Chemistry, Water, and Buffers

BB 450 / 550

Dr. Kevin Ahern
## Basic Chemistry

<table>
<thead>
<tr>
<th>Class</th>
<th>General Structure</th>
<th>Name</th>
<th>Functional Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkenes</td>
<td>RCH=CHR</td>
<td>Double Bond</td>
<td>C=C</td>
</tr>
<tr>
<td>Alcohols</td>
<td>ROH</td>
<td>Hydroxyl</td>
<td>OH</td>
</tr>
<tr>
<td>Ethers</td>
<td>ROR</td>
<td>Ether</td>
<td>O</td>
</tr>
<tr>
<td>Amines</td>
<td>RNH₂</td>
<td>Amino</td>
<td>N&lt;</td>
</tr>
<tr>
<td>Thiols</td>
<td>RSH</td>
<td>Sulphhydryl</td>
<td>SH</td>
</tr>
<tr>
<td>Aldehydes</td>
<td>R—C=H</td>
<td>Carboxyl</td>
<td>O</td>
</tr>
<tr>
<td>Ketones</td>
<td>R—C=R</td>
<td>Carboxyl</td>
<td>C</td>
</tr>
<tr>
<td>Carboxylic Acids</td>
<td>R—C—OH</td>
<td>Carboxyl</td>
<td>COOH</td>
</tr>
<tr>
<td>Amides</td>
<td>R—C—NR₂</td>
<td>Amide</td>
<td>C=N&lt;</td>
</tr>
<tr>
<td>Esters</td>
<td>R—C—OR'</td>
<td>Ester</td>
<td>C=OR</td>
</tr>
<tr>
<td>Phosphoric Acid</td>
<td>R—O—PO₃—OH</td>
<td>Phosphoric Ester</td>
<td>O—PO₃—OH</td>
</tr>
<tr>
<td>Phosphoric Acid</td>
<td>R—C—(PO₃)₂</td>
<td>Phosphoric Anhydride</td>
<td>P—O—P</td>
</tr>
</tbody>
</table>

- **Class** refers to different types of chemical compounds.
- **General Structure** shows the molecular structure of each class.
- **Name** indicates the name of the functional group.
- **Functional Group** represents the chemical bond or functional group associated with each class.
Geometry of Carbon
Geometry of Carbon
Geometry of Carbon

Tetrahedral
Geometry of Carbon

Tetrahedral

Handedness & Stereochemistry
Geometry of Carbon

Tetrahedral

Handedness & Stereochemistry
Basic Chemistry

Electronegativity
Basic Chemistry

Electronegativity
Relative “pull” of nuclei for outer shell electrons
Basic Chemistry

Electronegativity
Relative “pull” of nuclei for outer shell electrons

<table>
<thead>
<tr>
<th>Atom</th>
<th>Electronegativity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>3.5</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>3.0</td>
</tr>
<tr>
<td>Sulfur</td>
<td>2.6</td>
</tr>
<tr>
<td>Carbon</td>
<td>2.5</td>
</tr>
<tr>
<td>Phosphorous</td>
<td>2.2</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>2.1</td>
</tr>
</tbody>
</table>
Hydrogen Bonds

Partial Negative & Partial Positive Charges Arise From Different Electronegativities
Reduction / Oxidation
Reduction / Oxidation

Reduction - Gain of electrons
Reduction / Oxidation

Reduction - Gain of electrons
Oxidation - Loss of electrons
Reduction / Oxidation

