Chem 150, Spring 2015

Unit 4 - Acids & Bases

Introduction

- Patients with emphysema cannot expel CO_2 from their lungs rapidly enough.
  - This can lead to an increase of carbonic acid (H_2CO_3) levels in the blood and to a lowering of the *pH* of the blood by a process called respiratory acidosis.

$$CO_2 + H_2O \rightarrow H_2CO_3$$

Introduction

- Carbonic acid (H_2CO_3), along with its conjugate base, the bicarbonate ion (HCO_3^-), play an important role as a buffer that maintains blood *pH* at around 7.4.

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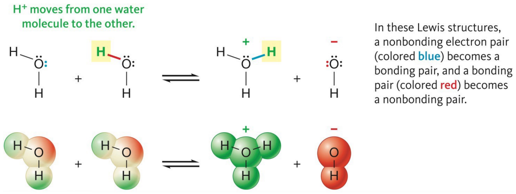
$$\underset{\text{acid}}{H_2CO_3} \rightleftharpoons \underset{\text{base}}{HCO_3^-} + H^+$$

7.1 The Self-Ionization of Water

- When two water molecules are hydrogen bonded to one another, the acceptor (base) occasionally pulls a hydrogen ion away from the donor (acid). The products are a hydronium ion (H_3O^+) and a hydroxide ion.



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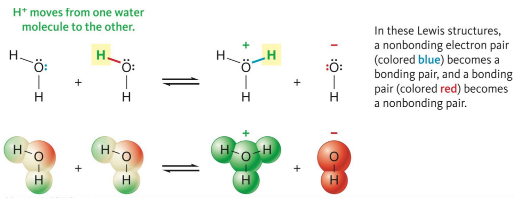

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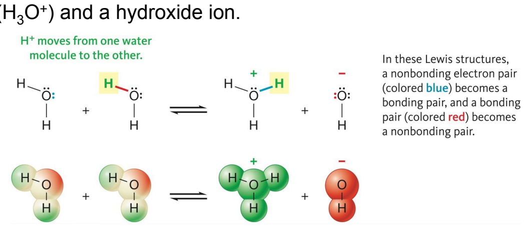

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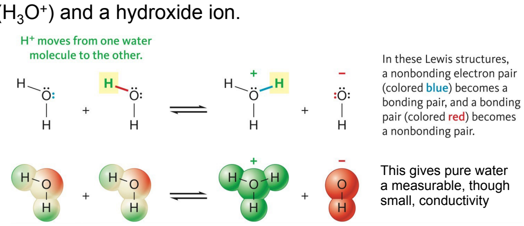

This gives pure water a measurable, though small, conductivity

base acid acid base

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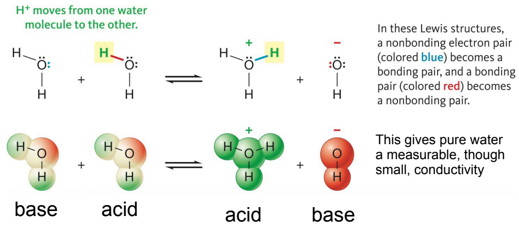

Just 1 ion (H_3O^+ or OH^-) per 280 million water molecules

Hydrogen Ion

- Since hydrogen atom contains one proton and one electron, a hydrogen ion (H^+) is simply a proton.
  - The terms *hydrogen ion* and *proton* are used interchangeably in chemistry.
- Although commonly represented as H^+, hydrogen ions do not exist as independent ions in an aqueous solution but instead are covalently bonded to water molecules.
  - The *hydronium ion* (H_3O^+) is also commonly used to represent a hydrogen ion.

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$H^+ = H_3O^+$

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Unlike pure water, the conductivity of hydrochloric acid and nitric acid solutions are very high, because both of these acids are strong acids and therefore strong electrolytes.

Bases

- Compounds that form hydroxide ions when they dissolve in water are bases.

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Because both NaOH and $Ca(OH)_2$ are ionic compounds (salts), and therefore strong electrolytes that produce a high conductivity when dissolved in water.

The Ion Product of Water

- Any reaction that forms H_3O^+ or OH^- ions has an effect on the equilibrium in water between H_2O molecules and H_3O^+ and OH^- ions.

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shift equilibrium

$$H_2O_{(l)} + H_2O_{(l)} \leftrightharpoons H_3O^+_{(aq)} + OH^-_{(aq)}$$

lower H_3O^+ add base

The Ion Product of Water

- At equilibrium,

$$H_2O_{(l)} + H_2O_{(l)} \leftrightharpoons H_3O^+_{(aq)} + OH^-_{(aq)}$$

$$K_w = [H_3O^+] \times [OH^-] = 1.0 \times 10^{-14}\ M^2$$

- K_w is called the ion product for water.

