

Chapter 2 Lecture

Water: The solvent of Biochemistry

⇒ Slide 1

⇒ Slide 2

1) Water Properties important to biology

a. Most abundant substance in living systems

→ 70% or more of the weight of most organisms

b. ^{Contributes} Important to the structure and function of biomolecules

→ Attractive forces between water molecules

→ " " with other molecules

→ Tendency to ionize

• Attractive forces with ions

2) Structure of water

Recall the ~~best~~ molecular bonding models:

a. Lewis Theory

b. Valence shell electron pair repulsion (VSEPR)

c. Valence bond theory (VBT)

⇒ Slide 3

H₂O Valence e⁻: 8 (Lewis Theory)



Central Atom O (Row 2 element): sp³ hybrid orbital

Four e⁻ group: Tetrahedral orbital geometry (VSEPR)

Two lone pairs: Bent molecular geometry

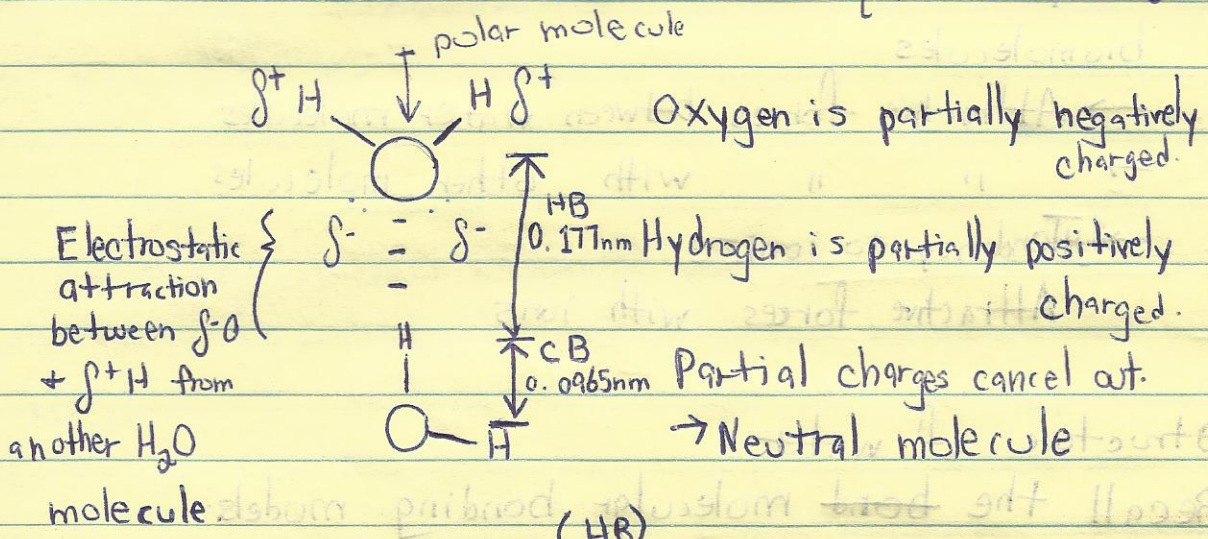
O (Row 2 element): sp³ hybrid orbital (VBT)
H-O-H angle: 104.5° otherwise would be 109.5°

3. Weak interactions in Aqueous solutions

- Many interactions in water are generally weak but collectively play a significant role in the 3D structure of biomolecules.

a. Hydrogen Bonding

- One of the most important properties of water.
- Gives it internal cohesion.
- Arises from the electronegativity differences of the atoms. O More EN than H. Unequal distribution of e⁻ density.



- This is called a Hydrogen bond (HB). It is NOT a covalent bond (CB). Only 10% covalent, 90% electrostatic.

~~O-H HB is longer than~~

Bond	Bond Dissociation Energy (kJ/mol)
O-H (hydrogen bond)	23
O-H (covalent bond)	470

Recall the longer a bond is, the weaker it is.

- Water molecules form HB with as many as four neighboring water molecules.

- HB with polar solutes

in these solutes
HB can exist between



⇒ Slide 5

Typically does not occur between ~~H-C~~ in H-C bonds.



very weakly polar

(EXTRA CREDIT: E-mail me an example of C-H HB)

- HB extremely important between biomolecules

⇒ Slide 5

- HB is strongest when the bonded molecules are oriented to maximize electrostatic interaction. ⇒ Slide 5

→ Straight line between two atoms sharing O.