Reduction - Gain of electrons
Oxidation - Loss of electrons

\[ \text{H}_3\text{CHC}=\text{O} + \text{NADH} + \text{H}^+ \rightleftharpoons \text{H}_3\text{CH}_2\text{COH} + \text{NAD}^+ \]
Gibbs Free Energy
$\Delta G = \Delta H - T\Delta S$

$$aA + bB \Leftrightarrow cC + dD$$

$$K_{eq} = \frac{\{[C]_{eq}[D]_{eq}\}}{\{[A]_{eq}[B]_{eq}\}}$$

$$\Delta G = \Delta G^{o'} + RT\ln \frac{\{[C]_{eq}[D]_{eq}\}}{\{[A]_{eq}[B]_{eq}\}}$$

$$\Delta G^{o'} = -RT\ln K_{eq}$$
Water & Buffers

Bond Angle: 104.3°

Covalent Bond: 0.095nm
Uneven Charge Distribution
Water & Buffers

Uneven Charge Distribution
Dipolar

Bond Angle: 104.3°

Covalent Bond: 0.095nm
Water & Buffers

Uneven Charge Distribution
Dipolar
Hydrogen Bonds

![Diagram of water molecule showing uneven charge distribution, dipole moments, and hydrogen bonds.]

- Covalent Bond: 0.095\,\text{nm}
- Bond Angle: 104.3^\circ
- \delta^+ (positive delta)
- \delta^- (negative delta)
Water & Buffers

Uneven Charge Distribution
Dipolar
Hydrogen Bonds
Hydrophilic vs Hydrophobic
## Hydrophilic vs Hydrophobic

<table>
<thead>
<tr>
<th>Hydrophobic</th>
<th>Hydrophilic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonpolar hydrocarbons (hexane)</td>
<td>Ionic compounds (NaCl)</td>
</tr>
<tr>
<td>Lipids (fats and cholesterol)</td>
<td>Polar organic compounds (alcohols, ketones or carboxyls)</td>
</tr>
<tr>
<td></td>
<td>Weak acids (phosphates, amino acids)</td>
</tr>
<tr>
<td></td>
<td>Sugars/carbohydrates</td>
</tr>
</tbody>
</table>
Hydrophilic vs Hydrophobic
Amphiphilic
Amphiphilic

\[ \text{CO}_2^\text{Na}^+ \]

Micelle
Other Amphiphilic Substances

Non-polar

Polar

\[
\begin{align*}
  & R^1 - C - O - CH_2 \\
  & R^2 - C - O - CH \\
  & H_2C - O - P - O - X
\end{align*}
\]
Other Amphiphilic Substances

Membrane Lipids

Non-polar

Polar
Other Amphiphilic Substances

Membrane Lipids

- Non-polar
- Polar
Other Amphiphilic Substances

Membrane Lipids

Non-polar

Polar

Chemical structures of amphiphilic substances.
Other Amphiphilic Substances

Membrane Lipids
Glycerophospholipids

Non-polar

Polar
Other Amphiphilic Substances

Membrane Lipids
Glycerophospholipids
Sphingolipids
Other Amphiphilic Substances

Membrane Lipids
  Glycerophospholipids
  Sphingolipids
Other Amphiphilic Substances

Membrane Lipids
  Glycerophospholipids
  Sphingolipids
Lipid Bilayers
Protein Folding
Protein Folding

UNFOLDED
Protein Folding

UNFOLDED  FOLDED
Protein Folding

Hydrophobic

Hydrophilic

UNFOLDED

FOLDED
Protein Folding

Hydrophobic

Hydrophilic

Outside

UNFOLDED  FOLDED
Protein Folding

Hydrophobic

Hydrophilic

Outside

Inside

UNFOLDED

FOLDED
Protein Folding

Hydrophobic

Hydrophilic

Outside

Inside

UNFOLDED

FOLDED

Water’s Chemistry Affects Molecules
Hydrogen Bonding Between Water Molecules
Hydrogen Bonding Between Water and Other Molecules
Hydrogen Bonding Between Water and Other Molecules

- Between a Proton of a Hydroxide and the Oxygen of Water
- Between Oxygen of Water and the Proton of an Amine
- Between a Proton on Water and a Carbonyl Group
Hydrogen Bonding Between Water and Other Molecules

**Ion-Dipole Interactions with Water**

- **Cation**
  - \( \delta^+ O - H \delta^+ \)
  - \( \delta^+ H - O \delta^- H \delta^+ \)
  - \( \delta^+ K^+ - O \delta^- H \delta^+ \)

