CHAPTER 8   ACID–BASE EQUILIBRIUM

Reflect on Your Learning

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1. The concentration of the hydrogen ion in pure water at SATP is equal to 1.0×10^{-7} mol/L.

   $pH = -\log [H^+_{(aq)}]$

   $\quad = -\log [1.0 \times 10^{-7}]$

   $pH = 7$

2. The pH of hydrochloric acid is lower because $HCl_{(aq)}$ is a stronger acid than acetic acid.
3. The products for the neutralization of $HCl_{(aq)}$ and $NaOH_{(aq)}$ are $NaCl_{(aq)}$ and water. Neither the sodium ion nor chloride hydrolyze to change the pH of water. However, the neutralization of acetic acid with sodium hydroxide produces water and sodium acetate. The acetate ion is a stronger base than chloride and hydrolyzes to release hydroxide ions in solution. The production of hydroxide accounts for why the resulting solution is basic.
4. The blood contains a variety of buffering agents, which resist changes in pH.

Try This Activity: Antacid Equilibrium

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(a) $Mg(OH)_{2(s)} \rightleftharpoons Mg^{2+}_{(aq)} + 2\,OH^-_{(aq)}$

(b) The equilibrium shifts to the right when hydrochloric acid is added. The evidence is the observation that the solution becomes clear, indicating that all the magnesium hydroxide had dissolved.

8.1   THE NATURE OF ACID–BASE EQUILIBRIA

PRACTICE

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Understanding Concepts

1. (a) $HCO^-_{3(aq)} / CO^{2-}_{3(aq)}$ $\qquad$ $HS^-_{(aq)} / S^{2-}_{(aq)}$

   (b) $H_2CO_{3(aq)} / HCO^-_{3(aq)}$ $\qquad$ $H_2O_{(l)} / OH^-_{(aq)}$

   (c) $HSO^-_{4(aq)} / SO^{2-}_{4(aq)}$ $\qquad$ $H_2PO^-_{4(aq)} / HPO^{2-}_{4(aq)}$

   (d) $H_2O_{(l)} / OH^-_{(aq)}$ $\qquad$ $H_3O^+_{(aq)} / H_2O_{(l)}$

2. Amphoteric substances in question 1 are $H_2O_{(l)}$, $HCO^-_{3(aq)}$.

3. $H_2CO_{3(aq)} / HCO^-_{3(aq)}$ $\qquad$ $HCO^-_{3(aq)} / CO^{2-}_{3(aq)}$

PRACTICE

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Understanding Concepts

4. (a) 0 mol/L

   (b) $[OH^-] = \dfrac{1.0 \times 10^{-14}}{0.30} = 3.3 \times 10^{-14}$ mol/L

5. $\qquad n_{HCl} = \dfrac{0.37 \text{ g}}{36.46 \text{ g/mol}}$

   $n_{HCl} = 0.010$ mol

   $[H^+] = \dfrac{0.010 \text{ mol}}{250 \times 10^{-3} \text{ L}}$

$[H^+] = 0.040 \text{ mol/L}$

$$[OH^-] = \frac{K_w}{[H^+]}$$

$$= \frac{1.0 \times 10^{-14}}{0.040}$$

$[OH^-] = 2.5 \times 10^{-13} \text{ mol/L}$

The hydroxide ion concentration is 2.5×10^{-13} mol/L.

6. $[H^+] = 4.40 \times 10^{-3} \text{ mol/L}$

$$[OH^-] = \frac{K_w}{[H^+]}$$

$$= \frac{1.0 \times 10^{-14}}{4.40 \times 10^{-3} \text{ mol/L}}$$

$[OH^-] = 2.3 \times 10^{-12} \text{ mol/L}$

The hydroxide ion concentration in the effluent is 2.3×10^{-12} mol/L.

