Chapter 3 – Chemical Reactions, Enzymes, and Nucleotides

Objectives

Given the synopsis in this chapter, competence in each objective will be demonstrated by responding to multiple choice, matching, put-in-order, or fill-in questions, at the level of 85% or greater proficiency for each student.

A. To explain the major types of chemical reactions, including the catabolic and anabolic reactions.
B. To explain the role of enzymes and enzyme regulation in chemical reactions, including the catabolic and anabolic reactions.
C. To explain the structure, features and roles of nucleosides, nucleotides, and nucleic acids.

Cells carry out numerous chemical reactions, most of which are enzymatically controlled. Metabolism is the collection of chemical reactions that occur in a cell and all cellular activity and metabolism is fueled by chemical energy.

Types of Chemical Reactions

Chemical reactions can be divided into those that break molecules into smaller fragments and those that can assemble larger molecules.

- **Anabolic** reactions (Synthesis) generally construct larger molecules from smaller molecules and consume energy
- **Catabolic** reactions (Decomposition) generally breakdown larger molecules into smaller molecules and produce energy

Many reactions are reversible and decomposition and synthesis occur simultaneously to varying extents. Sometimes molecules are shuffled around to make new molecules.

There are three major groups of reactions that involve synthesis and decomposition: dehydration synthesis and hydrolysis; phosphorylation and dephosphorylation; and reduction and oxidation.

Dehydration Synthesis and Hydrolysis

One of the most common groups of reactions involves water. In the expressions below, **AOH** represents any molecules containing –OH; **BH** represents any molecule containing –H; **AB** represents A and B joined by chemical bonds.

- **Dehydration synthesis** (Condensation) involves construction of molecules by removing water (anabolic)

$$\underline{A}OH + \underline{B}H \rightarrow \underline{AB} + H_2O$$

- **Hydrolysis** involves breakdown of molecules by adding water (catabolic)

$$\underline{A}B + H_2O \rightarrow \underline{A}OH + \underline{B}H$$

The construction of carbohydrates, glycerides and proteins involve **dehydration synthesis** as shown in Figure 3-1. Furthermore, the breakdown of carbohydrates, glycerides and proteins involve **hydrolysis** as shown in Figure 3-2.

