6.1 Arrhenius Definition of Acids and Bases

Definitions for acids and bases were proposed by the Swedish chemist Savante Arrhenius in 1884. **Acids** were defined as compounds that contain hydrogen and can dissolve in water to release hydrogen ions into solution. For example, HCl dissolves in water as follows:

\[ \text{HCl(g)} \rightarrow \text{H}^+(\text{aq}) + \text{Cl}^-(\text{aq}) \]

**Bases** are defined as substances that dissolve in water to release hydroxide ions (OH\(^-\)) into solution. For example, a typical base according to the Arrhenius definition is sodium hydroxide, NaOH:

\[ \text{NaOH(s)} \rightarrow \text{Na}^+(\text{aq}) + \text{OH}^-\text{(aq)} \]

The process that converts a molecule such as HCl into ions is called ionization. **Ionization** is the production of ions from molecular compounds. No ions were initially present.

The process of converting a solid ionic compound, such as NaOH, into ions in solution is called dissociation. **Dissociation** is the production of ions from ionic compounds. Ions were initially present, water just breaks apart ions.

**Some common acidic and basic substances:**

<table>
<thead>
<tr>
<th>Acidic</th>
<th>Basic</th>
</tr>
</thead>
<tbody>
<tr>
<td>citrus fruits</td>
<td>soap</td>
</tr>
<tr>
<td>vinegar</td>
<td>detergents</td>
</tr>
<tr>
<td>aspirin</td>
<td>milk of magnesia</td>
</tr>
</tbody>
</table>

**Some characteristic properties associated with acids and bases:**

<table>
<thead>
<tr>
<th>Acids</th>
<th>Bases</th>
</tr>
</thead>
<tbody>
<tr>
<td>sour taste</td>
<td>bitter taste</td>
</tr>
<tr>
<td>change litmus paper to red</td>
<td>change litmus paper to blue</td>
</tr>
<tr>
<td>react with hydroxide bases to produce salt</td>
<td>slippery, soapy feeling</td>
</tr>
</tbody>
</table>
Most acids are **oxyacids**; that is, they contain oxygen in addition to hydrogen and another element. The names of these acids come from the root name of the polyatomic ion. Suffixes are used based on the ending of the original name of the polyatomic anion. If the name of the polyatomic anion ends with \(-\text{ate}\), change it to \(-\text{ic}\) for the acid and if it ends with \(-\text{ite}\), change it to \(-\text{ous}\) in the acid.

HNO\(_3\), which contains the nitrate (NO\(_3^−\)), is called nitric acid.

HNO\(_2\), which contains the nitrite (NO\(_2^−\)), is called nitrous acid.

In addition to the oxyacids, there are a small number of acids that don’t contain oxygen, ie: HCl. To name these acids, the prefix *hydro-* is used before the name of the nonmetal ion, and its \(-\text{ide}\) ending is changed to \(-\text{ic acid}\).

HCl, the nonmetal ion is chlor\(-\text{ide}\), the \(-\text{ide}\) is changed to \(-\text{ic acid}\), so the name is hydrochloric acid.

**Worked Example 6-1**

Name the following acids:

- HF
- H\(_2\)CO\(_3\)
- HI
- HClO\(_3\)
- H\(_3\)PO\(_4\)
- HC\(_2\)H\(_3\)O\(_2\)

**Solution**

HF
The anion name is \(-\text{fluoride}\)- so the name is *hydrofluoric acid*.

H\(_2\)CO\(_3\)
The oxyanion is carbonate, which ends in \(-\text{ate}\); therefore the name of the acid is *carbonic acid*.

HI
The anion name is \(-\text{iodide}\)- so the name is *hydroiodic acid*.

HClO\(_3\)
The oxyanion is chlorate, which ends in \(-\text{ate}\); therefore the name of the acid is *chloric acid*.

H\(_3\)PO\(_4\)
The oxyanion is phosphate, which ends in \(-\text{ate}\); therefore the name of the acid is *phosphoric acid*.

