Session Plan

- General Characteristics of Enzymes
- Enzyme Structure
- Enzyme Nomenclature
- Enzyme Function
- Enzyme Specificity
- Factors Affecting Enzyme Activity
- Enzyme Inhibition
- Regulation of Enzyme Activity
- Medical Uses of Enzymes


NOTE: Vitamins are discussed in detail in the Nutrition Modules in your further studies.
General Characteristics of Enzymes

- **ENZYME**
  - Usually a *protein*, acting as *catalyst in specific biochemical reaction*

- Each cell in the human body contains 1,000s of different enzymes
  - Every reaction in the cell requires its own specific enzyme

- Most enzymes are globular proteins
  - A few enzymes are made of RNA
    - Catalyze biochemical reactions involving nucleic acids

- Enzymes undergo all the reactions of proteins
  - Enzymes denaturation due to pH or temperature change
    - A person suffering high fever runs the risk of denaturing certain enzymes

Animation of enzyme at work

http://highered.mheducation.com/sites/0072495855/student_view0/chapter2/animation__how_enzymes_work.html

http://bcs.whfreeman.com/webpub/Ektron/pol1e/Animated%20Tutorials/at0302/at_0302_enzyme_catalysis.html
Enzyme Structure

- **SIMPLE ENZYMES**
  Composed only of protein

- **CONJUGATED ENZYMES**
  Composed of:
  - Apoenzyme
    - Conjugate enzyme without its cofactor
  - Coenzyme (Cofactor)
    - Non-protein part of a conjugated enzyme
  - The apoenzyme can’t catalyze its reaction without its cofactor.
    - The combination of the apoenzyme with the cofactor makes the conjugated enzyme functional.
  - Holoenzyme = apoenzyme + cofactor
    - The biochemically active conjugated enzyme.
Coenzymes and cofactors

• Coenzymes provide additional chemically reactive functional groups besides those present in the amino acids of the apoenzymes
  – Are either small organic molecules or inorganic ions

• Metal ions often act as additional cofactors (Zn$^{2+}$, Mg$^{2+}$, Mn$^{2+}$ & Fe$^{2+}$)
  – A metal ion cofactor can be bound directly to the enzyme or to a coenzyme

• COENZYME
  – A small organic molecule, acting as a cofactor in a conjugated enzyme
    • Coenzymes are derived from vitamins or vitamin derivatives
      – Many vitamins act as coenzymes, esp. B-vitamins
## Enzyme definitions

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enzyme (simple)</td>
<td>Protein only enzyme that facilitates a chemical reaction</td>
</tr>
<tr>
<td>Coenzyme</td>
<td>Compound derived from a vitamin (e.g. NAD&lt;sup&gt;+&lt;/sup&gt;) that assists an enzyme in facilitating a chemical reaction</td>
</tr>
<tr>
<td>Cofactor</td>
<td>Metal ion (e.g. Mg&lt;sup&gt;2+&lt;/sup&gt;) that assists an enzyme in facilitating a chemical reaction</td>
</tr>
<tr>
<td>Apoenzyme</td>
<td>Protein only part of an enzyme (e.g. isocitrate dehydrogenase) that requires an additional coenzyme to facilitate a chemical reaction (not functional alone)</td>
</tr>
<tr>
<td>Holoenzyme</td>
<td>Combination of the apoenzyme and coenzyme which together facilitating a chemical reaction (functional)</td>
</tr>
</tbody>
</table>
Enzyme Nomenclature

Enzymes are named according to the type of reaction they catalyze and/or their substrate.