- **Anion**
  - \( \delta^+ H - O \delta^- H \delta^+ \)
  - \( \delta^+ H - O \delta^- H \delta^+ \)
  - \( \delta^+ H - O \delta^- H \delta^+ \)

**Dipole-Dipole Interactions of Polar Compounds with Water**

- **Alcohol**
  - \( \delta^+ H - O \delta^- H \delta^+ \)
  - \( \delta^+ H - O \delta^- H \delta^+ \)
  - \( \delta^+ H - O \delta^- H \delta^+ \)

- **Ketone**
  - \( \delta^+ H - O \delta^- H \delta^+ \)
  - \( \delta^+ H - O \delta^- H \delta^+ \)
  - \( \delta^+ H - O \delta^- H \delta^+ \)
Hydrogen Bonding in the Cell
Bond Strength
## Bond Strength

### Bond Energies

<table>
<thead>
<tr>
<th>Type of Bond</th>
<th>Bond Energy (kJ/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Covalent Bonds</strong></td>
<td></td>
</tr>
<tr>
<td>C—H</td>
<td>413</td>
</tr>
<tr>
<td>O—H</td>
<td>460</td>
</tr>
<tr>
<td><strong>Noncovalent Bonds</strong></td>
<td></td>
</tr>
<tr>
<td>Hydrophobic Interaction</td>
<td>4-12</td>
</tr>
<tr>
<td>Hydrogen Bond</td>
<td>20</td>
</tr>
<tr>
<td>Ion-dipole Interaction</td>
<td>20</td>
</tr>
</tbody>
</table>
## Ionization and Acid Strength

### Weak Acid pKₐ Values

<table>
<thead>
<tr>
<th>Name</th>
<th>Chemical Structure of Acid</th>
<th>Chemical Structure of Salt</th>
<th>pKₐ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetic Acid</td>
<td>CH₃COOH</td>
<td>CH₃COO⁻</td>
<td>4.76</td>
</tr>
<tr>
<td>Formic Acid</td>
<td>HCOOH</td>
<td>HCOO⁻</td>
<td>3.75</td>
</tr>
<tr>
<td>Lactic Acid</td>
<td>CH₃CHOHCOOH</td>
<td>CH₃CH—HCOO⁻</td>
<td>3.86</td>
</tr>
<tr>
<td>Pyruvic Acid</td>
<td>CH₃COCOOH</td>
<td>CH₃C—COO⁻</td>
<td>2.50</td>
</tr>
<tr>
<td>Oxalic Acid (1)</td>
<td>HOOC—COOH</td>
<td>HOOC—COO⁻</td>
<td>1.23</td>
</tr>
<tr>
<td>Oxalic Acid (2)</td>
<td>HOOC—COO⁻</td>
<td>OOC—COO⁻</td>
<td>4.19</td>
</tr>
<tr>
<td>Carbonic Acid (1)</td>
<td>H₂CO₃</td>
<td>HCO₃⁻</td>
<td>6.37</td>
</tr>
<tr>
<td>Carbonic Acid (2)</td>
<td>HCO₃⁻</td>
<td>CO₃²⁻</td>
<td>10.20</td>
</tr>
<tr>
<td>Malic Acid (1)</td>
<td>HOOC—CH₂—CHOH—COOH</td>
<td>HOOC—CH₂—CHOH—COO⁻</td>
<td>3.40</td>
</tr>
<tr>
<td>Malic Acid (2)</td>
<td>HOOC—CH₂—CHOH—COO⁻</td>
<td>&quot;OOC—CH₂—CHOH—COO⁻</td>
<td>5.26</td>
</tr>
<tr>
<td>Malonic Acid (1)</td>
<td>HOOC—CH₂—COOH</td>
<td>HOOC—CH₂—COO⁻</td>
<td>2.83</td>
</tr>
<tr>
<td>Malonic Acid (2)</td>
<td>HOOC—CH₂—COO⁻</td>
<td>&quot;OOC—CH₂—COO⁻</td>
<td>5.69</td>
</tr>
<tr>
<td>Phosphoric Acid (1)</td>
<td>H₃PO₄</td>
<td>H₃PO₄⁻</td>
<td>2.14</td>
</tr>
<tr>
<td>Phosphoric Acid (2)</td>
<td>H₂PO₄⁻</td>
<td>HPO₄²⁻</td>
<td>7.20</td>
</tr>
<tr>
<td>Phosphoric Acid (3)</td>
<td>HPO₄²⁻</td>
<td>PO₄³⁻</td>
<td>12.40</td>
</tr>
<tr>
<td>Succinic Acid (1)</td>
<td>HOOC—CH₂—CH₂—COOH</td>
<td>HOOC—CH₂—CH₂—COO⁻</td>
<td>4.21</td>
</tr>
<tr>
<td>Succinic Acid (2)</td>
<td>HOOC—CH₂—CH₂—COO⁻</td>
<td>&quot;OOC—CH₂—CH₂—COO⁻</td>
<td>5.63</td>
</tr>
</tbody>
</table>
Acid Measurement
Acid Measurement