HC\(_2\)H\(_3\)O\(_2\)
The oxyanion is acetate, which ends in \(-\text{ate}\); therefore the name of the acid is *acetic acid*.
Practice 6-1
Name the following acids:

$\text{H}_2\text{SO}_3 \quad \text{HBr} \quad \text{HClO}_4$

$\text{H}_2\text{S} \quad \text{HClO} \quad \text{H}_2\text{SO}_4$

Answer

6.3 | The pH Scale

The pH of a solution is a measure of the solution’s acidity. Mathematically, pH is defined in terms of the negative logarithm of the H⁺ concentration.

$$\text{pH} = \log[H^+]$$

Square brackets around $H^+$ indicate the concentration in moles per liter (M).

- pH less than 7.00 is an acidic solution
- pH = 7.00 is a neutral solution
- pH greater than 7.00 is a basic solution

Calculating pH From [H⁺]

Case (I)
Calculating the pH values for which the coefficient in the exponential expression is 1.0.
This is an easy case and you don’t need a calculator.

The pH is the negative of the exponent value of the power of 10.

$$[H^+] = 1.0 \times 10^{-4} \quad \text{pH} = \text{this number without sign} \quad (\text{pH} = 4.00)$$

If this number is exactly
**The Rule for Significant Figures in Logarithm Calculations**

The rules for logs are different from other mathematical operations. The number of decimal places for a log must be equal to the number of significant figures in the original number.

Number of significant figures in $[H^+] = \text{number of digits after decimal places in pH}$.

**Case (II)**

If the coefficient in the exponential expression is not 1.0, you need a calculator.

**Worked Example 6-2**

A solution has a $[H^+] = 3.7 \times 10^{-5}$ M. What is the pH?

**Solution**

**Steps for calculating pH on a TYPICAL calculator.**

<table>
<thead>
<tr>
<th>Operation</th>
<th>Display</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Press 3.7</td>
<td>3.7</td>
</tr>
<tr>
<td>2. Press EE or EXP</td>
<td>3.7 00</td>
</tr>
<tr>
<td>3. Press 5</td>
<td>3.7 05</td>
</tr>
<tr>
<td>4. Press +/- (change-of-sign)</td>
<td>3.7 -05</td>
</tr>
<tr>
<td>5. Press LOG key</td>
<td>-4.431798276</td>
</tr>
<tr>
<td>6. Press +/- (change-of-sign)</td>
<td>4.431798276</td>
</tr>
</tbody>
</table>

After rounding, the reported value is 4.43.

Two significant figures in $H^+$ ..... two digits to the right of the decimal point.
**Practice 6-2**

Calculate the pH of each of the following solutions and classify the solution as acidic or basic:

- Lemon juice: \([H^+] = 1.1 \times 10^{-2}\) M
- Soft drink: \([H^+] = 2.5 \times 10^{-4}\) M
- Urine: \([H^+] = 1.2 \times 10^{-6}\) M
- Blood: \([H^+] = 3.9 \times 10^{-8}\) M
- Antiseptic: \([H^+] = 1.2 \times 10^{-10}\) M
- Beer: \([H^+] = 5.0 \times 10^{-3}\) M
- Coffee: \([H^+] = 7.9 \times 10^{-6}\) M
- Detergent: \([H^+] = 3.2 \times 10^{-11}\) M

**Answer**

<table>
<thead>
<tr>
<th>Substance</th>
<th>([H^+]) M</th>
<th>pH</th>
<th>Acidic or Basic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lemon juice</td>
<td>1.1 \times 10^{-2}</td>
<td>1.96</td>
<td>Acidic</td>
</tr>
<tr>
<td>Soft drink</td>
<td>2.5 \times 10^{-4}</td>
<td>3.60</td>
<td>Acidic</td>
</tr>
<tr>
<td>Urine</td>
<td>1.2 \times 10^{-6}</td>
<td>5.92</td>
<td>Acidic</td>
</tr>
<tr>
<td>Blood</td>
<td>3.9 \times 10^{-8}</td>
<td>7.41</td>
<td>Basic</td>
</tr>
<tr>
<td>Antiseptic</td>
<td>1.2 \times 10^{-10}</td>
<td>9.92</td>
<td>Basic</td>
</tr>
<tr>
<td>Beer</td>
<td>5.0 \times 10^{-3}</td>
<td>2.30</td>
<td>Acidic</td>
</tr>
<tr>
<td>Coffee</td>
<td>7.9 \times 10^{-6}</td>
<td>5.10</td>
<td>Acidic</td>
</tr>
<tr>
<td>Detergent</td>
<td>3.2 \times 10^{-11}</td>
<td>10.49</td>
<td>Basic</td>
</tr>
</tbody>
</table>