**Substrate** = the reactant upon which the specific enzyme acts
- Enzyme physically binds to the substrate

- **Suffix of an enzyme** – *ase
  - Lactase, amylase, lipase or protease
    - Denotes an enzyme

- Some digestive enzymes have the suffix –*in
  - Pepsin, trypsin & chymotrypsin
    - These enzymes were the first ones to be studied

- **Prefix** denotes the type of reaction the enzyme catalyzes
  - Oxidase: redox reaction
  - Hydrolase: Addition of water to break one component into two parts

- **Substrate identity** is often used together with the reaction type
  - Pyruvate carboxylase, lactate dehydrogenase
<table>
<thead>
<tr>
<th>Enzyme Class</th>
<th>Reaction Catalyzed</th>
<th>Examples in Metabolism</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Oxidoreductase</strong></td>
<td>Redox reaction (reduction &amp; oxidation)</td>
<td>Examples are dehydrogenases which catalyse reactions in which a substrate is oxidised or reduced</td>
</tr>
<tr>
<td><strong>Transferase</strong></td>
<td>Transfer of a functional group from 1 molecule to another</td>
<td>Transaminases which catalyze the transfer of amino group or kinases which catalyze the transfer of phosphate groups.</td>
</tr>
<tr>
<td><strong>Hydrolase</strong></td>
<td>Hydrolysis reaction</td>
<td>Lipases catalyze the hydrolysis of lipids, and proteases catalyze the hydrolysis of proteins</td>
</tr>
<tr>
<td><strong>Lyase</strong></td>
<td>Addition / removal of atoms to / from double bond</td>
<td>Decarboxylases catalyze the removal of carboxyl groups</td>
</tr>
<tr>
<td><strong>Isomerase</strong></td>
<td>Isomerization reaction</td>
<td>Isomerases may catalyze the conversion of an aldose to a ketose, and mutases transfer functional group from one atom to another within a substrate.</td>
</tr>
<tr>
<td><strong>Ligase</strong></td>
<td>Synthesis reaction (Joining of 2 molecules into one, forming a new chemical bond, coupled with ATP hydrolysis)</td>
<td>Synthetases link two smaller molecules are form a larger one.</td>
</tr>
</tbody>
</table>

The table explains the functions of enzymes and how they are classified and named.
Enzyme Active Site

- **Active site**
  - The specific portion of an enzyme (location) where the substrate binds while it undergoes a chemical reaction

- The active site is a 3-D ‘crevice-like’ cavity formed by secondary & tertiary structures of the protein part of the enzyme
  - Crevice formed from the folding of the protein
    - Aka binding cleft
  - An enzyme can have more than only one active site
  - The amino acids R-groups (side chain) in the active site are important for determining the specificity of the substrate

Stoker 2014, Figure 21-2 p750
Enzyme – Substrate Complex

- When the substrate binds to the enzyme active site an **Enzyme-Substrate Complex** is formed temporarily
  - Allows the substrate to undergo its chemical reaction much faster
Lock & Key Model of Enzyme Action

- The active site is fixed, with a rigid shape (LOCK)
- The substrate (KEY) must fit exactly into the rigid enzyme (LOCK)
- Complementary shape & geometry between enzyme and substrate
  - Key (substrate) fits into the lock (enzyme)
- Upon completion of the chemical reaction, the products are released from the active site, so the next substrate molecule can bind

Stoker 2014, Figure 21-3 p750
Induced Fit Model of Enzyme Action

• Many enzymes are flexible & constantly change their shape
  – The shape of the active site changes to accept & accommodate the substrate
    • Conformation change in the enzyme’s active site to allow the substrate to bind
  • Analogy: a glove (enzyme) changes shape when a hand (substrate) is inserted into it
Enzyme Specificity

• Absolute Specificity
  – An enzyme will catalyze a particular reaction for only one substrate
  – Most restrictive of all specificities
    • Not common
      – **Catalase** has absolute specificity for hydrogen peroxide ($H_2O_2$)
      – **Urease** catalyzes only the hydrolysis of urea

• Group Specificity
  – The enzyme will act only on similar substrates that have a specific functional group
    • **Carboxypeptidase** cleaves amino acids one at a time from the carboxyl end of the peptide chain
    • **Hexokinase** adds a phosphate group to hexoses
Enzyme Specificity

