Do the following end-of-chapter problems: 74, 76, 78

Problem Club Question HH. Phosphoric acid, H_3PO_4, is a weak acid in aqueous solution. Write the three equilibria equation that show how phosphoric acid dissociates in water. For each equation, write the appropriate Ka expression. Which equilibrium lies farthest to the right?

Answer: The first equilbrium lies farthest to the right:

$H_3PO_4 + H_2O \rightleftharpoons H_3O^+ + H_2PO_4^-$ $K_a = [H_3O^+][H_2PO_4^-]/[H_3PO_4]$

$H_2PO_4^- + H_2O \rightleftharpoons H_3O^+ + HPO_4^{-2}$ $K_a = [H_3O^+][HPO_4^{-2}]/[H_2PO_4^-]$

$HPO_4^{-2} + H_2O \rightleftharpoons H_3O^+ + PO_4^{-3}$ $K_a = [H_3O^+][PO_4^{-3}]/[HPO_4^{-2}]$

Read Sections 15.12 Equilibrium in solutions of weak bases and 15.13. Relation between K_a and K_b

Learning Objective 28: What is the relationship between K_a and K_b? Or pK_a and pK_b?

Learning Objective 29: Determine the K_b and pK_b of a weak base given the molarity of base and pH.

Learning Objective 30: Determine the pH of a weak base given the molarity of base and K_b or pK_b

Learning Objective 31: Given the value of K_b, determine the pK_b

Learning Objective 32: Given a list of bases and the K_b or pK_b, rank them in order of strength

Learning Objective 33: Rank the conjugate acid of a base in order of acid strength.

Do Problems 19 - 21 embedded within these sections.

Do the following end-of-chapter problems: 82, 84, 86

Problem Club Question II. Methyl amine, CH_3NH_2 is a weak base in water. Write the equilibrium equation that shows how CH_3NH_2 dissociates in water. What is the conjugate acid?

Answer: $CH_3NH_2 + H_2O \rightleftharpoons OH^- + CH_3NH_3^+$ (b) $CH_3NH_3^+$ is conjugate acid

Problem Club Question JJ. Write the chemical equilibrium and the corresponding Kb expression for each of the following substances behaving as bases in solution: (a) CN^- (b) HPO_4^{-2} (c) SO_4^{-2}

Answer:

(a) $CN^- + H_2O \rightleftharpoons OH^- + HCN$ $K_b = [OH^-][HCN]/[CN^-]$

(b) $HPO_4^{-2} + H_2O \rightleftharpoons OH^- + H_2PO_4^-$ $K_b = [OH^-][H_2PO_4^-]/[HPO_4^{-2}]$

(c) $SO_4^{-2} + H_2O \rightleftharpoons OH^- + HSO_4^-$ $K_b = [OH^-][HSO_4^-]/[SO_4^{-2}]$

Problem Club Question KK. The bisulfite ion can behave as either and acid or base in solution. Write the chemical equilibrium and the corresponding equilibrium expression (K) for the bisulfite ion behaving as (a) an acid and (b) a base in solution Is the bisulfite ion a better weak acid or weak base and why?

Answer:

(a) $HSO_3^- + H_2O \rightleftharpoons H_3O^+ + SO_3^{-3}$ $K_a = [H_3O^+][SO_3\text{-}2]/[HSO_3^-]$

(b) $HSO_3^- + H_2O \rightleftharpoons OH^- + H_2SO_3$ $K_b = [OH^-][H_2SO_3]/[HSO_3^-]$

(c) Bisulfite is a better weak acid than weak base because K_a for bisulfite is larger than K_b for bisulfite.

Problem Club Question LL. The following are weak acids with accompanying Ka (or pK_a) values. Write the conjugate base and calculate its K_b and pK_b value.

(a) HCN, $K_a = 6.2 \times 10^{-10}$; (b) HOCl, $K_a = 3.5 \times 10^{-8}$; (c) HNO_2, $pK_a = 3.40$

Answer:

weak acid/K_a (or pK_a)	conjugate base	K_b	pK_b
(a) HCN $K_a = 6.2 \times 10^{-10}$	CN^-	1.61×10^{-5}	4.79
(b) HOCl $K_a = 3.5 \times 10^{-8}$	OCl^-	2.86×10^{-7}	6.54
(c) HNO_2 $pK_a = 3.40$	NO_2^-	2.51×10^{-11}	10.60

Problem Club Question MM. Which would be the most acidic: sodium dihydrogen phosphate or disodium hydrogen phosphate? Look up the K_a values and calculate the ratio {larger K_a}/{smaller K_a} in order to see how much more acidic one is than the other.

Answer:

(a) $H_2PO_4^-$;

(b) K_a (for $H_2PO_4^-$)/K_a (for HPO_4^{-2}) = $6.2 \times 10^{-8}/4.8 \times 10^{-13} = 1.3 \times 10^5$

Read Sections 15.14 Acid-base properties of salts

Learning Objective 34: Given the K_a or pK_a of a weak acid determine the K_a or pK_a of its conjugate partner.