### 6.4 Brønsted-Lowry Acids and Bases

A broader definition of an acid and base was introduced (independently) in 1923 by the Danish chemist **Johannes Brønsted** and the English chemist **Thomas Lowry**. The definition is called Brønsted-Lowry Acids and Bases, honoring the names of its founders. The Brønsted-Lowry definition of an acid is very similar to the Arrhenius definition. Any substance that can donate a hydrogen ion is an acid according to Brønsted-Lowry. Acids are often referred to as **proton** donors because an \(H^+\) ion (hydrogen without its electron) is simply a proton.

The Brønsted-Lowry definition of a **base** is quite different from the Arrhenius definition. The Brønsted-Lowry base is defined as any substance that can accept a hydrogen ion. In essence, a base is the opposite of an acid.

- **Acid**: An acid is a proton \((H^+)\) donor
- **Base**: A base is a proton \((H^+)\) acceptor
According to the Brønsted-Lowry definition, HCl is an acid because it donates H\(^+\) to a water molecule.

\[ \text{HCl(g)} + \text{H}_2\text{O(l)} \rightarrow \text{H}_3\text{O}^+(aq) + \text{Cl}^-(aq) \]

acid base

According to the Brønsted-Lowry definition, NH\(_3\) is a base because it accepts H\(^+\) from the water molecule.

\[ \text{NH}_3(g) + \text{H}_2\text{O(l)} \rightleftharpoons \text{NH}_4^+(aq) + \text{OH}^-(aq) \]

base acid

6.5 | Conjugate Acid-Base Pairs

Most Brønsted-Lowry acid-base reactions are reversible reactions in equilibrium.

Consider the reaction: \[ \text{HF} + \text{H}_2\text{O} \rightleftharpoons \text{F}^- + \text{H}_3\text{O}^+ \]

HF is the acid in the forward reaction because it donates H\(^+\) to become F\(^-\), while H\(_2\)O is the base because it accepts H\(^+\) to become H\(_3\)O\(^+\). For the reverse reaction, F\(^-\) is the base because it accepts H\(^+\) to become HF, and H\(_3\)O\(^+\) is the acid because it donates H\(^+\) to become H\(_2\)O.

The products of an acid-base reaction are themselves acids and bases. HF and F\(^-\) or H\(_2\)O and H\(_3\)O\(^+\) are called conjugate acid-base pairs because their formulas differ by one H\(^+\).

\[ \text{HF} + \text{H}_2\text{O} \]  \[ \text{H}_3\text{O}^+ + \text{F}^- \]

acid base acid base

conjugate pair  conjugate pair
**Worked Example 6-3**

For the following reaction, label each substance as an acid or a base and show the conjugate acid-base pairs.

\[ \text{NH}_3 + \text{H}_2\text{O} \rightleftharpoons \text{NH}_4^+ + \text{OH}^- \]

**Solution**

In the forward reaction, \( \text{NH}_3 \) is the base (it accepts \( \text{H}^+ \) to become \( \text{NH}_4^+ \)) and \( \text{H}_2\text{O} \) is the acid (it donates \( \text{H}^+ \) to become \( \text{OH}^- \)). For the reverse reaction, \( \text{NH}_4^+ \) is the acid (it donates \( \text{H}^+ \) to become \( \text{NH}_3 \)) and \( \text{OH}^- \) is the base (it accepts \( \text{H}^+ \) to become \( \text{H}_2\text{O} \)).