\[ \text{pH} = -\log[H^+] \]
Acid Measurement

\[ \text{pH} = -\log[H^+] \]
\[ \text{pOH} = -\log[OH^-] \]
Acid Measurement

\[
pH = -\log[H^+] \\
pOH = -\log[OH^-] \\
pKevinAhern = -\log[KevinAhern]
\]
Acid Measurement

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

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

\[\text{pKevinAhern} = -\log[\text{KevinAhern}]\]

\[\text{pH} + \text{pOH} = 14\]
Weak Acid Dissociation
Weak Acid Dissociation

\[ \text{HA} \rightleftharpoons \text{H}^+ + \text{A}^- \]

Acid
Salt
Weak Acid Dissociation

Buffering Region

\[ \text{pK}_a = 6.37 \]

\[ 5.37 \]

\[ 7.37 \]

Inflection Point

\[ [\text{Acid}] = [\text{Salt}] \]

\[ [\text{H}_2\text{CO}_3] = [\text{HCO}_3^-] \]

\[ \text{H}_2\text{CO}_3 \text{ excess} \quad \text{HCO}_3^- \text{ excess} \]

\[ \text{pH} \]

\[ \text{Equivalents of OH}^- \]

\[ 0.5 \]

\[ 1.0 \]

\[ \text{HCO}_3^- \]
Henderson Hasselbalch Equation
Henderson Hasselbalch Equation

\[ \text{pH} = \text{pKa} + \log \left( \frac{[\text{HCO}_3^-]}{[\text{H}_2\text{CO}_3]} \right) \]
Henderson Hasselbalch Equation

\[ \text{pH} = \text{pK}_a + \log \left( \frac{[\text{HCO}_3^-]}{[\text{H}_2\text{CO}_3]} \right) \]

\[ \text{pH} = \text{pK}_a + \log \left( \frac{[\text{Ac}^-]}{[\text{HAc}]} \right) \]
Henderson Hasselbalch Equation

\[ \text{pH} = \text{pK}_a + \log \left( \frac{[\text{HCO}_3^-]}{[\text{H}_2\text{CO}_3]} \right) \]

\[ \text{pH} = \text{pK}_a + \log \left( \frac{[\text{Ac}^-]}{[\text{HAc}]} \right) \]

In General,
Henderson Hasselbalch Equation

\[ \text{pH} = \text{pK}_a + \log \left( \frac{[\text{HCO}_3^-]}{[\text{H}_2\text{CO}_3]} \right) \]

\[ \text{pH} = \text{pK}_a + \log \left( \frac{[\text{Ac}^-]}{[\text{HAc}]} \right) \]

In General,

\[ \text{pH} = \text{pK}_a + \log\left( \frac{[\text{Salt}]}{[\text{Acid}]} \right) \]
pKa and Acid Strength
pKa and Acid Strength