7.2 The pH Scale

- In most cases, $[H_3O^+]$ is very small can vary over a wide range of magnitudes, therefore, its concentration is often express in terms of *pH*..
- The *pH* is a logarithmic scale and it value is determine by taking the negative logarithm of the H_3O^+ concentration.
  - For exact powers of 10, it is just the negative value of the exponent:

If $[H_3O^+]$ =	then, pH =
10^{-4}	***4***
10^{-7}	***7***
10^{-11}	***11***

Acids, Bases, and pH

- If the *pH* of a solution is *below* 7, the solution is acidic, and,

$$\left[H_3O^+\right] > \left[OH^-\right] \quad \text{acidic}$$

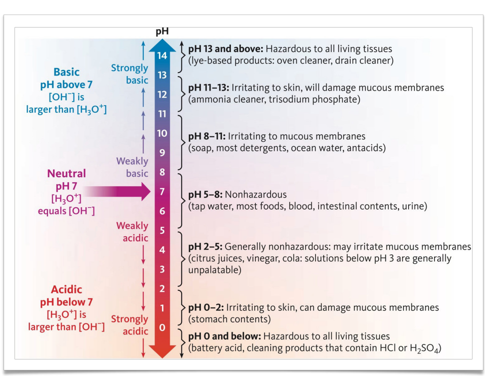
- If the pH of a solution is 7, the solution is neutral, and

$$\left[H_3O^+\right] = \left[OH^-\right] \quad \text{neutral}$$

- If the pH of a solution is *above* 7, the solution is basic or alkaline, and,

$$\left[H_3O^+\right] < \left[OH^-\right] \quad \text{basic or alkaline}$$

pH of Common Substances



Try It!

$[H_3O^+]$	$[OH^-]$	*pH*	Acid, Base, or Neutral
***10^{-5}* M**			
	***10^{-3}* M**		
			Neutral

Try It!

$[H_3O^+]$	$[OH^-]$	*pH*	Acid, Base, or Neutral
***10^{-5}* M**	*10^{-9}* M		
	***10^{-3}* M**		
			Neutral

Try It!

$[H_3O^+]$	$[OH^-]$	*pH*	Acid, Base, or Neutral
***10^{-5}* M**	*10^{-9}* M	*5*	
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$[H_3O^+]$	$[OH^-]$	*pH*	Acid, Base, or Neutral
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pH, Logarithm, and Antilogarithm

- When $[H_3O^+]$ is not an exact power of 10, use the [Log] key on your calculator:

$$pH = -\log\left(\left[H_3O^+\right]\right)$$

- Example 1: If $[H_3O^+] = 7.3 \times 10^{-5}$, what is the pH?

  On a TI-83 calculator
  [(-)] [Log] 7.3 [EE] [(-)] 5 [Enter]

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$$pH = 4.14$$

pH, Logarithm, and Antilogarithm

- To calculate $[H_3O^+]$ from the *pH*, take 10 to the -*pH* power, do this using the the $[10^{-x}]$ key on you calculator.

$$\left[H_3O^+\right] = 10^{-pH}$$

- Example 2: If *pH* = 8.35, what is $[H_3O^+]$?

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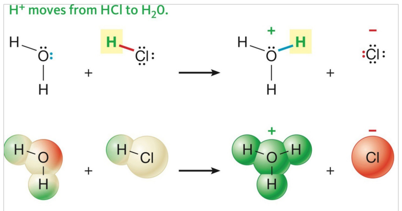
On a TI-83 calculator
$[10^{-x}]$ [(-)] 8.35 [Enter]

$$\left[H_3O^+\right] = 4.5 \times 10^{-9}\ \text{M}$$

7.3 Properties of Acids

- An acid is a compound that can lose a H^+ ion.
- Since a hydrogen ion is just a proton, acids are often called proton donors.



In this figure, the reaction is written
$H_2O + HCl \longrightarrow H_3O^+ + Cl^-$
Remember that you can write the reactants (and the products) in a chemical equation in any order you choose.

Common Acids

TABLE 7.2 Some Common Acids and Their Ionization Reactions

Formula	Name	Ionization Reaction
HCl	Hydrochloric acid	$HCl(aq) + H_2O(l) \rightarrow H_3O^+(aq) + Cl^-(aq)$
HNO_3	Nitric acid	$HNO_3(aq) + H_2O(l) \rightarrow H_3O^+(aq) + NO_3^-(aq)$
H_2SO_4	Sulfuric acid	$H_2SO_4(aq) + H_2O(l) \rightarrow H_3O^+(aq) + HSO_4^-(aq)$
H_3PO_4	Phosphoric acid	$H_3PO_4(aq) + H_2O(l) \rightarrow H_3O^+(aq) + H_2PO_4^-(aq)$
H_2CO_3	Carbonic acid	$H_2CO_3(aq) + H_2O(l) \rightarrow H_3O^+(aq) + HCO_3^-(aq)$
$HC_2H_3O_2$	Acetic acid	$HC_2H_3O_2(aq) + H_2O(l) \rightarrow H_3O^+(aq) + C_2H_3O_2^-(aq)$