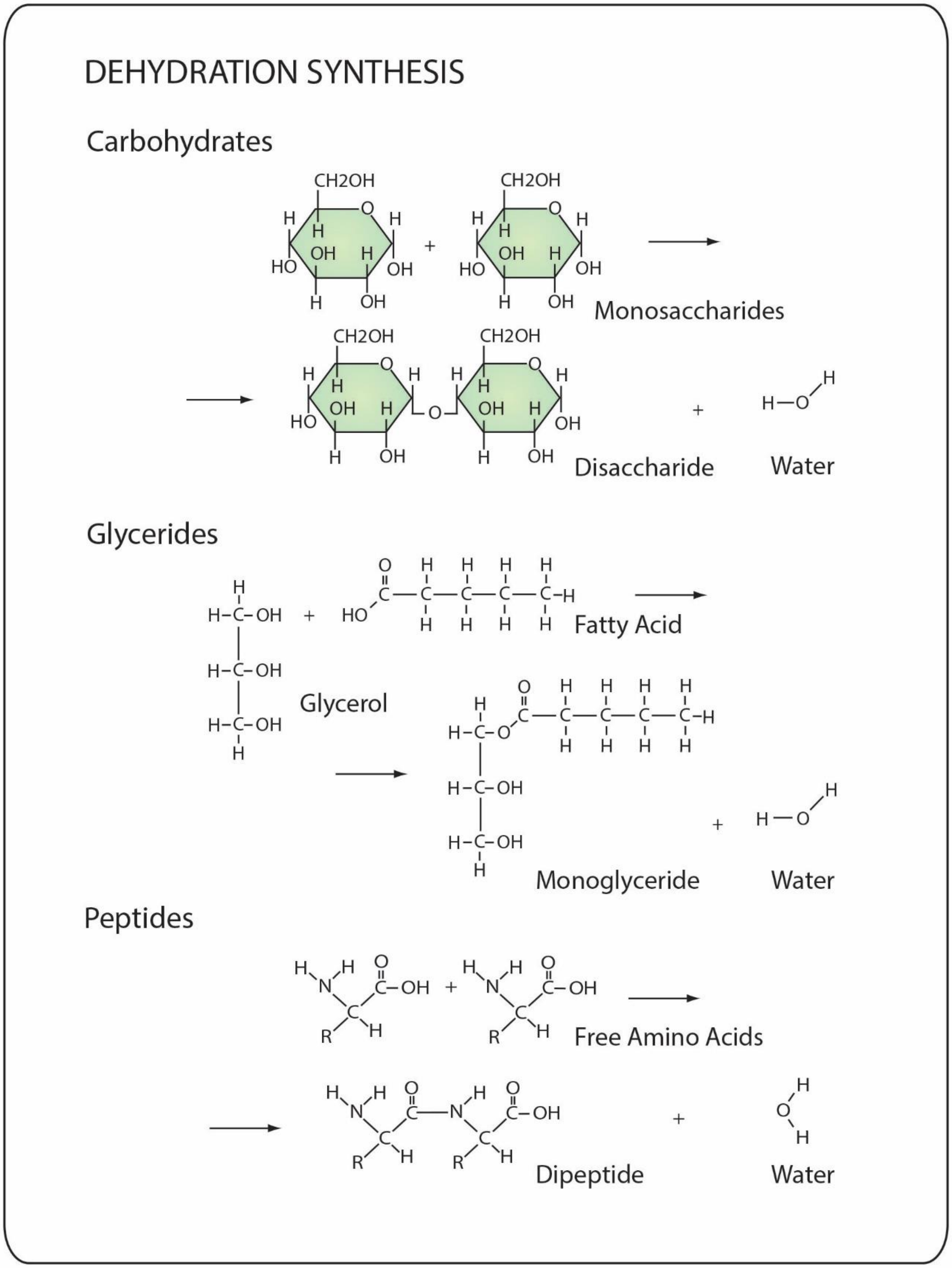

Figure 3-1 © 2018 David G. Ward, PhD

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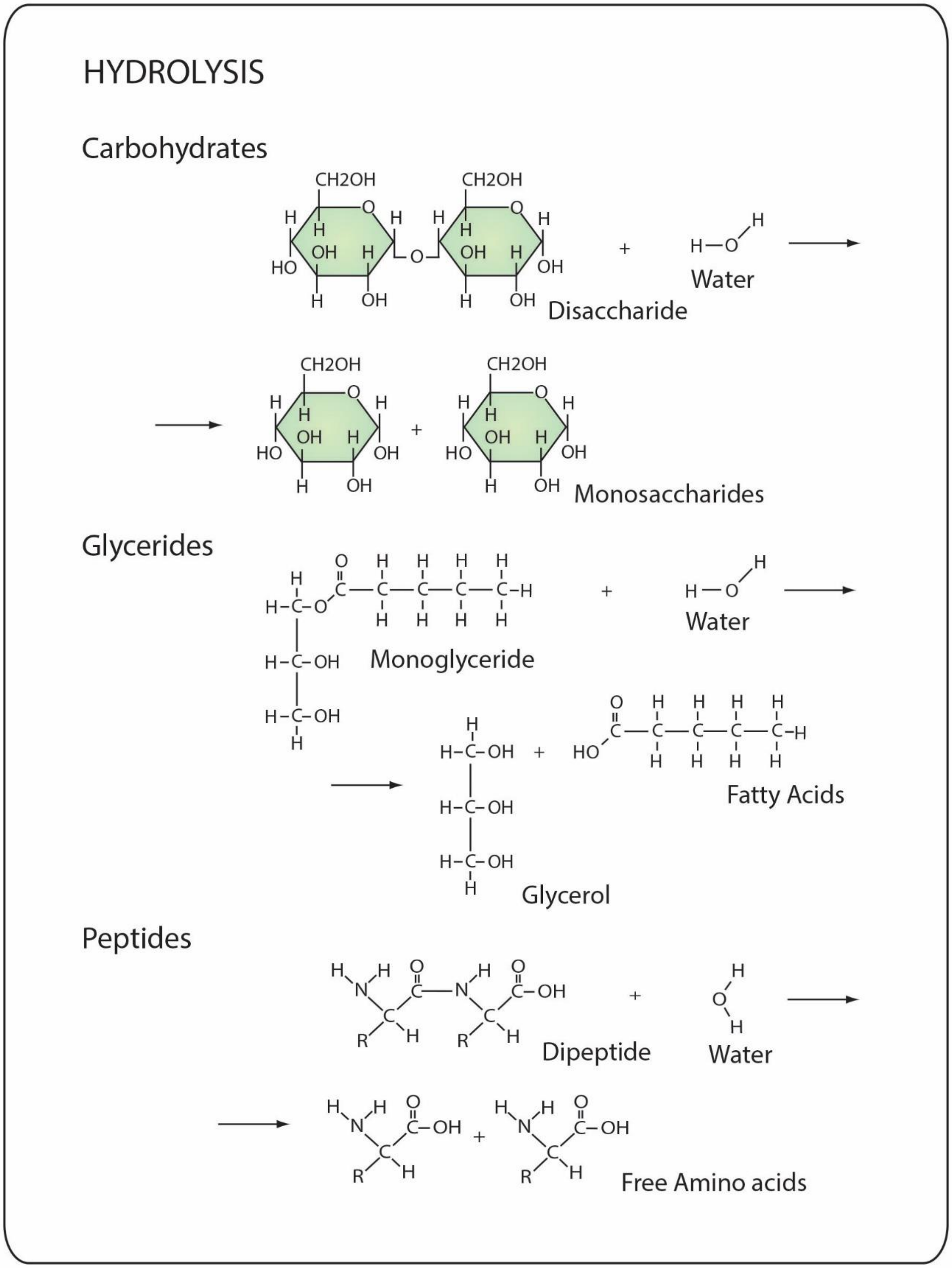

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Phosphorylation and Dephosphorylation

Another critical group of reactions involves the addition or removal of phosphate. In the expressions below, **A** represents any molecule, commonly a protein, which can be phosphorylated. In the expressions below, **P_i** represents any inorganic phosphate.

- **Phosphorylation** involves adding phosphate to a molecule (anabolic), consumes or stores energy and often changes the shape and function of molecules

$$\underline{A} + P_i \rightarrow \underline{A}P_i$$

- **Dephosphorylation** involves removing phosphate from a molecule (catabolic), produces or releases energy and often changes shape and function of molecules.

$$\underline{A}P_i \rightarrow \underline{A} + P_i$$

The addition of phosphates is critical for the formation of the nucleotides, including the high energy compounds ATP and GTP (see Figure 3-8). The addition of phosphates also is critical for many cellular reactions where proteins are phosphorylated to activate or change the **conformation** (shape) of that protein. We will have much more to say about phosphorylation of proteins in subsequent chapters. The addition of phosphates to a protein often involves the removal of a phosphate from a high energy compound such as ATP, leaving ADP, as shown in Figure 3-3.