Applying Inquiry Skills

7. **Prediction**

An increase in the hydrogen ion concentration should shift the equilibrium to the right.
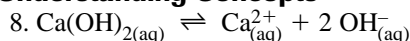
Experimental Design

1. Half-fill one test tube with 0.1 mol/L potassium chromate, K_2CrO_4.
2. Add 5 drops of 1.0 mol/L hydrochloric acid, HCl, to the test tube. Stopper the test tube and carefully mix its contents.
3. Continue adding acid, if necessary, until a colour change is observed.

PRACTICE

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Understanding Concepts

8. $Ca(OH)_{2(aq)} \rightleftharpoons Ca^{2+}_{(aq)} + 2\ OH^-_{(aq)}$

$[Ca(OH)_{2(aq)}] = 6.9 \times 10^{-3} \text{ mol/L}$

$[OH^-] = 2[Ca(OH)_{2(aq)}]$

$[OH^-] = 1.38 \times 10^{-2} \text{ mol/L}$

$$[H^+] = \frac{K_w}{[OH^-]}$$

$$= \frac{1.0 \times 10^{-14}}{1.38 \times 10^{-2} \text{ mol/L}}$$

$[H^+] = 7.2 \times 10^{-13} \text{ mol/L}$

9. $[OH^-] = 0.299 \times 10^{-3} \text{ mol/L}$

$$[H^+] = \frac{K_w}{[OH^-]}$$

$$= \frac{1.00 \times 10^{-14}}{0.299 \times 10^{-3} \text{ mol/L}}$$

$[H^+] = 3.34 \times 10^{-11} \text{ mol/L}$

The hydrogen ion concentration in the cleaning solution is 3.34×10^{-11} mol/L.

10. $$n_{KOH} = \frac{20.0 \text{ g}}{56.11 \text{ g/mol}}$$

$$n_{KOH} = 0.356 \text{ mol}$$

$$[OH^-] = \frac{0.356 \text{ mol}}{0.500 \text{ L}}$$

$$[OH^-] = 0.713 \text{ mol/L}$$

$$[H^+] = \frac{K_w}{[OH^-]}$$

$$= \frac{1.00 \times 10^{-14}}{0.713}$$

$$[H^+] = 1.40 \times 10^{-14} \text{ mol/L}$$

The hydrogen ion concentration is 1.40×10^{-14} mol/L.

11. $$n_{H_2O} \text{ in } 1.000 \text{ L} = \frac{1000 \text{ g}}{18.02 \text{ g/mol}}$$

$$n_{H_2O} = 55.5 \text{ mol}$$

$$[H_2O] = \frac{55.5 \text{ mol}}{1.000 \text{ L}}$$

$$[H_2O] = 55.5 \text{ mol/L}$$

$$\text{percent dissociation} = \frac{[H^+]}{[H_2O]} \times 100$$

$$= \frac{1.00 \times 10^{-7} \text{ mol/L}}{55.5 \text{ mol/L}} \times 100$$

$$\text{percent dissociation} = 1.80 \times 10^{-7}\%$$

The percent dissociation of water is $1.80 \times 10^{-7}\%$.

Try This Activity: Magic Markers

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Source	Colour (as is)	Colour with distilled water (neutral pH)	Colour with dilute baking soda (basic pH)	Colour with vinegar (acidic pH)	Colour with "magic" marker
Marker	Blue	Blue	Cyan	Blue	Cyan
Marker	Yellow	Yellow	Magenta	Yellow	Magenta
Marker	Red	Red	Red	Red	Red
Marker	Green	Green	Purple	Green	Purple
Marker	Black	Black	Orange	Black	Orange
Marker	Purple	Purple	Pink	Purple	Pink
Red cabbage leaf	Purple	Purple	Green	Blue	Green

(a) The changes in colour that occurred with baking soda correspond to those that occurred with the "magic" marker in the case of blue, yellow, green, black, and purple inks, and red cabbage juice. This indicates that the "magic" marker most likely contains a clear, colourless basic solution.

(b) The tip of the "magic" marker could be touched to litmus paper to determine whether the solution is acidic or basic, or it can be touched to wide-range pH paper to estimate its pH.

(c) (See table, above.)