• **Linkage Specificity**
  – The enzyme will act on a particular type of chemical bond, irrespective of the rest of the molecular structure
  – The most general of the enzyme specificities
    • *Phosphatases* hydrolyze phosphate–ester bonds in all types of phosphate esters
    • *Chymotrypsin* catalyzes the hydrolysis of peptide bonds

• **Stereochemical Specificity**
  – The enzyme can distinguish between stereoisomers
  – Chirality is inherent in an active site (as amino acids are chiral compounds)
    • *L-Amino-acid oxidase* catalyzes reactions of L-amino acids but not of D-amino acids
Factors Affecting Enzyme Activity

Enzyme activity
• Measure of the rate at which an enzyme converts substrate to products in a biochemical reaction

4 factors affect enzyme activity:
• Temperature
• pH
• Substrate concentration: [substrate]
• Enzyme concentration: [enzyme]
Temperature ($t$)

- With increased $t$ the $E_{\text{KIN}}$ increases
  - More collisions
  - Increased reaction rate

- **Optimum temperature** ($t_{\text{OPT}}$) is the $t$, at which the enzyme exhibits maximum activity
  - The $t_{\text{OPT}}$ for human enzymes = 37$^\circ$C

- When the $t$ increases beyond $t_{\text{OPT}}$
  - Changes in the enzyme’s tertiary structure occur, inactivating & denaturing it (e.g. fever)

- Little activity is observed at low $t$
**Optimum pH** ($pH_{OPT}$) is the pH, at which the enzyme exhibits maximum activity.

- Most enzymes are active over a very narrow pH range
  - Protein & amino acids are properly maintained
  - Small changes in pH (low or high) can result in enzyme denaturation & loss of function
- Each enzyme has its characteristic $pH_{OPT}$, which usually falls within physiological pH range 7.0 - 7.5

*Digestive enzymes are exceptions:*
- *Pepsin* (in stomach) – $pH_{OPT} = 2.0$
- *Trypsin* (in SI) – $pH_{OPT} = 8.0$
Substrate Concentration

• If [enzyme] is kept constant & the [substrate] is increased
  – The reaction rate increases until a \textit{saturation point} is met
    • At saturation the reaction rate stays the same even if the [substrate] is increased

  – At \textit{saturation point} substrate molecules are bound to all available active sites of the enzyme molecules

• Reaction takes place at the active site
  – If they are all active sites are occupied the reaction is going at its maximum rate
    • Each enzyme molecule is working at its maximum capacity

  – The incoming substrate molecules must “wait their turn”
Enzyme Concentration

- If the [substrate] is kept constant & the [enzyme] is increased
  - The reaction rate increases
  - The greater the [enzyme], the greater the reaction rate

- **RULE:**
  - The rate of an enzyme-catalyzed reaction is always directly proportional to the amount of the enzyme present

- **In a living cell:**
  - The [substrate] is much higher than the [enzyme]
    - Enzymes are not consumed in the reaction
    - Enzymes can be reused many times
THE MECHANISM OF ENZYME ACTION
Formation of an enzyme–substrate complex as an intermediate species provides an alternative pathway, with lower activation energy, through which a reaction can occur.

Lock-and-Key Model
The active site has a fixed geometric shape. Only a substrate with a matching shape can fit into it.

Substrate
Enzyme active site

Induced-Fit Model
The active site has a flexible shape that can change to accept a variety of related substrates. Enzymes vary in their degree of specificity for substrates.

Substrates
Enzyme active site

FACTORS THAT AFFECT THE RATE OF ENZYME ACTIVITY

Temperature
Reaction rate increases with temperature until the point at which the protein is denatured and activity drops sharply.

pH
Maximum enzymatic activity is possible only within a narrow pH range; outside this pH range, the protein is denatured and activity drops sharply.

Concentration of Substrate
Reaction rate increases with substrate concentration until full saturation occurs; then the rate levels off.

Concentration of Enzyme
Reaction rate increases with increasing enzyme concentration, assuming enzyme concentration is much lower than that of substrate.
What is the function of an enzyme in a chemical reaction?