\( \text{NH}_3 \) and \( \text{NH}_4^+ \) or \( \text{H}_2\text{O} \) and \( \text{OH}^- \) differ by one \( \text{H}^+ \) and therefore conjugate acid-base pairs.

\begin{align*}
\text{NH}_3 + \text{H}_2\text{O} & \rightleftharpoons \text{OH}^- + \text{NH}_4^+ \\
\text{base} & \text{acid} & \text{OH}^- & \text{base} & \text{acid}
\end{align*}

\[ \text{conjugate pair} \]
\[ \text{conjugate pair} \]

**Practice 6-3**

For the following reaction label each substance as an acid or a base and show the conjugate acid-base pairs.

\[ \text{H}_2\text{CO}_3 + \text{H}_2\text{O} \rightleftharpoons \text{H}_3\text{O}^+ + \text{HCO}_3^- \]

**Answer**

\[ \text{Acid} \quad \text{Base} \]
\[ \text{Conjugate pair} \]
\[ \text{Conjugate pair} \]
Water: an Acid and a Base

Compounds or ions that can act as an acid or a base are called amphoteric substances. Water is the most common example of an amphoteric substance; others include hydrogen carbonate (HCO$_3^-$) and the amino acids (building blocks of proteins).

Water acts as an acid when it reacts with a base:

$$\text{NH}_3 + \text{H}_2\text{O} \rightleftharpoons \text{NH}_4^+ + \text{OH}^-$$

Water acts as a base when it reacts with an acid:

$$\text{HF} + \text{H}_2\text{O} \rightleftharpoons \text{F}^- + \text{H}_3\text{O}^+$$

Water can act as both an acid and a base in the same reaction:

$$\text{H}_2\text{O} + \text{H}_2\text{O} \rightleftharpoons \text{H}_3\text{O}^+ + \text{OH}^-$$

The above reaction illustrates the **self-ionization of water**. It does not proceed to the right to a large extent because water is a weak acid and base.

A more simplified version of the self-ionization reaction is:

$$\text{H}_2\text{O} \rightleftharpoons \text{H}^+ + \text{OH}^-$$

There is a common practice of substituting H$^+$ for H$_3$O$^+$ to simplify the equation. *Whenever you see the symbol H$^+$ (hydrogen ion), you should realize that we are actually referring to H$_3$O$^+$ (hydronium ion).*

In pure water H$^+$ and OH$^-$ form in equal amounts, therefore their concentrations are equal. The concentrations of H$^+$ and OH$^-$ at 25°C are each 1.0 x 10$^{-7}$ mol/L (M).

In pure water:

$$[\text{H}^+] = 1.0 \times 10^{-7} \text{ M}$$
$$[\text{OH}^-] = 1.0 \times 10^{-7} \text{ M}$$

The square brackets, [ ], are used to indicate concentration in moles per liter (M).

Multiplying [H$^+$] and [OH$^-$] concentrations gives a constant called **ion product of water**, symbol $K_w$.

$$K_w = [\text{H}^+] \times [\text{OH}^-] = (1.0 \times 10^{-7}) \times (1.0 \times 10^{-7}) = 1.0 \times 10^{-14}$$

$K_w = [\text{H}^+] [\text{OH}^-]$ applies, not only to pure water, but to any aqueous solution. Notice that [H$^+$] and [OH$^-$] are inversely proportional. This means that if [H$^+$] goes up, the [OH$^-$] must come down so that the product of the two is still 1.0 x 10$^{-14}$. 

6-8
Acidic solution:  \([\text{H}^+] > 10^{-7}\text{ M}\) and \([\text{OH}^-] < 10^{-7}\text{ M}\)
Neutral solution:  \([\text{H}^+] = 10^{-7}\text{ M}\) and \([\text{OH}^-] = 10^{-7}\text{ M}\)
Basic solution:  \([\text{H}^+] < 10^{-7}\text{ M}\) and \([\text{OH}^-] > 10^{-7}\text{ M}\)

**Worked Example 6-4**

Calculate the concentration of OH\(^-\) in an aqueous solution if the H\(^+\) concentration is 2.8 \(\times\) 10\(^{-3}\).

**Solution**

We know that \(K_w = [\text{H}^+] \times [\text{OH}^-] = 1.0 \times 10^{-14}\)

The [H\(^+\)] is given and we solve for [OH\(^-\)].

\[
[\text{OH}^-] = \frac{1.0 \times 10^{-14}}{2.8 \times 10^{-3}} = 3.6 \times 10^{-12}\text{ M}
\]

**Practice 6-4**

A) Calculate the [H\(^+\)] given the [OH\(^-\)] in each of the following aqueous solutions and classify each solution as acidic or basic.