PRACTICE

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Understanding Concepts

12. (a) $pH = -\log [H^+]$

$= -\log [0.006]$

$pH = 2.2$

$pOH = 14.0 - pH$

$= 14.0 - 2.2$

$pOH = 11.8$

$[OH^-] = 10^{-pOH}$

$= 10^{-11.8}$

$[OH^-] = 2 \times 10^{-12} \text{ mol/L}$

(b) $pH = -\log [H^+]$

$= -\log [0.025]$

$pH = 1.60$

$pOH = 14.0 - pH$

$= 14.00 - 1.60$

$pOH = 12.40$

$[OH^-] = 10^{-pOH}$

$= 10^{-12.40}$

$[OH^-] = 4.0 \times 10^{-13} \text{ mol/L}$

(c) $pH = -\log [H^+]$

$= -\log [0.010]$

$pH = 2.00$

$pOH = 14.0 - pH$

$= 14.00 - 2.00$

$pOH = 12.00$

$[OH^-] = 10^{-pOH}$

$= 10^{-12.00}$

$[OH^-] = 1.0 \times 10^{-12} \text{ mol/L}$

13. $n_{NaOH} = \dfrac{26 \text{ g}}{40.00 \text{ g/mol}}$

$n_{NaOH} = 0.65 \text{ mol}$

$[NaOH] = \dfrac{0.65 \text{ mol}}{0.150 \text{ L}}$

$[NaOH] = 4.33333333 \text{ mol/L}$

$pOH = -\log [OH^-]$

$$= -\log [4.333333]$$

$$\text{pOH} = -0.64$$

$$\text{pH} = 14.00 - \text{pOH}$$

$$= 14.00 - (-0.64)$$

$$\text{pH} = 14.64$$

14. $\text{pOH} = 14.0 - 11.5$

   $\text{pOH} = 2.5$

   $[\text{OH}^-] = 3 \times 10^{-3}$ mol/L

   $n_{\text{KOH}} = [3 \times 10^{-3}\ \text{mol/L}][0.5\ \text{L}]$

   $n_{\text{KOH}} = 1.5 \times 10^{-3}$ mol

   $m_{\text{KOH}} = [1.5 \times 10^{-3}\ \text{mol}][56.11\ \text{g/mol}]$

   $m_{\text{KOH}} = 0.09$ g

Making Connections

15. (a) (Solution provided for oranges. Calculations for other fruits are similar.)
   Oranges:

$$[\text{OH}^-] = \frac{1.0 \times 10^{-14}}{5.5 \times 10^{-3}}$$

   $[\text{OH}^-] = 1.8 \times 10^{-12}$ mol/L

   $\text{pOH} = -\log [\text{OH}^-]$

   $= -\log [1.8 \times 10^{-12}]$

   $\text{pOH} = 11.74$

   $\text{pH} = 14.00 - \text{pOH}$

   $= 14.00 - 11.74$

   $\text{pH} = 2.26$

Food	$[\text{H}^+_{(aq)}]$	$[\text{OH}^-_{(aq)}]$	pH	pOH
Oranges	**5.5 × 10⁻³**	1.8×10^{-12}	2.26	11.74
Asparagus	4×10^{-9}	3×10^{-6}	8.4	**5.6**
Olives	5.0×10^{-4}	**2.0 × 10⁻¹¹**	3.30	10.70
Blackberries	4.0×10^{-4}	2.5×10^{-11}	3.40	**10.60**

(b) Oranges and olives would taste the most sour because they have the lowest pH.

(c) Blackberries may relieve heartburn caused by excess stomach acid because they are basic.

(d) Diet suggestions: The speed of movement of sperm decreases with increasing acidity. Vaginal secretions are slightly acidic while uterine secretions are slightly alkaline – a more favourable environment to sperm. Foods that result in an increase in the acidity of vaginal secretions should be avoided.

16. (a) The hydrogen ion concentration increases after the change in pH.