Strong Acids, like HCl, essentially have no pKa value
pKa and Acid Strength

Strong Acids, like HCl, essentially have no pKa value
Low pKa - Stronger Weak Acid
pKa and Acid Strength

Strong Acids, like HCl, essentially have no pKa value

Low pKa - Stronger Weak Acid
High pKa - Weaker Weak Acid
pKa and Acid Strength

Strong Acids, like HCl, essentially have no pKa value

Low pKa - Stronger Weak Acid
High pKa - Weaker Weak Acid

Formic Acid (pKa = 3.75) vs Acetic Acid (pKa = 4.76)
Buffers
Buffers

Resist Changes in pH
Buffers

Resist Changes in pH

Weak Acid Systems
Buffers

Resist Changes in pH

Weak Acid Systems

Buffering Capacity
Buffers

Resist Changes in pH

Weak Acid Systems

Buffering Capacity

Buffering Region

\[
\text{pK}_a = 6.37
\]

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

Inflection Point

\[\text{[Acid]} = \text{[Salt]}\]

\[\text{[H}_2\text{CO}_3] = \text{[HCO}_3^-]\]

\[
\text{pH} = 7.37
\]

\[
\text{pH} = 5.37
\]

Equivalents of OH\(^-\)

\[
0.5
\]

\[
1.0
\]

H\(_2\text{CO}_3\) excess

HCO\(_3^-\) excess
Buffers

Resist Changes in pH

Weak Acid Systems

Buffering Capacity

Rapid pH Change

Buffering Region

\[ \text{pK}_a = 6.37 \]

\[ 7.37 \]

\[ 5.37 \]

H$_2$CO$_3$

Inflection Point

\[ [\text{Acid}] = [\text{Salt}] \]

\[ [\text{H}_2\text{CO}_3] = [\text{HCO}_3^-] \]

H$_2$CO$_3$ excess

HCO$_3^-$ excess

Rapid pH Change

Equivalents of OH$^-$
Buffers

Resist Changes in pH
Weak Acid Systems
Buffering Capacity

\[
pH = pK_a + \log \left( \frac{[\text{Salt}]}{[\text{Acid}]} \right)
\]

Buffering Region

\[
pK_a = 6.37
\]

Rapid pH Change

Limited pH Change

Inflection Point

\[
[\text{Acid}] = [\text{Salt}]
\]

\[
[H_2CO_3] = [HCO_3^-]
\]

Rapid pH Change

HCO_3^-

H_2CO_3 excess

HCO_3^- excess

Equivalents of OH^-
Acids With Multiple pKa Values
Acids With Multiple pKa Values

Titration of Aspartate with Sodium Hydroxide

\[
\text{pH} = \frac{\text{pK}_{a1} + \text{pK}_{a2}}{2}
\]

\[
\text{pK}_{a1} = 2.10, \quad \text{pK}_{a2} = 3.86
\]
Acids With Multiple pKa Values

Titration of Aspartate with Sodium Hydroxide

\[ \text{pK}_{a1} = 2.10, \quad \text{pK}_{a2} = 3.86, \quad \text{pK}_{a3} = 9.82 \]

\[ \text{pI} = \frac{\text{pK}_{a1} + \text{pK}_{a2}}{2} = \frac{2.10 + 3.86}{2} \]
Acids With Multiple pKa Values

Titration of Aspartate with Sodium Hydroxide

\[
pK_a^1 = 2.10 \quad pK_a^2 = 3.86 \quad pK_a^3 = 9.82
\]

\[
\text{pI} = \frac{2.10 + 3.86}{2}
\]
Acids With Multiple pKa Values

Titration of Aspartate with Sodium Hydroxide

\[
\text{pI} = \frac{2.10 + 3.86}{2}
\]
Acids With Multiple pKa Values

Titration of Aspartate with Sodium Hydroxide

\[ pK_{a1} = 2.10 \]
\[ pK_{a2} = 3.86 \]
\[ pK_{a3} = 9.82 \]

\[ pI = \frac{2.10 + 3.86}{2} \]