\([\text{OH}^-] = 6.2 \times 10^{-3}\text{ M}\) \hspace{1cm} \([\text{OH}^-] = 1.3 \times 10^{-11}\text{ M}\)

B) Calculate the [OH\(^-\)] given the [H\(^+\)] in each of the following aqueous solutions and classify each solution as acidic or basic.

\([\text{H}^+] = 7.4 \times 10^{-5}\text{ M}\) \hspace{1cm} \([\text{H}^+] = 2.3 \times 10^{-9}\text{ M}\)

**Answer**

\[
\begin{array}{c}
\text{Acidic or basic?} \\
6.2 \times 10^{-3}\text{ M} \hspace{1cm} 1.6 \times 10^{-12}\text{ M} \hspace{1cm} \text{basic} \\
1.3 \times 10^{-11}\text{ M} \hspace{1cm} 7.7 \times 10^{-4}\text{ M} \hspace{1cm} \text{acidic}
\end{array}
\]

\[
\begin{array}{c}
\text{Acidic or basic?} \\
7.4 \times 10^{-5}\text{ M} \hspace{1cm} 1.4 \times 10^{-10}\text{ M} \hspace{1cm} \text{acidic} \\
2.3 \times 10^{-9}\text{ M} \hspace{1cm} 4.3 \times 10^{-6}\text{ M} \hspace{1cm} \text{basic}
\end{array}
\]
6.7 **Strengths of Acids and Bases**

**Strong acids** ionize in water completely or nearly so.

\[ \text{HCl} + \text{H}_2\text{O} \rightarrow \text{H}_3\text{O}^+ + \text{Cl}^- \]  
(Single arrow indicates complete ionization.)

**Weak acids** ionize only slightly in water.

\[ \text{HF} + \text{H}_2\text{O} \rightleftharpoons \text{H}_3\text{O}^+ + \text{F}^- \]  
(Equilibrium arrow indicates partial ionization.)

Common strong and weak acids:

<table>
<thead>
<tr>
<th>Strong Acids</th>
<th>Weak Acids</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCl</td>
<td>hydrochloric acid</td>
</tr>
<tr>
<td>HBr</td>
<td>hydrobromic acid</td>
</tr>
<tr>
<td>HI</td>
<td>hydroiodic acid</td>
</tr>
<tr>
<td>HNO\textsubscript{3}</td>
<td>nitric acid</td>
</tr>
<tr>
<td>HClO\textsubscript{4}</td>
<td>perchloric acid</td>
</tr>
<tr>
<td>H\textsubscript{2}SO\textsubscript{4}</td>
<td>sulfuric acid</td>
</tr>
</tbody>
</table>

**Strong bases** dissociate in water completely or nearly so.

\[ \text{NaOH(s)} + \text{H}_2\text{O} \rightarrow \text{Na}^+(aq) + \text{OH}^-(aq) \]

**Weak bases** ionize in water only slightly.

\[ \text{NH}_3 + \text{H}_2\text{O} \rightleftharpoons \text{NH}_4^+ + \text{OH}^- \]

Common strong and weak bases:

<table>
<thead>
<tr>
<th>Strong Bases</th>
<th>Weak Bases</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaOH</td>
<td>sodium hydroxide</td>
</tr>
<tr>
<td>KOH</td>
<td>potassium hydroxide</td>
</tr>
<tr>
<td>Ca(OH)\textsubscript{2}</td>
<td>calcium hydroxide</td>
</tr>
</tbody>
</table>
Worked Example 6-5

For a 6.8 x 10^{-4} M KOH solution, determine the following:

a) [OH^-]  
b) [H^+],  
c) the pH

Solution

a) Because KOH is a strong base, it completely dissociates:

KOH → K^+ + OH^-  

So the concentration of hydroxide ion of a 6.8 x 10^{-4} M KOH solution is 6.8 x 10^{-4} M.