What happens to the enzymes when the body temperature rises from 37°C to 42°C?

If an enzyme has broken down and is non-functional, would the chemical reaction that the enzyme normally assists take place? Explain.
Concept: Enzymes facilitate chemical reactions
Context: Each chemical reaction that takes place in the body uses an enzyme catalyst. Enzymes make it easier for chemical reactions to occur, where reactants are converted into products.

Question: Which of the following accurately describes how an enzyme allows chemical reactions to occur more often than without an enzyme?

a) The reaction will occur more often when an enzyme is present, as the amount of energy needed to begin the reaction (activation energy) is reduced

b) When an enzyme is present there is less energy available, so the reactants move more slowly and collide to form the products

c) When an enzyme is present there is more energy available, so the reactants move more quickly and collide to form the products

d) An enzyme will increase the concentration of the reactants involved in the chemical reaction, thereby increasing the likelihood that the reactants will be converted into products
Concept: Enzymes at high temperature

Context: The temperature of the human body is maintained at about 37°C. An increase in the temperature of the body to above 40°C lead to the breakdown of some of the enzymes. We rely on enzymes for many processes including to generate cellular energy (ATP) through metabolic reactions.

Question: Which of the following best explains what happens to the enzymes in the human body at temperatures above 40°C?

a) The enzymes of the human body can function equally well at 37°C and 40°C

b) While some of the enzymes will breakdown, the function of other enzymes will be enhanced by the high temperature

c) Even after enzymes have broken down they can still facilitate chemical reactions

d) Prolonged exposure to 40°C will see more and more of the enzymes breakdown, compromising the body’s ability to perform chemical reactions
Enzyme Inhibition

- **ENZYME INHIBITOR**
  - A substance that slows down or stops the normal catalytic function of an enzyme by binding to the enzyme

- *Three types of inhibition:*
  - Reversible competitive inhibition
  - Reversible non-competitive inhibition
  - Irreversible inhibition
Reversible Competitive Inhibition

- A *competitive inhibitor* resembles the substrate
  - Inhibitor competes with the substrate for binding to the active site of the enzyme
  - If an inhibitor is bound to the active site:
    - Prevents the substrate molecules to access the active site
      - Decreasing / stopping enzyme activity

- The binding of the competitive inhibitor to the active site is a reversible process
  - Add much more substrate to outcompete the competitive inhibitor

- Many drugs are competitive inhibitors:
  - Anti-histamines inhibit *histidine decarboxylase*, which converts histidine to histamine

Stoker 2014, Figure 21-11 p758
Reversible Noncompetitive Inhibition

- A non-competitive inhibitor decreases enzyme activity by binding to a site on the enzyme other than the active site
  - The non-competitive inhibitor alters the tertiary structure of the enzyme & the active site
    - Decreasing enzyme activity
    - Substrate cannot fit into active site
  - Process can be reversed only by lowering the [non-competitive inhibitor]
- Example:
  - Heavy metals Pb^{2+} & Hg^{2+} bind to −SH of Cysteine, away from active site
    - Disrupt the secondary & tertiary structure

Stoker 2004, Figure 21.11, p.634
Stoker 2004, Figure 21.12, p.634
Irreversible Inhibition

- An irreversible inhibitor inactivates an enzyme by binding to its active site by a strong covalent bond
  - Permanently deactivates the enzyme
  - Irreversible inhibitors do not resemble substrates

- Addition of excess substrate doesn’t reverse this process
  - Cannot be reversed

- Chemical warfare (nerve gases)

- Organophosphate insecticides
**ENZYME INHIBITORS**

Substances that bind to an enzyme and stop or slow its normal catalytic activity.

**Competitive Enzyme Inhibitor**
A molecule closely resembling the substrate. Binds to the active site and temporarily prevents substrates from occupying it, thus blocking the reaction.

**Noncompetitive Enzyme Inhibitor**
A molecule that binds to a site on an enzyme that is not the active site. The normal substrate still occupies the active site but the enzyme cannot catalyze the reaction due to the presence of the inhibitor.