Equivalents of OH⁻
Acids With Multiple pKa Values

Titration of Aspartate with Sodium Hydroxide

\[ \text{pI} = \frac{\text{pK}_{a1} + \text{pK}_{a2}}{2} \]
Acids With Multiple pKa Values

Titration of Aspartate with Sodium Hydroxide

\[ \text{pI} = \frac{\text{pK}_{a1} + \text{pK}_{a2}}{2} \]
Acids With Multiple $pK_a$ Values

Titration of Aspartate with Sodium Hydroxide

$\text{H}_3\text{N}^+\text{CH} - \text{COOH}$

1. $pK_{a1} = 2.10$
2. $pK_{a2} = 3.86$
3. $pK_{a3} = 9.82$

$pI = \frac{pK_{a1} + pK_{a2}}{2}$
Estimating Weak Acid Charge
Estimating Weak Acid Charge

1. If pH > pKa by one or more pH units - Proton OFF
Estimating Weak Acid Charge

1. If pH > pKa by one or more pH units - Proton OFF
2. If pH < pKa by one or more pH units - Proton ON
Estimating Weak Acid Charge

1. If pH > pKa by one or more pH units - Proton OFF
2. If pH < pKa by one or more pH units - Proton ON

-COOH vs -COO⁻
Estimating Weak Acid Charge

1. If pH > pKa by one or more pH units - Proton OFF
2. If pH < pKa by one or more pH units - Proton ON

-COOH vs -COO⁻
-NH₃⁺ vs -NH₂
Metabolic Melody
Henderson Hasselbalch
(To the tune of "My Country 'Tis of Thee")
Copyright © Kevin Ahern
Henderson Hasselbalch
(To the tune of "My Country 'Tis of Thee")
Copyright © Kevin Ahern

Henderson Hasselbalch
You put my brain in shock
   Oh woe is me
The pKa’s can make
   Me lie in bed awake
They give me really bad headaches
   Oh hear my plea

   Salt - acid RA-ti-os
Help keep the pH froze
   By buf-fer-ING
They show tenacity
   Complete audacity
If used within capacity
   To maintain things
Henderson Hasselbalch
(To the tune of "My Country 'Tis of Thee")
Copyright © Kevin Ahern

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   Oh hear my plea

Salt - acid RA-ti-os
Help keep the pH froze
   By buf-fer-ING
They show tenacity
Complete audacity
If used within capacity
To maintain things

I know when H’s fly
   A buffer will defy
   Them actively
Those protons cannot waltz
When they get bound to salts
With this the change in pH halts
   All praise to thee

Thus now that I’ve addressed
   This topic for the test
I’ve got know-how
The pH I can say
Equals the pKA
In sum with log of S o’er A
   I know it now
Metabolic Melody
The Number Song
(to the tune of “Everybody Loves Somebody Sometime”)
Copyright © Kevin Ahern
Avogadro’s number is a huge one
Boltzmann's constant's rather miniscule
   Values differing enormously
   As WE learned in school

Science numbers need to have dimensions
   Size is not the most important thing
   Units give the yardsticks needed
       For under-STAN-ding

   Bridge
       It’s taught in the ivory towers
       By professors it's so ballyhooed
       Values can have such diff’rent powers
That to know them we must have their magnitudes
The Number Song
(to the tune of “Everybody Loves Somebody Sometime”)
Copyright © Kevin Ahern

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Bridge
It’s taught in the ivory towers
By professors it's so ballyhood
Values can have such diff’rent powers
That to know them we must have their magnitudes

One light year’s a really lengthy distance
Grams define the masses high and low
The ohm can measure the resistance
If current should flow

Bridge
One set of factors you SHOULD know
The roots of seven and of three et al
Cannot be expressed as a ratio
Oh these numbers all are quite irration-al

Three point one four one five nine two six five
No end to Pi’s digits it’s absurd
Endlessly reminding me that I’ve
BEEN SO OUT-num-bered