[OH^-] = 6.8 x 10^{-4}

b) Substituting the [OH^-] value in Kw = [H^+] x [OH^-] = 1.0 x 10^{-14} yields:

[H^+] = \frac{1.0 \times 10^{-14}}{6.8 \times 10^{-4}} = 1.5 \times 10^{-11} M

c) pH = -log [H^+]  
pH = -log(1.5 \times 10^{-11})  
pH = 10.82

Practice 6-5

For a 7.4 x 10^{-3} M HCl solution, determine the following:

a) [H^+]  
b) [OH^-]  
c) The pH

Answer

For a 7.4 x 10^{-3} M HCl solution, determine the following:

a) [H^+]  
b) [OH^-]  
c) The pH
A neutralization reaction is when an acid reacts with a base to form a salt and water.

\[
\text{HCl(aq) + NaOH(aq)} \rightarrow \text{NaCl(aq) + H}_2\text{O(l)}
\]

Acid          Base              Salt            Water

This reaction is a double-replacement reaction where the $\text{H}^+$ from the acid reacts with the $\text{OH}^-$ from the base to produce the molecular compound water ($\text{H}_2\text{O}$). Salt is an ionic compound formed by combination of a cation and an anion. The salt contains the cation from the base and the anion from the acid.

For any neutralization reaction we can write the molecular equation, ionic equation, and net ionic equation. See unit (4).

**Worked Example 6-6**

Write molecular, ionic, and net ionic equation for the reaction of HNO$_3$ and NaOH.

**Solution**

**Molecular equation:**
Neutralization is a double replacement reaction. See unit 4. We write each substance as if it were a molecular substance:

\[
\text{HNO}_3\text{(aq) + NaOH(aq)} \rightarrow \text{NaNO}_3\text{(aq) + H}_2\text{O(l)}
\]

**Ionic equation:**
The formula HNO$_3$(aq) actually means $\text{H}^+$ (aq) and NO$_3^-$ (aq). The formula NaOH(aq) actually means Na$^+$ (aq) and OH$^-$ (aq). The formula NaNO$_3$(aq) actually means Na$^+$ (aq) and NO$_3^-$ (aq). We can replace the molecular equation with the following ionic equation:

\[
\text{H}^+(aq) + \text{NO}_3^-(aq) + \text{Na}^+(aq) + \text{OH}^-(aq) \rightarrow \text{Na}^+(aq) + \text{NO}_3^-(aq) + \text{H}_2\text{O(l)}
\]

**Net ionic equation:**
Removing spectator ions (ions that have not changed) from the ionic equation gives the following:

\[
\text{H}^+(aq) + \text{OH}^-(aq) \rightarrow \text{H}_2\text{O(l)}
\]
Write molecular, ionic, and net ionic equation for the reaction of HCl and KOH.

**Answer**

Molecular equation:

\[ \text{HCl(aq)} + \text{KOH(aq)} \rightarrow \text{KCl(aq)} + \text{H}_2\text{O(l)} \]

Ionic equation:

The formula HCl(aq) actually means H\(^+\)(aq) and Cl\(^-\)(aq)

The formula KOH(aq) actually means K\(^+\)(aq) and OH\(^-\)(aq)

The formula KCl(aq) actually means K\(^+\)(aq) and Cl\(^-\)(aq)

We can replace the molecular equation with the following ionic equation:

\[ \text{H}^+(aq) + \text{Cl}^-(aq) + \text{K}^+(aq) + \text{OH}^-(aq) \rightarrow \text{K}^+(aq) + \text{Cl}^-(aq) + \text{H}_2\text{O(l)} \]

Net ionic equation:

Removing spectator ions from the ionic equation gives the following

\[ \text{H}^+(aq) + \text{OH}^-(aq) \rightarrow \text{H}_2\text{O(l)} \]

All strong acid/strong base neutralization reactions have the same net ionic equation.
6.9 **Acid-Base Titrations**

The theory and principles of acid-base neutralization are combined with stoichiometry (*unit 4*) in a laboratory procedure called a *titration*. A titration can be used to determine the concentration of an unknown acid or base. The core concept is quite simple, if the concentration of one (acid, or base) is known, the concentration of the other can be determined.

For example, consider an acid-base titration involving acetic acid (in vinegar) and NaOH (base). The concentration of the base is known and our task is to determine the concentration of the acid.

In the titration, the solution of unknown concentration (in this case vinegar) is placed in a flask. The solution of known concentration (in this case NaOH) is placed in a buret. The NaOH (from the buret) is carefully added to the vinegar (in the flask). The addition continues in small portions until an observed “color change” signals that the titration is complete. This is called the *end point* or *equivalence point* of the titration. The end point (color change) is signaled by an *indicator*, a dye that changes color depending on the acidity or basicity of the solution.