**Irreversible Enzyme Inhibitor**
A molecule that forms a covalent bond to a part of the active site, permanently preventing substrates from occupying it.

Stoker 2014, p760
Allosteric Enzymes

- Allosteric enzymes have a quaternary structure
  - Are composed of 2 or more protein chains
  - Possess 2 or more binding sites

- **2 types of binding sites:**
  - One binding site for the substrate
    - Active site
  - Second binding site for a regulator molecule
    - Regulatory site

- Active & regulatory binding sites are distinct from each other in shape & location

- Binding of a regulator molecule to its regulatory site causes changes in 3-D structure of the enzyme & the active site
  - Binding of a **Positive regulator** up-regulates enzyme activity
    - Enhances active site, more able to accept substrate
  - Binding of a **Negative regulator** (non-competitive inhibitor) down-regulates enzyme activity
    - Compromises active site, less able to accept substrate
The different effects of Positive & Negative regulators on an Allosteric enzyme

Stoker 2014, Figure 21-13 p762
Feedback Control

- A process in which activation or inhibition of one of the earlier reaction steps in a reaction sequence is controlled by a product of this reaction sequence.
  - One of the mechanisms in which allostERIC enzymes are regulated
  - Most biochemical processes proceed in several steps & each step is catalyzed by a different enzyme
    - The product of each step is the substrate for the next step / enzyme.

Observe animation of feedback control


Example:
The degradation of glucose through a metabolic pathway can be regulated in several ways

The enzyme PFK is allosterically inhibited by the product ATP

Glycolysis (makes ATP) is slowed when cellular ATP is in excess

Feedback control

Inhibition of enzyme 1 by product D

ReactiON 1: converts reagent A into product B

ReactiON 2: converts reagent B into product C

ReactiON 3: converts reagent C into product D
Proteolytic Enzymes & Zymogens

- 2nd mechanism of allosteric enzyme regulation
  - Production of an enzyme in an inactive form
  - Activated when required (right time & place)
    - Activated aka "turned on"

- **Proteolytic enzymes** catalyze breaking of peptide bond in proteins
  - To prevent these enzymes from destroying the tissues, that produced them, they are released in an inactive form = ZYMOGENS

- Most digestive & blood-clotting enzymes are proteolytic
  - Blood clotting enzymes break down proteins within the blood so that they can form the clot
    - Platelets interspersed with tangled protein (collagen and thrombin)

- Activation of a zymogen requires the removal of a peptide fragment from the zymogen structure
  - Changing the 3-D shape & affecting the active site
    - E.g. Pepsiongen (zymogen)
      - >>> Pepsin (active proteolytic enzyme)
Activation of a Zymogen

- Zymogen (inactive form of a proteolytic enzyme)
- Activation
- Peptide fragment to be removed
- Proteolytic enzyme (an active enzyme)

Stoker 2014, Figure 21-14 p763
Covalent Modification of Enzymes

- Covalent modifications are the 3rd mechanism of enzyme activity regulation
  - A process of altering enzyme activity by covalently modifying the structure of the enzyme
    - Adding / removing a group to / from the enzyme

- Most common covalent modification = addition & removal of phosphate group:
  - Phosphate group is often derived from an ATP molecule
    - Addition of phosphate = phosphorylation is catalyzed by a Kinase enzyme
    - Removal of phosphate = dephosphorylation is catalyzed by a Phosphatase enzyme
  - **Glycogen synthase**: involved in synthesis of glycogen
    - Deactivated by phosphorylation
  - **Glycogen phosphorylase**: involved in breakdown of glycogen
    - Activated by phosphorylation.
Vitamins as Coenzymes

- Many enzymes require B vitamins as coenzymes
  - Allow the enzyme to function

- Coenzymes serve as temporary carriers of atoms or functional groups
  - Coenzymes provide chemical reactivity that the apoenzyme lacks
  - Important in metabolism reactions to release energy from foods
    - E.g. redox reactions where they facilitate oxidation or reduction

- B vitamins don’t remain permanently bonded to the apoenzyme
  - After the catalytic action the vitamin is released & can be repeatedly used by various enzymes
  - This recycling reduces the need for large amounts of B vitamins

Stoker 2014, Figure 21-20 p779
Participation+

Key concept: sites with enzymes, coenzymes

Why is the enzyme’s active site important to the function of the enzyme?