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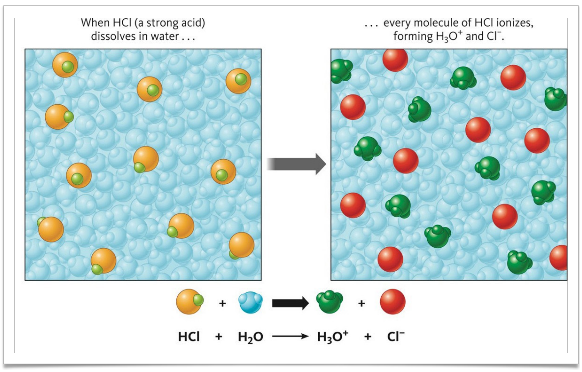
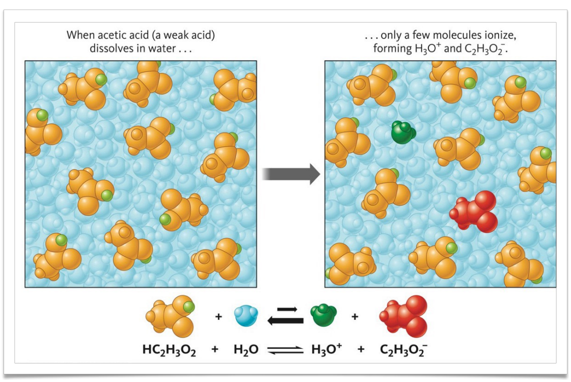
Acids: Strong or Weak Electrolytes

- All acids are electrolytes because they form ions when they dissolve in water.
- Any compound that *ionizes completely* in water is a strong electrolyte. An acid that is a strong electrolyte is classified as a strong acid.
- Any compound that ionizes to a limited extent when it dissolves in water is a weak electrolyte. An acid that is a weak electrolyte is classified as a weak acid.

Ionization of a Strong Acid



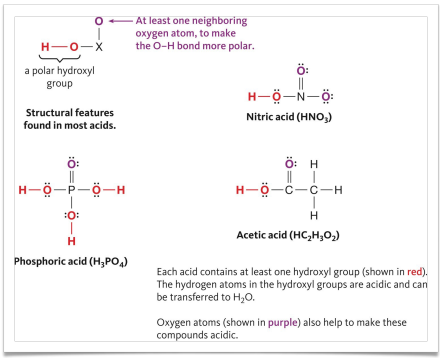
Ionization of a Weak Acid



Common Structural Features of Acids

- We can recognize two structural features that are found in most acids:
  - Acids normally contain at least one hydroxyl (-OH) group.
  - The atom that is attached to the hydroxyl group is normally bonded to at least one other oxygen atom.
- In on convention, the chemical formulas of acids start with H, and the chemical formulas of compounds that are not acids start with some other element.

Structural Features

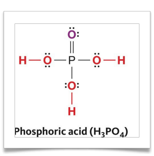


Try It!

Question:
Write the chemical equation for the ionization of *lactic acid* ($HC_3H_5O_3$) in aqueous solution.

Polyprotic Acids

- A monoprotic acid is only able to transfer one hydrogen ion to water.
- Polyprotic acids are capable of losing more than one hydrogen ion:



$$H_3PO_4 + H_2O \rightleftharpoons H_2PO_4^- + H_3O^-$$
$$H_2PO_4^- + H_2O \rightleftharpoons HPO_4^{2-} + H_3O^-$$
$$HPO_4^{2-} + H_2O \rightleftharpoons PO_4^{3-} + H_3O^-$$

- In most polyprotic acids, the second hydrogen is more difficult to remove than the first.

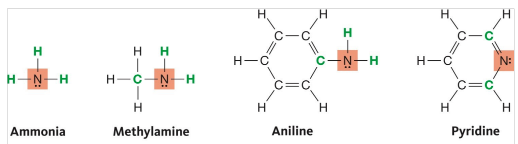
7.4 Properties of Bases

- Bases neutralize acids by forming a covalent bond to the hydrogen ion from the acid.
- A base is any compound that can bond to H^+.
- Since a hydrogen ion is a proton, bases are also called proton acceptors.
- When we mix a base with water, the base pulls a hydrogen ion away from a water molecule:

$$NH_3 + H_2O \rightleftharpoons NH_4^+ + OH^-$$

Common Structural Features of Bases

- We can recognize two structural features that are common among bases:
  - Most anions are bases because opposite charges attract each other.
  - Most molecules that contain nitrogen covalently bonded to carbon, hydrogen, or both are bases.



Each of these bases contains nitrogen bonded to carbon or hydrogen.

Strong or Weak Bases

- Bases are classified as strong or weak based on how effective they are at removing hydrogen ions from water molecules.
- If every molecule of a substance removes a proton from a water molecule, the substance is a strong electrolyte and a strong base.
- Weak bases are weak electrolytes and react with water to produce hydroxide ions, but only to a limited extent.