When the equivalence point is reached, the volume of the base is determined from the buret. We can calculate the number of moles of reacted base from volume and concentration of the base. Next, we use stoichiometry to calculate the moles of the unknown acid which is required to calculate the molarity of the acid.
Worked Example 6-7

A 5.00-mL sample of vinegar requires 7.20 mL of a 0.584 M solution of NaOH for titration to the equivalence point. A) Calculate the molarity of the acetic acid in the vinegar solution. B) Calculate the percent (m/v) of the acetic acid in the vinegar solution.

\[ \text{HC}_2\text{H}_3\text{O}_2(aq) + \text{NaOH}(aq) \rightarrow \text{NaC}_2\text{H}_3\text{O}_2(aq) + \text{H}_2\text{O}(l) \]

acetic acid

Solution

**Step 1** The amount of base reacted (the moles of NaOH).

The volume of the base (in L) multiplied by the molarity of the base, gives the number of moles of the base.

\[
0.00720 \text{ L NaOH} \times \frac{0.584 \text{ mol NaOH}}{1 \text{ L NaOH}} = 0.00420 \text{ mol NaOH}
\]

**Step 2** Since the stoichiometry factor is 1 (see balanced equation above - 1 mol HC\(_2\)H\(_3\)O\(_2\) requires 1 mol NaOH), therefore the number of moles of the acid equals the number of moles of the base.

Moles acid = 0.00420 mol

**Step 3** Molarity of the acid is moles of acid (0.00420) divided by the volume of acid in L (0.00500 L).

\[
\text{Molarity} = \frac{0.00420 \text{ mol}}{0.00500 \text{ L}} = 0.840 \text{ M}
\]

Grams of acid:
The molar mass (from periodic table) of HC\(_2\)H\(_3\)O\(_2\) is 60.06 g/mol.

\[
\text{Grams acid} = 0.00420 \text{ mol acid} \times \frac{60.06 \text{ g acid}}{1 \text{ mol acid}} = 0.252 \text{ g acid}
\]

\[
\text{percent (m/v)} = \frac{\text{mass of acid}}{\text{mL of solution}} \times 100\%
\]

\[
\text{percent (m/v)} = \frac{0.252 \text{ g}}{5.00 \text{ mL}} \times 100\% = 5.05\%
\]
6.10 Buffer Solutions

The pH of water and most solutions changes drastically when you add a small amount of acid or bases to them. A buffer is a solution that resists changes in pH when small amounts of acid or base are added. Buffers contain two chemicals:

1) A substance to react with and remove the ADDED acid.
2) A substance to react with and remove the ADDED base.

Generally a buffer is a solution containing nearly equal concentrations of a weak acid and the salt of its conjugate base (recall Brønsted-Lowry acid-base).

The following table lists some weak acids and their conjugate bases.

<table>
<thead>
<tr>
<th>Weak Acid</th>
<th>Conjugate Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetic acid (HC₂H₃O₂)</td>
<td>Acetate ion (C₂H₃O₂⁻)</td>
</tr>
<tr>
<td>Carbonic acid (H₂CO₃)</td>
<td>Hydrogen carbonate ion (HCO₃⁻)</td>
</tr>
<tr>
<td>Ammonium ion (NH₄⁺)</td>
<td>Ammonia (NH₃)</td>
</tr>
</tbody>
</table>

**How Does a Buffer Work?**

A common buffer solution may be prepared from acetic acid (HC₂H₃O₂) and sodium acetate (NaC₂H₃O₂). Remember that HC₂H₃O₂ is a weak acid so in solution it exists primarily in its molecular form HC₂H₃O₂. The NaC₂H₃O₂ however, is an ionic substance that will ionize in solution to the C₂H₃O₂⁻ and Na⁺ ions.

**A) The Response of a HC₂H₃O₂/C₂H₃O₂⁻ Buffer to the Addition of H₃O⁺ Ions**

What happens if a small amount of a strong acid such as HCl is added to the buffer solution?
The buffer must remove most of the added H₃O⁺ ions from the strong acid, otherwise the pH would drop dramatically.
The H₃O⁺ ions combine with the acetate ions and are removed according to the equation below:

\[ H_3O^+ + C_2H_3O_2^- \rightarrow HC_2H_3O_2 + H_2O \]

Since most of the new H₃O⁺ ions are removed, the pH remains relatively constant.