→ Highly directional + confers specific geometric

~~Polar molecules dissolve in water.~~ arrangement, which is important to the 3D structure of biomolecules.

II. Ionic compounds are soluble in water

- Water dissolves NaCl by stabilizing ~~and~~ the

⇒ Slide 6 Na⁺ + Cl⁻ ions and weakening their electrostatic

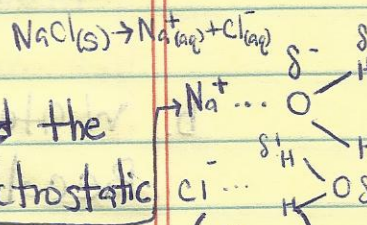
interactions. Breaking the NaCl crystal lattice is thermodynamically ($\Delta G < 0$)

- It does the same with charged biomolecules

- A measure of a solvent's ability to screen the electrostatic interactions between ions is the dielectric constant (ϵ)

$$F = \frac{Q_1 Q_2}{\epsilon r^2}$$

F = force of ionic interactions, Q = Magnitude of charges
r = distance between ions.



Solvent	ϵ
H ₂ O	78.5
Benzene	4.6

III. Nonpolar molecules are poorly soluble in water

⇒ Slide 7

- Three biologically important gases CO₂, O₂, + N₂ are nonpolar.
- The movement of ~~gases~~ molecules from disordered gas phase into aqueous solution → decrease in entropy.
 - Contributes to poor solubility
- O₂ is very poorly soluble in blood ($\frac{0.03 \text{ mL O}_2}{\text{L blood} \times \text{mmHg}}$)
 - The protein hemoglobin binds O₂, increasing its solubility, + facilitates its transport.

- When a nonpolar solvent mixes with water

→ Two phases form depending on solvent density

→ Interactions with these solvents would interfere

with the hydrogen bonding among water molecules

that are not compensated for as when ionic compounds dissolve and form new solute-water interactions

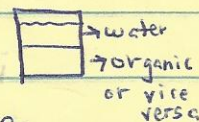
→ Enthalpy increases for HB breaking

→ Entropy decreases because water molecules near

nonpolar ~~solute~~ ^{solute} molecules will have constrained orientations

Form cage-like shells around each solute molecule

→ $\Delta G > 0$; not favorable



- A clathrate is a crystalline compound of nonpolar solutes + water

III. The interaction of amphipathic compounds with water

- Amphipathic compounds contain regions that are polar (or charged) and regions that are nonpolar.

- The hydrophilic region interacts favorably with the solvent

- The nonpolar regions avoid contact. They cluster together to present the smallest hydrophobic area to the aqueous solvent

- The polar regions are arranged to maximize their interaction with the solvent. Hydrophobic interactions stabilize these nonpolar regions.

⇒ Slide 8

- The result is stable structures of amphipathic compounds in water called micelles.

→ May contain hundreds or thousands of molecules.

- The example of amphipathic molecules gives insight into the ^{intricate} structures that biomolecules take form.

⇒ Slide 9 Examples of different types of biomolecules.

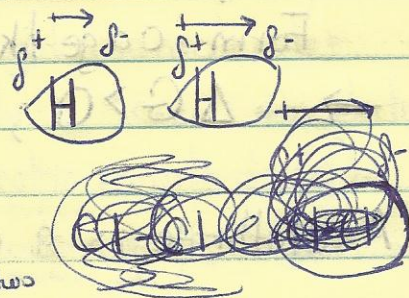
Polar, nonpolar, amphipathic

⊙ c. Van der Waals interactions

- Weak interatomic attractions

- Induced dipole moment

- Two dipoles will weakly attract bringing two nuclei together without bonding.



8

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⇒ Slide 10

Van der Waals radii are significantly longer than covalent radii ∴ weaker

- London forces are molecular Van der Waals interactions $\delta^+ \delta^-$
Cl-Cl

10
d. Summary of weak but important noncovalent interactions in water

⇒ Noncovalent interactions are generally significantly weaker than covalent ones.

⇒ Slide 11

- a. Hydrogen bonds
- b. Ionic interactions
- c. Hydrophobic interactions
- d. Van der Waals

- HOWEVER, the cumulative effect of many such interactions can be very significant.
- The noncovalent interaction of a small molecule to its macromolecular partner may involve numerous H Bonds, ionic, hydrophobic, & van der Waals interactions.