Why is the enzyme’s regulatory binding site important for controlling the activity of the enzyme?

Why are coenzymes that are derived from vitamins important to the function of some enzymes (apoenzymes)?
Concept: **Active site of an enzyme**

Context: Allosteric enzymes contain two sites where components can bind, the active site and the regulatory site. The substrate (reactant) binds to an enzyme to assist its conversion into a product.

Question: Which component binds to the active site of the enzyme & why?

a) Multiple substrates will bind to the enzyme’s active site simultaneously, allowing substrate to be converted into product quickly

b) Another component not involved in the chemical reaction such as ADP will bind to the enzyme’s active site to facilitate the conversion of reactant into product

c) A single substrate binds to the enzyme’s active site, facilitating the conversion of the substrate into product

d) The product of the reaction will bind to the enzyme’s active site at the beginning of the chemical reaction, which aids the production of more product from the remaining substrate
Concept: Regulatory site of an enzyme

Context: Allosteric enzymes contain two sites where components can bind, the active site and the regulatory site. The substrate (reactant) binds to an enzyme to assist its conversion into a product.

Question: Which component would bind to the regulatory site of the enzyme & why?

a) The enzyme’s regulatory site will bind both substrate or product compounds so that the chemical reaction will take place.

b) The enzyme’s regulatory site is usually empty unless the enzyme is not required anymore and it will bind to a component that breaks down the enzyme.

c) The enzyme’s regulatory site can bind to substrates which allow the substrate to be converted into product through the process of the chemical reaction.

d) The enzyme’s regulatory site will bind components that will either enhance or decrease the enzyme’s capacity to facilitate the chemical reaction in order to regulate how often the chemical reaction occurs.
Concept: Role of coenzymes in chemical reactions
Context: Many metabolic processes are reliant on coenzymes that are synthesised from B vitamins. For example, the NAD$^+$ and FAD coenzymes are needed for the citric acid cycle. Coenzymes are used in combination with an apoenzyme (protein part of the enzyme) to facilitate a specific chemical reaction.

Question: What does the coenzyme provide to help the chemical reaction take place?

a) The coenzyme stabilises the apoenzyme, so that the apoenzyme can be used again and again to facilitate the chemical reaction

b) The coenzyme provides chemical reactivity (that the apoenzyme does not provide), such as the capacity to engage the substrate in a redox reaction which are often used in metabolism

c) The coenzyme functions as a tag to show the apoenzyme that the substrate is ready to be converted to the product in the chemical reaction

d) The coenzyme prevents the apoenzyme from causing oxidative damage to the body
Drugs Inhibiting Enzyme Activity

• Many prescription drugs inhibit enzymes

• ACE Inhibitors
  – Inhibit Angiotensin-Converting Enzyme
    • Lowers blood pressure

• Sulfa drugs
  – Antibiotics acting as competitive inhibitors of bacterial enzymes
    • Involved in conversion of PABA to Folic acid
      – Deficiency of folic acid retards bacterial growth, eventually killing them

• Penicillin's
  – β-lactam antibiotics inhibit transpeptidase
    • Transpeptidase enzyme strengthens the cell wall
      – Forms peptide cross links between polysaccharides strands in bacterial cell walls
      – Without transpeptidase enzyme (inhibited by Penicillin) >>> weakened cell wall, bacteria dies
Medical Uses of Enzymes

• Enzymes can be used in diagnosis & treatment of certain diseases

• *Lactate dehydrogenase (LDH)* is normally not found in high levels in blood, as it is produced in cells
  - Increased levels of LDH in the blood indicate myocardial infarction (MI) (Heart attack)