**B) The Response of a HC₂H₃O₂/C₂H₃O₂⁻ Buffer to the Addition of OH⁻ Ions**

What happens if a small amount of a strong base such as NaOH is added to the buffer solution?
The newly added base (OH⁻) reacts with the acetic acid and is removed from solution.

\[ OH^- + HC_2H_3O_2 \rightarrow C_2H_3O_2^- + H_2O \]

Again, since most of the new OH⁻ ions are removed, the pH remains relatively constant.
Homework Problems

6.1 Write the formula for each of the following:
   a. lithium hydroxide
   b. iron(III) hydroxide
   c. aluminum hydroxide
   d. chlorous acid
   e. strontium hydroxide
   f. lead(II) hydroxide
   g. phosphorous acid
   h. ammonia

6.2 Calculate the pH of the following solutions:
   a. \([H_3O^+] = 5.6 \times 10^{-3}\]
   b. \([H_3O^+] = 3.8 \times 10^{-4}\]
   c. \([H_3O^+] = 2.7 \times 10^{-5}\]
   d. \([H_3O^+] = 1.0 \times 10^{-9}\]

6.3 For each of the following strong base solutions, determine \([OH^-]\), \([H_3O^+]\), and pH.
   a. \(6.5 \times 10^{-1}\) M NaOH
   b. \(4.7 \times 10^{-2}\) M KOH
   c. \(1.2 \times 10^{-2}\) M LiOH
   d. \(8.8 \times 10^{-3}\) M NaOH

6.4 Write equations for the reaction of each of the following Brønsted-Lowry acids and bases. Identify the conjugated acids and bases.
   a. Acid: \(H_2O\); base: \(NH_3\)
   b. Acid: \(NH_4^+\); base: \(OH^-\)
   c. Acid: \(HSO_4^-\); base: \(H_2O\)
   d. Acid: \(HCl\); base: \(H_3PO_4^-\)
6.5 Four solutions of unknown H\textsubscript{2}SO\textsubscript{4} concentration are titrated with solutions of NaOH. The following table lists the initial volume of each unknown H\textsubscript{2}SO\textsubscript{4} solution titrated, the volume of NaOH solution required to reach end point, and the molarity of each NaOH solution used. Calculate the molarity of the acid in each case. The equation for the reaction is

\[
\text{H}_2\text{SO}_4 (\text{aq}) + 2\text{NaOH}(\text{aq}) \rightarrow \text{Na}_2\text{SO}_4(\text{aq}) + 2\text{H}_2\text{O}(l)
\]

<table>
<thead>
<tr>
<th>H\textsubscript{2}SO\textsubscript{4} volume</th>
<th>NaOH volume</th>
<th>[NaOH]</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) 10.00 mL</td>
<td>16.50 mL</td>
<td>0.1820 M</td>
</tr>
<tr>
<td>b) 15.00 mL</td>
<td>10.85 mL</td>
<td>0.7550 M</td>
</tr>
<tr>
<td>c) 20.00 mL</td>
<td>24.10 mL</td>
<td>0.5923 M</td>
</tr>
<tr>
<td>d) 25.00 mL</td>
<td>12.77 mL</td>
<td>0.9505 M</td>
</tr>
</tbody>
</table>

6.6 Write an equation for each of the following buffer actions:

a. The response of HClO/ClO\textsuperscript{−} buffer to the addition of H\textsubscript{3}O\textsuperscript{+} ions.
b. The response of HClO/ClO\textsuperscript{−} buffer to the addition of OH\textsuperscript{−} ions.
c. The response of H\textsubscript{2}PO\textsubscript{4}\textsuperscript{−}/HPO\textsubscript{4}\textsuperscript{2−} buffer to the addition of H\textsubscript{3}O\textsuperscript{+} ions.
d. The response of H\textsubscript{2}PO\textsubscript{4}\textsuperscript{−}/HPO\textsubscript{4}\textsubscript{2−} buffer to the addition of OH\textsuperscript{−} ions.