(b) The stomach is made up of layers of tissue, each with a specific function. The outermost layer, called the serosa, is tough and acid resistant. Specialized cells in an inner layer of the stomach called the epithelium secrete mucus, which protects the epithelium and underlying tissues from attack by stomach acid and digestive proteins.

PRACTICE

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Understanding Concepts

17. $[OH^-_{(aq)}] = 0.15$ mol/L

$pOH = -\log 0.15$

$pOH = 0.8239$ (extra digits carried)

$pH = 14 - pOH$

$= 14 - 0.8239$

$pH = 13.18$

The pH of the sodium hydroxide solution is 13.18.

18. $[OH^-_{(aq)}] = 2 \times [Ba(OH)_{2(aq)}]$

$= 2 \times 0.032$ mol/L

$[OH^-_{(aq)}] = 0.064$ mol/L

$pOH = -\log 0.064$

$pOH = 1.194$ (extra digits carried)

$pH = 14 - pOH$

$= 14 - 1.194$

$pH = 12.81$

The pH of the barium hydroxide solution is 12.81.

19. $n_{Ca(OH)_{2(aq)}} = \dfrac{0.80 \text{ g}}{74.10 \text{ g/mol}}$

$n_{Ca(OH)_{2(aq)}} = 0.0108$ mol   (extra digits carried)

$[Ca(OH)_{2(aq)}] = \dfrac{0.0108 \text{ mol}}{0.100 \text{ L}}$

$[Ca(OH)_{2(aq)}] = 0.108$ mol/L

$[OH^-] = 2 \times [Ca(OH)_{2(aq)}]$

$= 2 \times 0.108$

$[OH^-] = 0.216$ mol/L

$pOH = -\log 0.216$

$pOH = 0.666$

$pH = 14 - 0.666$

$pH = 13.33$

The pH of the barium hydroxide solution is 13.33.

SECTION 8.1 QUESTIONS

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Understanding Concepts

1. (a) Hydrogen ion concentration is equal to the hydroxide ion concentration.
   (b) Hydrogen ion concentration is greater than the hydroxide ion concentration.
   (c) Hydrogen ion concentration is less than the hydroxide ion concentration.
2. Two diagnostic tests to distinguish a weak acid from a strong acid are:
   (i) Measure the pH with indicators, pH test strips, or a pH meter. Strong acids have a lower pH than weak acids.
   (ii) Reactivity with active metals. A strip of magnesium bubbles more vigorously in a strong acid than in a weak acid.
3. According to Arrhenius's theory, all bases contain hydroxide.
4. $pOH = 14.00 - 10.35$

   $pOH = 3.65$

   $[OH^-] = 10^{-pOH}$

   $= 10^{-3.65}$

   $[OH^-] = 2.24 \times 10^{-4}$ mol/L

   $n_{NaOH} = (2.24 \times 10^{-4}$ mol/L $)(2.00$ L$)$

   $n_{NaOH} = 4.48 \times 10^{-4}$ mol

   $m_{NaOH} = (4.48 \times 10^{-4}$ mol$)(40.00$ g/mol$)$

   $m_{NaOH} = 0.018$ g

5. (a) blue
   (b) yellow
6. (a) less than 6
   (b) greater than 10
   (c) greater than 3.8
   (d) 7
7. (a) pH 5
   (b) $[H^+] = 1 \times 10^{-5}$ mol/L