  • Tissue plasminogen activator (TPA) activates the enzyme *plasminogen* that dissolves blood clots
    • Used in the treatment of MI

• There is no direct test to measure urea in the blood
  - *Urease* converts urea into ammonia, which is easily measured & is used as urea indicator
    • Blood Urea Nitrogen (BUN) is used to measure kidney function
  - High urea levels in the blood indicate kidney malfunction
Isoenzymes

- Isoenzyme catalyze the same reaction in different tissues in the body
  - e.g. lactate dehydrogenase (LDH) consists of 5 isoenzymes
    - Each isoenzyme of LDH has the same function
      - Converts lactate to pyruvate
    - LDH₁ isoenzyme is more prevalent in heart muscle
    - LDH₅ form is found in skeletal muscle & liver
  - Isoenzymes can be used to identify the damaged or diseased organ or tissue
    - It is a marker for a particular location
  - If LDH₁ isoenzyme was found in the blood >>> indicates heat muscle damage
<table>
<thead>
<tr>
<th>Enzyme</th>
<th>Condition Indicated by Abnormal Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>lactate dehydrogenase (LDH)</td>
<td>heart disease, liver disease</td>
</tr>
<tr>
<td>creatine phosphokinase (CPK)</td>
<td>heart disease</td>
</tr>
<tr>
<td>aspartate transaminase (AST)</td>
<td>heart disease, liver disease, muscle damage</td>
</tr>
<tr>
<td>alanine transaminase (ALT)</td>
<td>heart disease, liver disease, muscle damage</td>
</tr>
<tr>
<td>gamma-glutamyl transpeptidase (GGTP)</td>
<td>heart disease, liver disease</td>
</tr>
<tr>
<td>alkaline phosphatase (ALP)</td>
<td>bone disease, liver disease</td>
</tr>
</tbody>
</table>

Stoker 2014, Table 21-3 p768
<table>
<thead>
<tr>
<th>B Vitamin</th>
<th>Coenzymes</th>
<th>Groups Transferred</th>
</tr>
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<tbody>
<tr>
<td>thiamin</td>
<td>thiamin pyrophosphate (TPP)</td>
<td>aldehydes</td>
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<tr>
<td></td>
<td>flavin mononucleotide (FMN)</td>
<td>hydrogen atoms</td>
</tr>
<tr>
<td></td>
<td>flavin adenine dinucleotide (FAD)</td>
<td>hydrogen atoms</td>
</tr>
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<td>niacin</td>
<td>nicotinamide adenine dinucleotide (NAD$^+$)</td>
<td>hydrogen atoms</td>
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<tr>
<td></td>
<td>nicotinamide adenine dinucleotide phosphate (NADP$^+$)</td>
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<tr>
<td>pantothenic acid</td>
<td>coenzyme A (CoA)</td>
<td>acyl groups</td>
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<td>vitamin B$_6$</td>
<td>pyridoxal-5-phosphate (PLP)</td>
<td>amino groups</td>
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<td>pyridoxine-5′-phosphate (PNP)</td>
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<td>pyridoxamine-5′-phosphate (PMP)</td>
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<td>biotin</td>
<td>biotin</td>
<td>carbon dioxide (carboxyl group)</td>
</tr>
<tr>
<td>folate</td>
<td>tetrahydrofolate (THF)</td>
<td>one-carbon groups other than CO$_2$</td>
</tr>
<tr>
<td>vitamin B$_{12}$</td>
<td>methylcobalamin</td>
<td>methyl groups, hydrogen atoms</td>
</tr>
</tbody>
</table>

Stoker 2014, Table 21-7 p780
Readings & Resources

• Stoker, HS 2004, *General, Organic and Biological Chemistry*, 3rd edn, Houghton Mifflin, Boston, MA.
• Timberlake, KC 2014, *General, organic, and biological chemistry: structures of life*, 4th edn, Pearson, Boston, MA.