Weak Bases

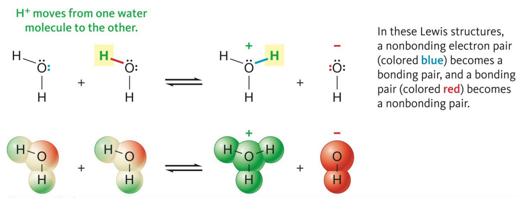
TABLE 7.3 Some Weak Bases and Their Reactions with Water

Formula	Name	Reaction with Water
C_5H_5N	Pyridine	$C_5H_5N(aq) + H_2O(l) \rightleftharpoons HC_5H_5N^+(aq) + OH^-(aq)$
N_2H_4	Hydrazine	$N_2H_4(aq) + H_2O(l) \rightleftharpoons N_2H_5^+(aq) + OH^-(aq)$
C_2H_7NO	Ethanolamine	$C_2H_7NO(aq) + H_2O(l) \rightleftharpoons HC_2H_7NO^+(aq) + OH^-(aq)$
$C_2H_3O_2^-$	Acetate ion	$C_2H_3O_2^-(aq) + H_2O(l) \rightleftharpoons HC_2H_3O_2(aq) + OH^-(aq)$
CO_3^{2-}	Carbonate ion	$CO_3^{2-}(aq) + H_2O(l) \rightleftharpoons HCO_3^-(aq) + OH^-(aq)$
PO_4^{3-}	Phosphate ion	$PO_4^{3-}(aq) + H_2O(l) \rightleftharpoons HPO_4^{2-}(aq) + OH^-(aq)$

Conjugate Acids and Bases

- When an acid or a base reacts with water, the reactant and the product bear a special relationship with each other.
- In both cases, the formulas of the reactant and product differ by only one hydrogen ion.
- Two substances whose formulas differ by one hydrogen ion are called a conjugate pair.
- The substance with the hydrogen ion is the conjugate acid, and the substance that is missing the hydrogen ion is the conjugate base.

Conjugate Pairs



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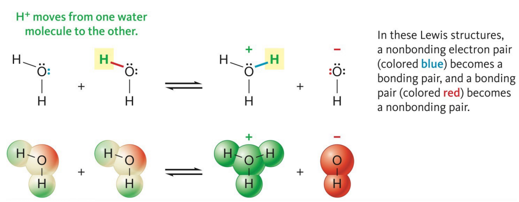
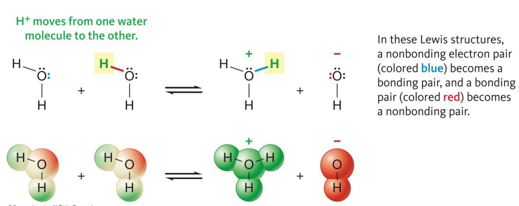


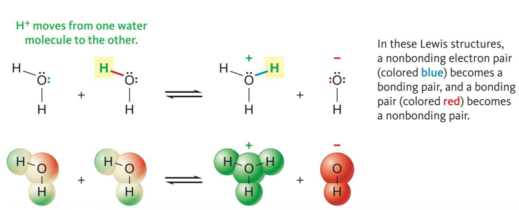
acid

Conjugate Pairs



acid ⟶ conjugate base

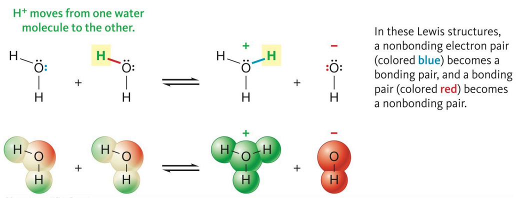
Conjugate Pairs



acid ⟶ conjugate base

base

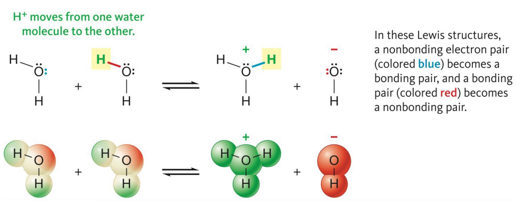
Conjugate Pairs



acid → conjugate base

base conjugate acid

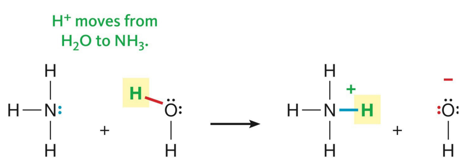
Conjugate Pairs



acid → conjugate base

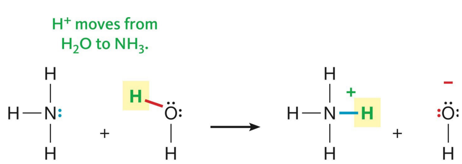
base → conjugate acid

Conjugate Pairs



Reaction of ammonia with water

Conjugate Pairs



Reaction of ammonia with water

acid

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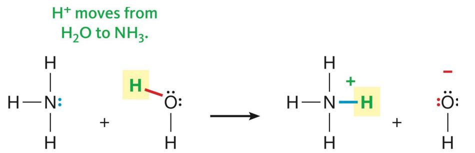
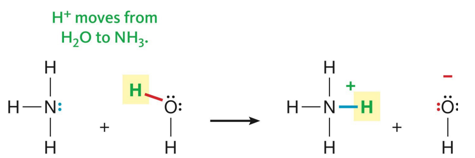