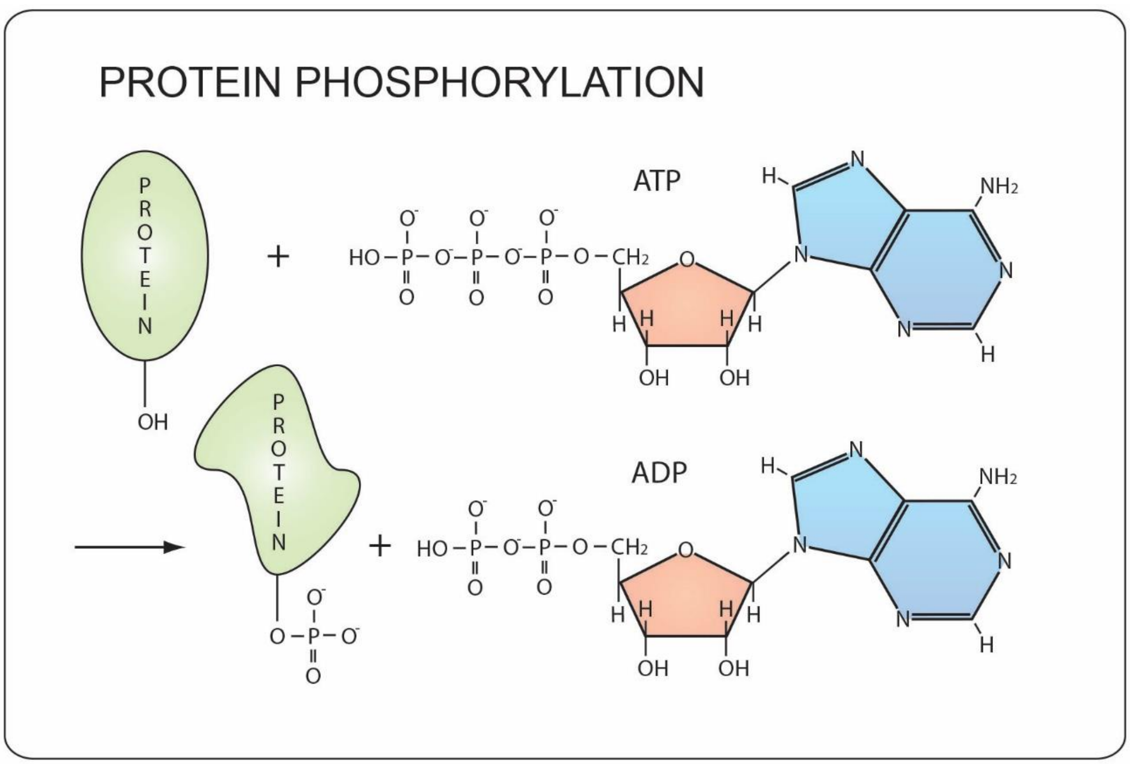


Figure 3-3 © 2018 David G. Ward, PhD

Reduction and Oxidation

A final group of reactions involves the addition or removal of oxygen or electrons.

Using as an example: CuO + Mg → Cu + MgO

- **In terms of Oxygen:**
  - **Reduction** is the removal of oxygen: CuO → Cu
  - **Oxidation** is the addition of oxygen: Mg → MgO
- **In terms of Electrons:**
  - **Reduction** is the addition of electrons: Cu^{2+} → Cu
  - **Oxidation** is the removal of electrons: Mg → Mg^{2+}

The addition of electrons and removal of electrons is critical for many reactions, especially those involved in ATP production from glucose. These are discussed later in chapter 23 and include glycolysis, decarboxylation, the tricarboxylic acid (TCA) cycle, and the electron transport system.

Role of Enzymes in Biochemical Reactions

A chemical reaction involves converting reactant(s) into products. As we have just seen, molecules (reactants) can be linked together to produce a new molecule (product). Conversely, a molecule (reactant) can be split apart to produce new molecules (products).

Substrate 1 + Substrate 2→ Product

Substrate → Product 1 + Product 2

- **Substrate**(s) are the beginning compound(s)
- **Product**(s) are the compound(s) produced by the reaction

When the potential energy of the products is greater than the potential energy of the reactants, the reaction requires energy. The rate of a chemical reaction is determined by several factors. These include the concentration of the reactants and the products, the temperature, and the activation energy.