Applying Inquiry Skills

8. **Experimental Design**
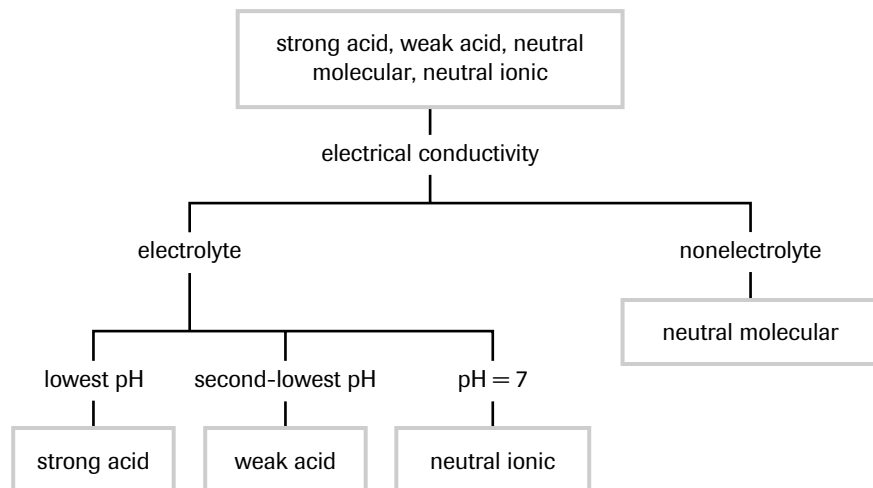
1. Test all solutions with pH test strips. The strong acid has the lowest pH, the weak acid has the next lowest pH, and the remaining solutions have pH 7.
2. Test the pH 7 solutions with a conductivity tester. The neutral ionic solution will test positive while the neutral molecular solution will test negative.

Making Connections

9. (a) Gastroesophageal reflux disease (GERD) is a condition that results in the movement of stomach or duodenal contents into the esophagus.
   (b) GERD can affect all age groups.
   (c) A thin spaghetti-like tube containing a tiny pH probe is passed down the throat to the esophagus where it measures acidity over a 24-h period. Data from the probe is recorded on a recording device. Hospitalization is usually required while the test is being done.
   (d) Treatments currently available include
   Monitoring diet: the following foods can aggravate acid reflux: deep-fried foods, whole milk, chocolate, creamy foods. The following foods can aggravate an already-inflamed lower esophagus: coffee and other caffeinated beverages, carbonated soft drinks, citric juices like orange and grapefruit juice.
   Surgery: the lower portion of the esophagus is surgically tightened, the end result being a one-way valve, which allows food to enter the stomach while preventing stomach contents from flowing upward.

10. (a) Prior to the 19th century, paper was handmade from linen or rags. To meet the skyrocketing demand for paper in the 19th century, chemists found that large quantities of paper could be made economically from wood pulp. During this process, alum (aluminum sulfate) was added to the paper to fill the microscopic holes in the paper. This procedure is known as sizing. Sizing prevents ink from bleeding across the paper. The acidity of the aluminum ion catalyzes the degradation of cellulose strands of the paper. Over a long period of time, acidic paper becomes extremely brittle. Acid-free paper is manufactured often with alkaline sizing agents such as alkyl ketene dimers (AKD).
   (b) Acid-free paper is used for important documents that must last a long time, such as birth certificates, marriage licences, photograph album pages, archival records, etc.
   (c) Acid-free paper lasts considerably longer and is stronger than regular acidic paper. It also requires less energy and fresh water to manufacture. Paper made from this process can be recycled more easily. One disadvantage of acid-free paper is that the sizing agents tend to form sticky deposits on the paper-making equipment, and sometimes on the paper itself.

8.2   WEAK ACIDS AND BASES

PRACTICE

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Understanding Concepts

1. $[H^+_{(aq)}] = 10^{-2.54}$

   $[H^+_{(aq)}] = 2.88 \times 10^{-3} \text{ mol/L}$

   $[H^+_{(aq)}] = \dfrac{p}{100} \times [HC_2H_3O_2]$

   $\quad p = \dfrac{[H^+_{(aq)}]}{[HC_2H_3O_2]} \times 100\%$

   $\quad\;\; = \dfrac{2.88 \times 10^{-3} \text{ mol/L}}{[0.46 \text{ mol/L}]} \times 100\%$

   $\quad p = 0.63\%$

2. $[H^+_{(aq)}] = 10^{-2.00}$

   $[H^+_{(aq)}] = 1.0 \times 10^{-2} \text{ mol/L}$

   $[H^+_{(aq)}] = \dfrac{p}{100} \times [HF_{(aq)}]$