Reaction of ammonia with water

acid → conjugate base

Conjugate Pairs

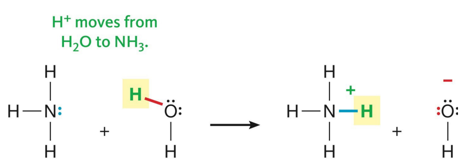


Reaction of ammonia with water

acid → conjugate base

base

Conjugate Pairs



Reaction of ammonia with water

acid → conjugate base

base → conjugate acid

Try It!

Question:
What is the conjugate base of the dihydrogen phosphate ($H_2PO_4^-$) ion?

A. H_3PO_4

B. $H_2PO_4^-$

C. HPO_4^{2-}

D. PO_4^{3-}

Try It!

Question:
What is the conjugate acid of the dihydrogen phosphate ($H_2PO_4^-$) ion?

A. H_3PO_4

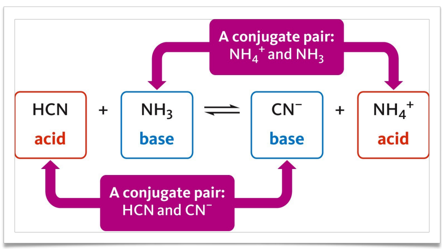
B. $H_2PO_4^-$

C. HPO_4^{2-}

D. PO_4^{3-}

7.5 Acid-Base Reactions

- In an acid-base reaction, a proton moves from the acid to the base.
- Acid-base reactions involve two conjugate pairs.



7.5 Acid-Base Reactions

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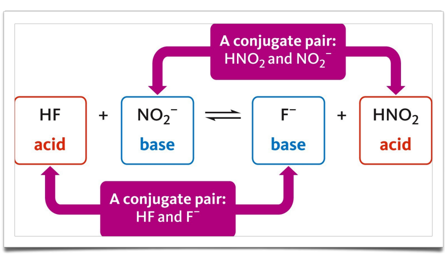

Polyprotic Acids React with Bases in Several Steps

- When a polyprotic acid reacts with a base, the base removes one hydrogen atom at a time.

$$H_3PO_4 + OH^- \rightarrow H_2O + H_2PO_4^-$$

$$H_2PO_4^- + OH^- \rightarrow H_2O + HPO_4^{2-}$$

$$HPO_4^{2-} + OH^- \rightarrow H_2O + PO_4^{3-}$$

Molecular and Net Ionic Equations

- We have been looking at net ionic equations where strong electrolytes are shown ionized without the counter ions that are not involved in the reaction (spectator ions).
- Molecular equations include spectator ions and do not make a distinction between weak, strong, and non-electrolytes.

$H_3O^+(aq) + OH^-(aq) \rightarrow 2\ H_2O(l)$ *(net ionic)*

$HCl(aq) + NaOH(aq) \rightarrow NaCl(aq) + H_2O(l)$ *(molecular)*

7.6 Amphiprotic Molecules and Ions

- Substances that can either gain or lose hydrogen ions are called amphiprotic.
- Water is an amphiprotic molecule since it can gain a proton to form a hydronium ion or lose a proton to form a hydroxide ion.
- Most negative ions that can lose hydrogen ions are amphiprotic
- Some molecular compounds are amphiprotic.

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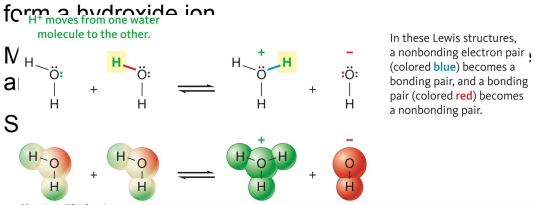
- S



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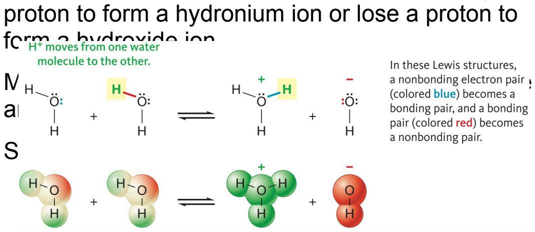

base acid

7.6 Amphiprotic Molecules and Ions

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- Water is an amphiprotic molecule since it can gain a proton to form a hydronium ion or lose a proton to form a hydroxide ion.
- Most negative ions that can lose hydrogen ions are amphiprotic
- Some molecular compounds are amphiprotic.