- The reaction will proceed from highest concentration to lowest concentration (law of mass action)
- Reactions will proceed more rapidly with higher temperature
- When reactants are stable, a certain amount of energy (the activation energy) is necessary to destabilize the reactants and allow a reaction to proceed.
  - By lowering the activation energy, the reaction will proceed more rapidly
  - **Enzymes** lower activation energy

- Most biochemical reactions need to be catalyzed by appropriate enzymes
  - Most enzymes are proteins made of amino acids
  - A smaller number of enzymes (ribozymes) are RNA molecules made of RNA nucleotides

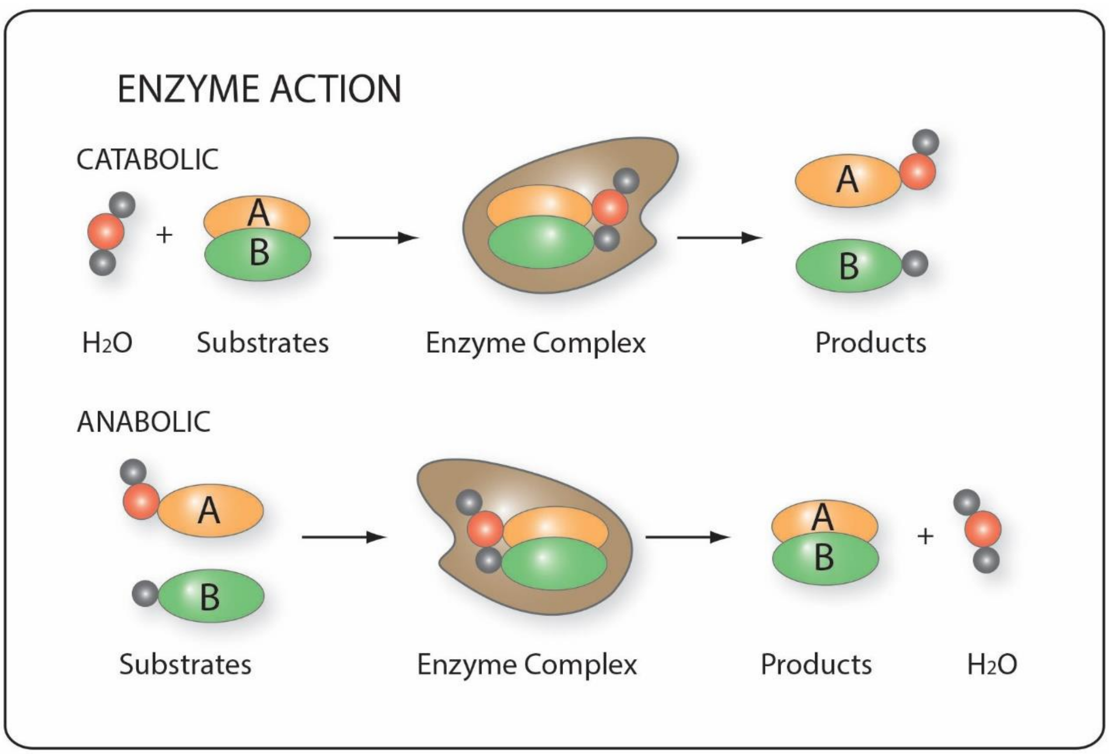
Enzymes accelerate the rate of specific chemical reactions; usually act by attaching to (a) substrate(s) and lowering the activation energy of the reaction. Enzymes hold reactants in the proper orientation, influence electronic character, and exert physical stress to weaken bonds. As a result, a greater percentage of the reactants possess the necessary energy to be converted to products. Enzyme action is shown schematically in Figure 3-4 (the free enzyme is not shown).

Catabolic:

(Free Enzyme) + Substrate → Enzyme-Substrate Complex
→ Product 1 + Product 2 + (Free enzyme)

Anabolic:

(Free Enzyme) + Substrate 1 + Substrate 2 → Enzyme-Substrate Complex
→ Product + (Free Enzyme)



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Regulation of Enzymatic activity

Enzymatic activity is affected by enzyme concentration, affinity of the enzyme for the reactant (substrate) and by allosteric and covalent control of the **conformation** (shape) of the enzyme. Figure 3-5 shows an example of allosteric inhibition of enzyme activity and covalent activation of enzyme activity.