4. Solutes affect the colligative Properties of Aqueous solutions

- solutes of all kinds alter certain physical properties of the solvent, water: vapor pressure, boiling point, melting point (freezing point), and osmotic pressure.

- These are called colligative properties because the effect of solutes on all four properties has the same basis: the concentration of water is lower in solutions than in pure water.

- Effect is independent of the chemical properties of the solutes.

⇒ Slide 12

(tendency of water molecules to escape to vapor phase)

a. Vapor pressure is lowered because @ surface there is less water

b. Boiling point increases, correspondingly.

c. Freezing point decreases → Movement from aqueous phase to gas phase is interfered by the presence of solute. Less tendency to crystallize

d. Osmotic pressure changes; increases when concentrations of ions ↑.

- Water molecules tend to move from a region of higher water concentration to one of lower water concentration, a process called osmosis.

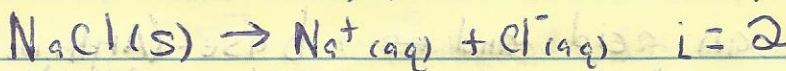
- When two different aqueous solutions are separated by a semi permeable membrane (allows only passage of water) water will diffuse into the region of lower concentration (Slide 12).

- Osmotic pressure, π , measured as the force necessary to resist water movement is represented by van't Hoff eq.

$$\pi = icRT$$

i is osmolarity of the solution, R is gas constant, T is Abs. Temp.

van't Hoff factor; i , is the # of ions produced by an ionic compound.



c : [solute]

@ 0.1M NaCl ; $i_c = 0.2M$

$\uparrow i, \uparrow \Pi; \uparrow c, \uparrow \Pi$

\therefore Osmosis is driven by differences in osmotic pressure.

- Solutions of equal osmolarity are isotonic

cells experience osmosis.

\rightarrow Cells surrounded by isotonic solution, neither gain nor lose water.

\rightarrow In a hypertonic solution (higher osmolarity than cytosol), the cell shrinks.

\rightarrow In a hypotonic solution (lower osmolarity), the cell swells.

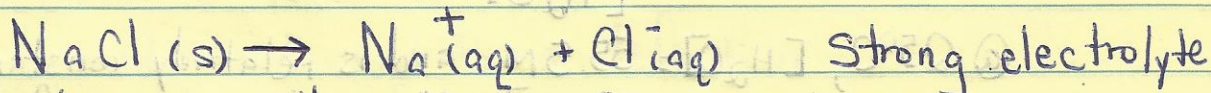
- Several mechanisms have evolved to prevent osmotic lysis of the cell due to swelling. In general, cells tend to have higher [biomolecules] + [ions] than surroundings.

\rightarrow cell membrane helps to control the flow of ions into + out of cells.

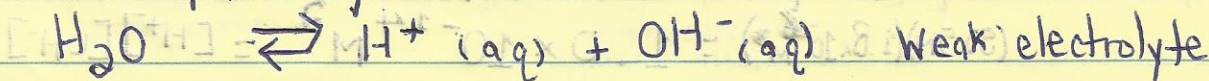
- Small molecules tend to have a larger effect on osmolarity than macromolecules as Π depends on $[C]$.

5. Ionization of water

- Recall, ionic compounds ionize completely in water



A. Water partially ionizes



H_2O is in equilibrium with H^+ + OH^- ions.
 \therefore Serves as both an acid and as a base. (Arrhenius acid + base)

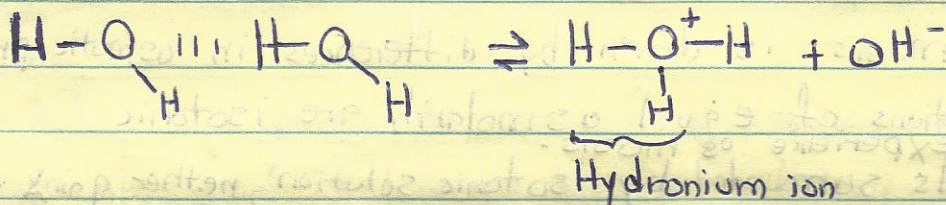
form H^+

forms OH^-

In actuality, the free H^+ does not exist in solution.

Rather

Brønsted Acid + Base



This is called "proton hopping" and results in high ionic mobility as a series of proton hops occur between hydrogen-bonded water molecules.

\Rightarrow slide 13

- This accounts for the rapid acid-base reactions in aqueous solutions. \rightarrow Important for biological proton transfer reactions.