Example of an Amphiprotic Ion

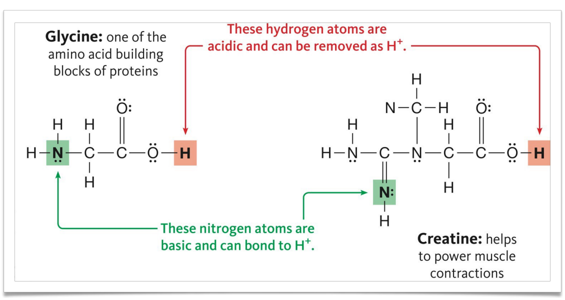
$HF(aq) + HCO_3^-(aq) \longrightarrow H_2CO_3(aq) + F^-(aq)$

HF: **acid** (loses H^+); HCO_3^-: **base** (gains H^+)

$HCO_3^-(aq) + NH_3(aq) \longrightarrow NH_4^+(aq) + CO_3^{2-}(aq)$

HCO_3^-: **acid** (loses H^+); NH_3: **base** (gains H^+)

Example of an Amphiprotic Molecular Compound



7.7 Buffers

- A buffer is a solution that resists a change in *pH* when acids and bases are added to them.
- A buffers is a solution that contain a mixture of a weak acid and its **conjugate base**.
- When the weak acid and its conjugate base are present at **equal concentrations**, the *pH* of a buffer is equal to the pK_a of the weak acid.
  - The *pH* of a buffer system can be fine-tuned by changing the proportions of acid and base in the solution.

Buffers and pH

- The pK_a is a measure of the strength of a weak acid
  - The *lower* the pK_a, the *stronger* the weak acid.

TABLE 7.4 Some Buffers and Their pH Values

Buffer Components	Source of the Conjugate Acid	Source of the Conjugate Base	Buffer pH (When the Molarities Are Equal)
$HC_2H_3O_2$ and $C_2H_3O_2^-$	$HC_2H_3O_2$ (acetic acid)	$NaC_2H_3O_2$ (sodium acetate)	4.74
H_3PO_4 and $H_2PO_4^-$	H_3PO_4 (phosphoric acid)	NaH_2PO_4 (sodium dihydrogen phosphate)	2.12
$H_2PO_4^-$ and HPO_4^{2-}	NaH_2PO_4 (sodium dihydrogen phosphate)	Na_2HPO_4 (sodium mono-hydrogen phosphate)	7.21
HPO_4^{2-} and PO_4^{3-}	Na_2HPO_4 (sodium mono-hydrogen phosphate)	Na_3PO_4 (sodium phosphate)	12.32
NH_4^+ and NH_3	NH_4Cl (ammonium chloride)	NH_3 (ammonia)	9.25

Buffers and pH

- Example: Acetic acid ($HC_2H_3O_2$) /Acetate ($C_2H_3O_2^-$) buffer (pK_a = 4.74)

Buffers and pH

- Example: Acetic acid ($HC_2H_3O_2$) /Acetate ($C_2H_3O_2^-$) buffer (pK_a = 4.74)

$HC_2H_3O_2$
weak
acid

Buffers and pH

- Example: Acetic acid ($HC_2H_3O_2$) /Acetate ($C_2H_3O_2^-$) buffer (pK_a = 4.74)

Buffer
- $HC_2H_3O_2$ weak acid
- $C_2H_3O_2^-$ weak base

Buffers and pH

- Example: Acetic acid ($HC_2H_3O_2$) /Acetate ($C_2H_3O_2^-$) buffer (pK_a = 4.74)

Buffer:

$HC_2H_3O_2$ + OH^-
weak acid, strong base

$C_2H_3O_2^-$
weak base

Buffers and pH

- Example: Acetic acid ($HC_2H_3O_2$) /Acetate ($C_2H_3O_2^-$) buffer (pK_a = 4.74)

Buffer:

$HC_2H_3O_2 + OH^- \longrightarrow C_2H_3O_2^- + HOH$
weak acid, strong base

$C_2H_3O_2^-$
weak base

Buffers and pH

- Example: Acetic acid ($HC_2H_3O_2$) /Acetate ($C_2H_3O_2^-$) buffer (pK_a = 4.74)

Buffer:

$HC_2H_3O_2 + OH^- \longrightarrow C_2H_3O_2^- + HOH$
weak acid, strong base → weak base, weak acid

$C_2H_3O_2^-$
weak base

Buffers and pH

- Example: Acetic acid ($HC_2H_3O_2$) /Acetate ($C_2H_3O_2^-$) buffer (pK_a = 4.74)

Buffer:

$HC_2H_3O_2 + OH^- \longrightarrow C_2H_3O_2^- + HOH$
weak acid, strong base → weak base, weak acid

$C_2H_3O_2^-$ + H_3O^+
weak base, strong acid

Buffers and pH

- Example: Acetic acid ($HC_2H_3O_2$) /Acetate ($C_2H_3O_2^-$) buffer (pK_a = 4.74)

Buffer:

$HC_2H_3O_2$ (weak acid) + OH^- (strong base) → $C_2H_3O_2^-$ (weak base) + HOH (weak acid)

$C_2H_3O_2^-$ (weak base) + H_3O^+ (strong acid) → $HC_2H_3O_2$ + HOH

Buffers and pH

- Example: Acetic acid ($HC_2H_3O_2$) /Acetate ($C_2H_3O_2^-$) buffer (pK_a = 4.74)

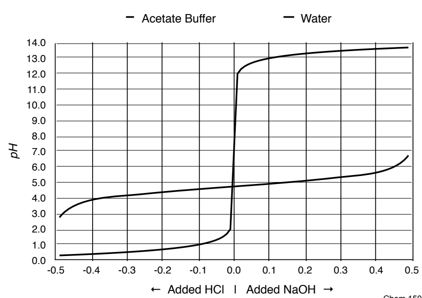
Buffer:

$HC_2H_3O_2$ (weak acid) + OH^- (strong base) → $C_2H_3O_2^-$ (weak base) + HOH (weak acid)

$C_2H_3O_2^-$ (weak base) + H_3O^+ (strong acid) → $HC_2H_3O_2$ (weak acid) + HOH (weak base)

7.7 Buffers

- An acetate buffer will resist changes to the *pH* around *pH* 4.74, when either a strong acid (HCl) or base (NaOH) are added to the solution.



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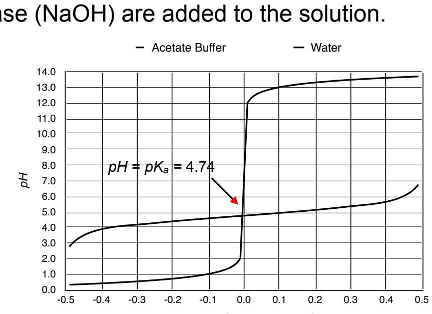

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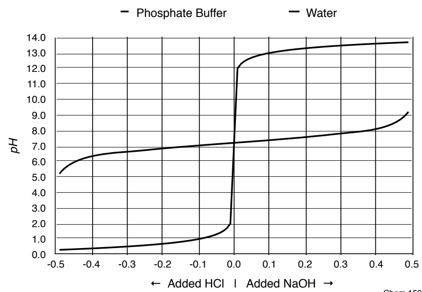

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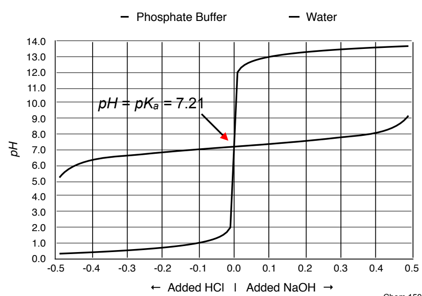
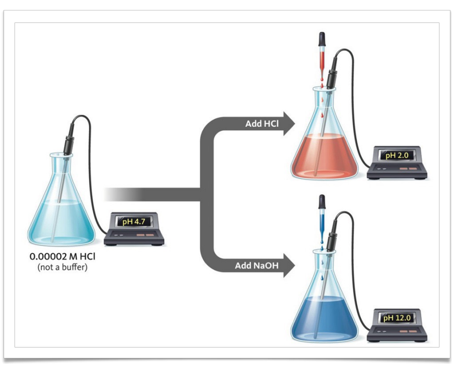
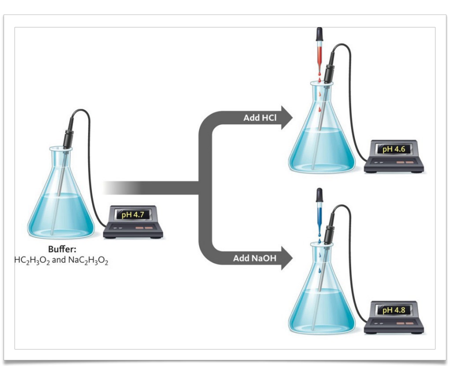


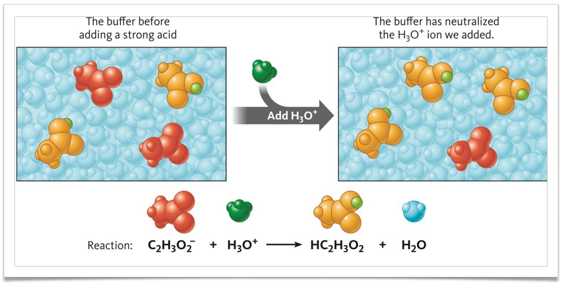
Significant pH Change (not buffered)