- **Allosteric** control involves the binding of the product of a chemical reaction to a site on the enzyme that changes the conformation of the enzyme. The binding of product to the enzyme can change the conformation of the enzyme so that it either is inhibited (more common) or it is activated.
  - Allosteric control permits feedback regulation

- **Covalent** control involves phosphorylation of the enzyme catalyzed by a protein kinase. The phosphorylation of the enzyme can change the conformation of the enzyme so that it either is activated (more common) or it is inhibited.

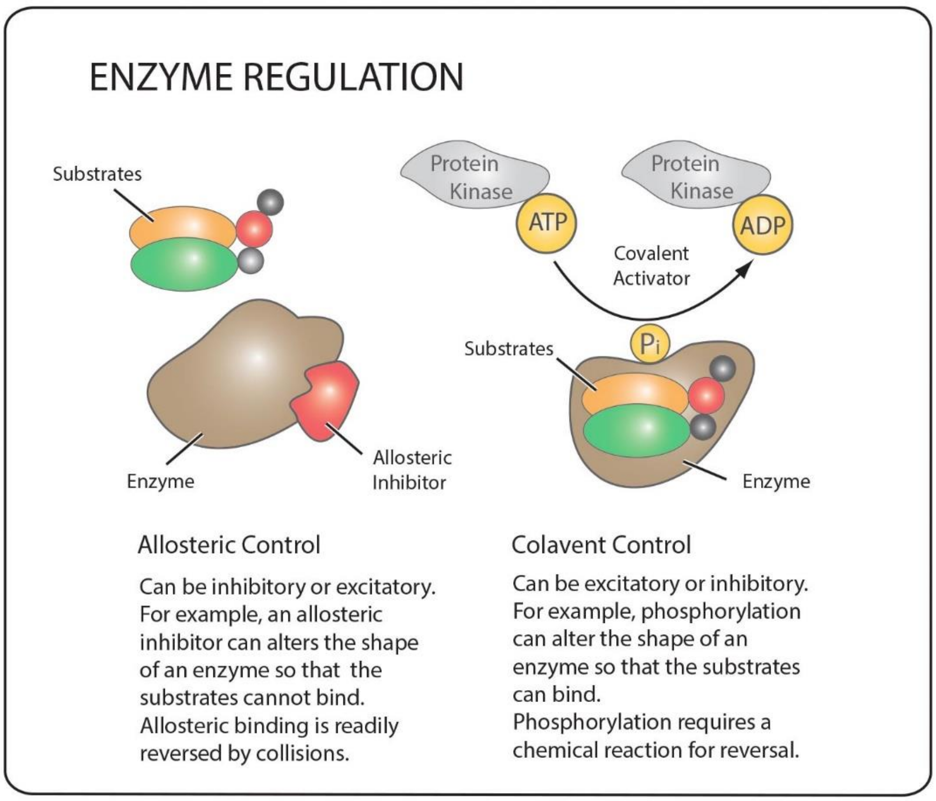


Figure 3-5 © 2019 David G. Ward, PhD

Cells use the allosteric effect to stabilize the concentrations of molecules. For example, the final product of a metabolic pathway inhibits an enzyme in the pathway. This is a classic example of a negative feedback control system (see Chapter 1). When ample product is present, the enzyme is inhibited, and less (or no) product is made. An example of allosteric regulation of an enzyme in a metabolic pathway is illustrated in Figure 3-6.