B. Equilibrium constant, K_{eq}



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

Water ionization:

$$K_{eq} = \frac{[H^+][OH^-]}{[H_2O]}$$

@ $25^\circ C$, $[H_2O] = 55.5 M$ and is relatively constant

$$(55.5) K_{eq} = [H^+][OH^-] = K_w \text{ ion product of water}$$

$$(55.5)(1.8 \times 10^{-16} M^2) = 1.0 \times 10^{-14} M^2 = [H^+][OH^-]$$

The product of $[H^+] \times [OH^-]$ always equals this number.

- When $[H^+] \times [OH^-]$ equal, the solution is at neutral pH

$[H^+] = [OH^-] = 10^{-7} M$

C. pH Scale designates $[H^+] \times [OH^-]$

$\log \frac{1}{[H^+]} = -\log [H^+]$

$\uparrow [H^+] \downarrow pH$ $pH = -\log [H^+]$; Similarly $pOH = -\log [OH^-]$

@ $[H^+] = [OH^-]$

$pH = 7$

- pH scale is logarithmic. (Refer to Table 2-6)

When ~~one~~ two solutions differ in pH by 1 pH unit, one solution has $10 \times [H^+]$ of the other.

- If given $[OH^-]$, use $K_w = [H^+][OH^-]$ to determine $[H^+]$.

\Rightarrow Slide 14 shows the pH of some aqueous fluids.

- The pH of fluids affects the structure and activity of biological macromolecules

\rightarrow Catalytic activity of enzymes is highly sensitive to pH

- pH of normal blood is 7.4

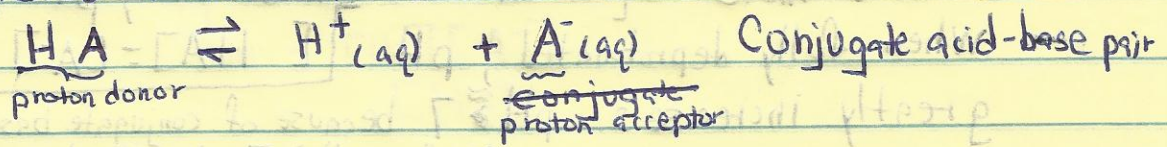
but of severely diabetic people, often below 7.4 \Rightarrow acidosis

- pH levels thus can represent a disease state

6. Weak acids and bases

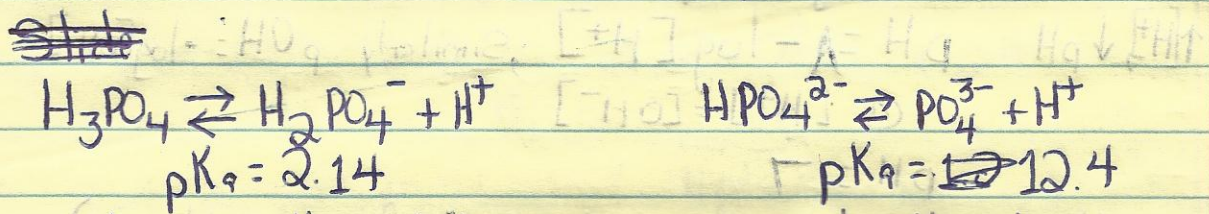
- Related to weak ionization

A-Bronsted Acid and base definition



B. $K_{eq} = \frac{[H^+][A^-]}{[HA]} = K_a$ dissociation constants
 $\uparrow K_a$, the stronger the acid, $\downarrow pK_a$

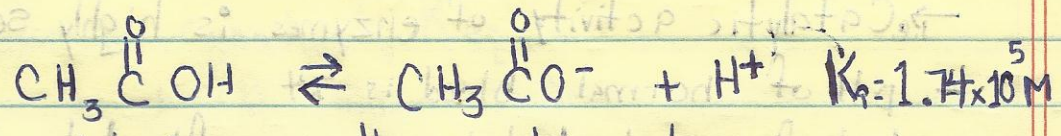
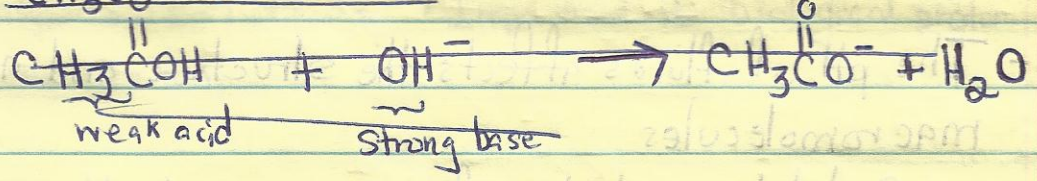
Typically use $pK_a = \log \frac{1}{K_a} = -\log K_a$