Learning Objective 35: Given the formula of a salt dissolved in water, determine if the salt solution is acidic, basic, or neutral.

Learning Objective 36: Given the molar concentration of an aqueous salt solution, determine the pH, pOH, $[H_3O^+]$, and $[OH^-]$.

Do Problems 22 - 25 embedded within this section.

Do the following end-of-chapter problems: 36, 88, 90, 92

Problem Club Question NN. A 0.108 M solution of sodium fluoride is prepared. What does sodium fluoride do when it dissolves? Write the solubility rule that applies. What ions are present in an aqueous solution of sodium fluoride? (b) Write the appropriate acid/base equilibrium reaction expression for sodium fluoride in water. (c) Write the appropriate K (K_a or K_b?) equilibrium equation. (d) If you had only a table of K_a values, could you find the necessary K_b? Which one would you use? Do so. (e) Determine the pH of this solution. Does it make sense that the answer is >7?

Answer:

(a) $NaF \rightarrow Na^+ + F^-$

(b) $F^- + H_2O \rightleftharpoons OH^- + HF$

(c) $K_b = [OH\text{-}][HF]/[F^-]$

(d) $K_a = 3.5 \times 10^{-4}$; $K_b = 2.86 \times 10^{-11}$

(e) pH = 8.24

Problem Club Question OO. Of the salts listed below, predict whether the solutions they would form would be acidic, basic, or neutral. If the solution has a pH other than 7.0, write the appropriate acid/base equilibrium. (a) KBr; (b) KCN; (b) NH_4Cl; (c) NaAc (sodium acetate, $NaC_2H_3O_2$); (d) $NaNO_3$; (e) Na_2SO_4

Answer:

KBr: neutral

KCN: WB: $CN^- + H_2O \rightleftharpoons OH^- + HCN$

NH_4Cl: WA $NH_4^+ + H_2O \rightleftharpoons H_3O^+ + NH_3$

NaAc: WB $Ac^- + H_2O \rightleftharpoons OH^- + HAc$ or $C_2H_3O_2^- + H_2O \rightleftharpoons OH^- + HC_2H_3O_2$

$NaNO_3$: neutral

Na_2SO_4: WB $SO4^{-2} + H_2O \rightleftharpoons OH^- + HSO4^{-2}$

Problem Club Question PP. Given that nitrous acid has a $pK_a = 3.40$, calculate the pH of a 1.11 M solution of sodium nitrite.

Answer: pH = 8.72

Problem Club Question QQ. (ACS Style) Answer: D

Problem Club Question RR. (ACS Style Answer: A*?*

Problem Club Question SS. (ACS Style) Answer: D

Problem Club Question TT. (ACS Style) Answer: A

Problem Club Question UU. (ACS Style) Answer: C

Read Section 15.15 Factors that affect acid strength.

Learning Objective 37: Given a list of binary or oxyacids, rank them in order of acid strength.

Do Problems 26 at the end of this section.

Do the following end-of-chapter problems: 94, 96, 98

Problem Club Question VV. Which would be the most acidic: hydrogen sulfate or hydrogen sulfite? Look up the K_a values and calculate the ratio {larger K_a}/{smaller K_a} in order to see how much more acidic one is than the other.

Answer: The hydrogen sulfate ion is more acidic because the extra oxygen helps stabilize the anion in SO^{-2} vs SO^{-2}

Problem Club Question WW. Predict the order of acidity for HClO. x = 1, 2, 3, 4.

Answer: Acidity increases with an increase in x -- so HClO is the strongest acid in the series.

Problem Club Question XX. (ACS Style) Answer: D*?*

Read Section 15.16 Lewis acids and bases

Learning Objective 38: Define the terms "Lewis acid" and "Lewis base".

Learning Objective 39: Use the Lewis structure to explain Lewis acid or base character.

Learning Objective 40: Given formulas of chemical compounds, select those that are Lewis acids or bases.

Learning Objective 41: In a given chemical reaction, identify the Lewis acid and Lewis base.

Do Problems 27 and 28 at the end of this section.

Do the following end-of-chapter problems: 100

Problem Club Question YY. Identify the Lewis acid and Lewis base in each of these Lewis acid/base reactions. Draw Lewis dot structures to support your answers.

(a) $NH_3 + BF_3$ ⇌ NH_3BF_3

(b) $HCl + H_2O$ ⇌ $H_3O^+ + Cl^-$

(c) $NH_3 + H_2O$ ⇌ $NH_4^+ + OH^-$

(d) $Fe^{+3} + SCN^-$ ⇌ $FeSCN^{+2}$

Answer:

(a) NH_3 (LB) and BF_3 (LA)

(b) HCl (LA) and H_2O (LB)

(c) NH_3 (LB) and H_2O (LA)

(d) Fe^{+3}(LA) +and SCN^- (LB)

Problem Club Question ZZ. (ACS Style) Answer: C