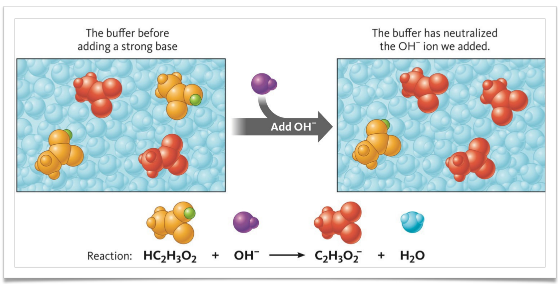
Buffer Solutions Resist Change in pH



Buffers Neutralize Acids



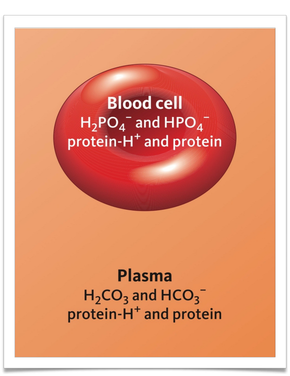
Buffers Neutralize Bases



7.8 The Role of Buffers in Human Physiology

- If blood *pH* drops below 7.35, you have acidosis.
- If blood *pH* rises above 7.45, you have alkalosis.
- There are three important buffers in the human body:
  1. Protein buffer system—proteins that contain amino acid that can serve as buffers.
  2. Phosphate buffer system—this system works with the protein buffer to maintain the *pH* of intercellular fluid.
  3. Carbonic acid buffer system (H_2CO_3) — the concentration of CO_2 in the blood can affect the plasma *pH*.

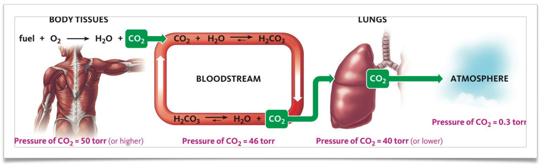
Buffers in Human Blood



Carbon Dioxide and the Carbonic Acid buffer

$$CO_2 + H_2O \leftrightharpoons H_2CO_3$$

- When CO_2 *increases*, the plasma pH goes *down*.
- When CO_2 *decreases*, the plasma pH goes *up*.



Carbon Dioxide and the Carbonic Acid buffer

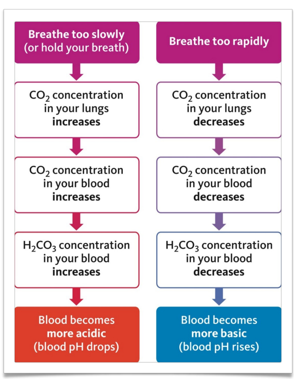
- Like combustions, the foods we eat for fuel are broken down to $CO_2 + H_2O$
  - The CO_2 dissolves in the plasma and is converted to carbonic acid

$$CO_2 + H_2O \leftrightharpoons H_2CO_3$$

- When CO_2 *increases*, the plasma pH goes *down*.
- When CO_2 *decreases*, the plasma pH goes *up*.

CO2 + H2O ⇋ H2CO3

Plasma pH and the Breathing Rate



Carbon Dioxide and the Carbonic Acid buffer

- The kidneys respond to elevated levels of CO_2 (H_2CO_3), by elevating the level of the conjugate base (HCO^-).

$$H_2CO_3 + H_2O \leftrightharpoons HCO_3^- + H_3O^+$$

Carbon Dioxide and the Carbonic Acid buffer

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$$H_2CO_3 + H_2O \leftrightharpoons HCO_3^- + H_3O^+$$

excreted by the kidneys

Kidneys Help Regulate Blood pH

TABLE 7.6 Acid–Base Regulation by the Kidneys

Substance Eliminated	Type of Substance	Result of Excretion	Comments
H_3O^+	Strong acid	Plasma pH *rises*	The kidneys make H_3O^+ by removing H^+ from H_2CO_3; the HCO_3^- is retained in the blood. This is the body's primary way to make HCO_3^- ions.
NH_4^+	Weak acid	Plasma pH *rises*	The kidneys make NH_4^+ by breaking down amino acids, so the body eliminates NH_4^+ only if the diet contains excess protein.
$H_2PO_4^-$	Weak acid*	Plasma pH *rises*	$H_2PO_4^-$ is only available if excess phosphate is present in the diet.
HCO_3^-	Weak base*	Plasma pH *drops*	This is the body's primary means of eliminating excess base.

* $H_2PO_4^-$ and HCO_3^- are amphiprotic ions, but $H_2PO_4^-$ functions as an acid and HCO_3^- functions as a base under physiological conditions.

Chapter 7—Key Health Science Notes

- *Respiratory acidosis* can be caused by
  - emphysema, pneumonia, asthma, pulmonary edema
  - drugs that suppress breathing
- *Metabolic acidosis*
  - hyperthyroidism and and sever diabetes which results in the over production of ketone bodies
  - Diarrhea, which disrupts the reabsorption of bicarbonate by the large intestine

Chapter 7—Key Health Science Notes

- *Respiratory alkalosis* can be caused by
  - hyperventilation brought on by anxiety
- *Metabolic alkalosis*
  - vomiting, which results in the loss of stomach acid

Next up

- Exam I on Thursday, 19. Feb.
  - Will cover Units 1 - 4