Low pH solution High pH solution

\hookrightarrow pK_a values for weak acids can be measured using titration curves

\Rightarrow Slide 15 Titration of CH_3COOH (Acetic Acid)



- Perform titration with a strong base



As you add more + more aliquots of OH^- , CH_3COOH ionizes more to reach a new equilibrium state. Enter a buffering region with gradual change in pH

- @ 0.5 mole equivalent addition of OH^- , $pH = pK_a$

- When fully deprotonated, pH greatly increases. $[HA] = [A^-]$
 $pH \approx 7$ because of conjugate base actually $pH > 7$ slightly basic

D. Biological systems use buffering to control against pH changes

I. Buffers are mixtures of weak acids + their conjugate bases

- Aqueous systems that resist changes in pH when small amounts of H^+ or OH^- are added.

- Weak acids buffer well @ pH values that are 1 pH unit on either side of its pKa value.

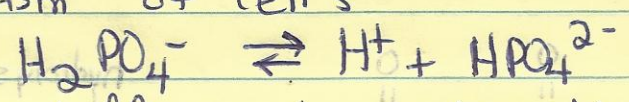
(Recall acetic acid example in slide 15)

- Buffering results from two reversible reaction equilibria occurring in a solution of nearly equal concentration of HA + A^- (conjugate acid, base pair)

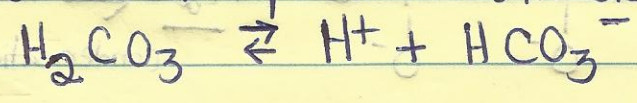
⇒ Slide 16 Buffering by acetic acid.

- Each conjugate acid-base pair has a characteristic pH zone in which it is an effective buffer.

i.e. Phosphate buffer system acts in the cytoplasm of cells



Bicarbonate buffer system acts in blood plasma



II. Simple expression for buffer concentration

$$K_a = \frac{[H^+][A^-]}{[HA]}$$

$$[H^+] = K_a \frac{[HA]}{[A^-]}$$

$$-\log[H^+] = -\log K_a - \log\left(\frac{[HA]}{[A^-]}\right)$$

$$pH = pK_a - \log\left(\frac{[HA]}{[A^-]}\right)$$

$$pH = pK_a + \log\left(\frac{[A^-]}{[HA]}\right)$$

$$pH = pK_a + \log \frac{[proton\ acceptor]}{[proton\ donor]}$$

Henderson-Hasselbach equation

if $pH > pK_a$; $[PA] > [PD]$ $pH < pK_a$; $[PA] < [PD]$

7. Water as a Reactant/Product

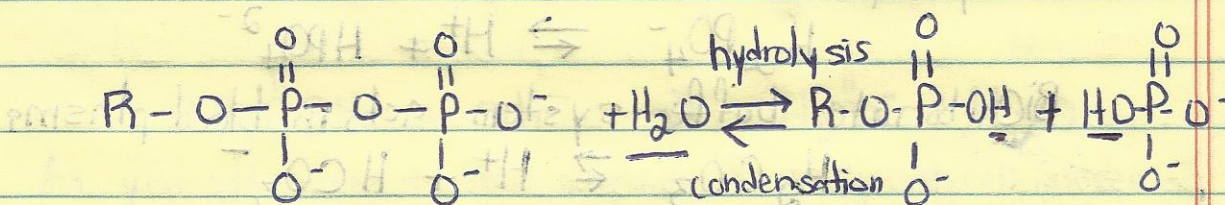
- Water is not just a solvent but also ^{participates} ~~reactant~~ in biochemical reactions.

Hydrolysis

A. ~~Condensation~~ rxn.

~~The elements of water are eliminated.~~

Clearance accompanied by the addition of water



B. Condensation rxn.

Reverse of ~~cond~~ hydrolysis.

- A product forms resulting in elements of water being eliminated

(15)

Hydrolysis rxns., catalyzed by enzymes called hydrolases, are typically exergonic ($\Delta G < 0$).

∴ The reverse are endergonic but cells overcome this by coupling the process with exergonic processes.

There are many other rxns. in which water plays an active role.