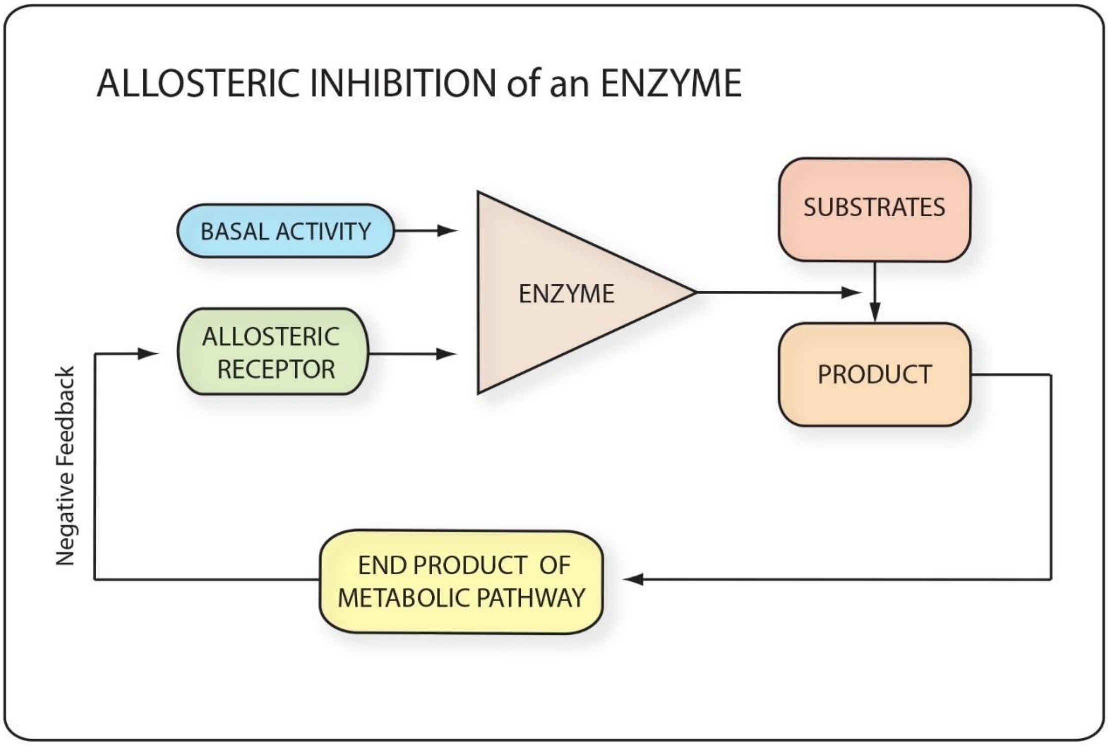


Figure 3-6 © 2019 David G. Ward, PhD

Enzymes are regulated not only by allosteric and covalent control, but also by control of the expression of the genes that carry instructions for the production of enzymes. The role of gene expression in production of proteins (and enzymes) is considered in Chapter 4.

Cofactors

Cofactors, which include various metal ions and vitamins, help an enzyme hold its normal conformation.

Coenzymes

Coenzymes participate in reactions catalyzed by enzymes and usually carry particular chemical groups from one reaction to another. The role of coenzymes in metabolism and production of ATP is considered further in Chapter 23. Major coenzymes include:

- Nicotinamide adenine dinucleotide (NAD^+ / NADH) shuttles electrons
  - NAD^+ is the oxidized form / NADH is the reduced form
- Flavin adenine dinucleotide (FAD / $FADH_2$) shuttles electrons
  - FAD is the oxidized form / $FADH_2$ is the reduced form
- CoA (coenzyme A) carries acetyl groups ($-CH_2COOH$)

Nucleosides, Nucleotides and Nucleic Acids

The nucleosides are composed of ribose or deoxyribose attached to a nitrogenous base. The nucleotides are comprised of nucleosides attached to one, two, or three phosphate groups. The nucleotides form the foundation for high energy molecules, such as ATP and GTP, and for nucleic acids.

Nitrogenous Bases

The nitrogenous bases include the purines and the pyrimidines. The structure of the nitrogenous bases is shown in Figure 3-7.

- The Purines include Adenine and Guanine
- The Pyrimidines include Cytosine, Thymine, and Uracil

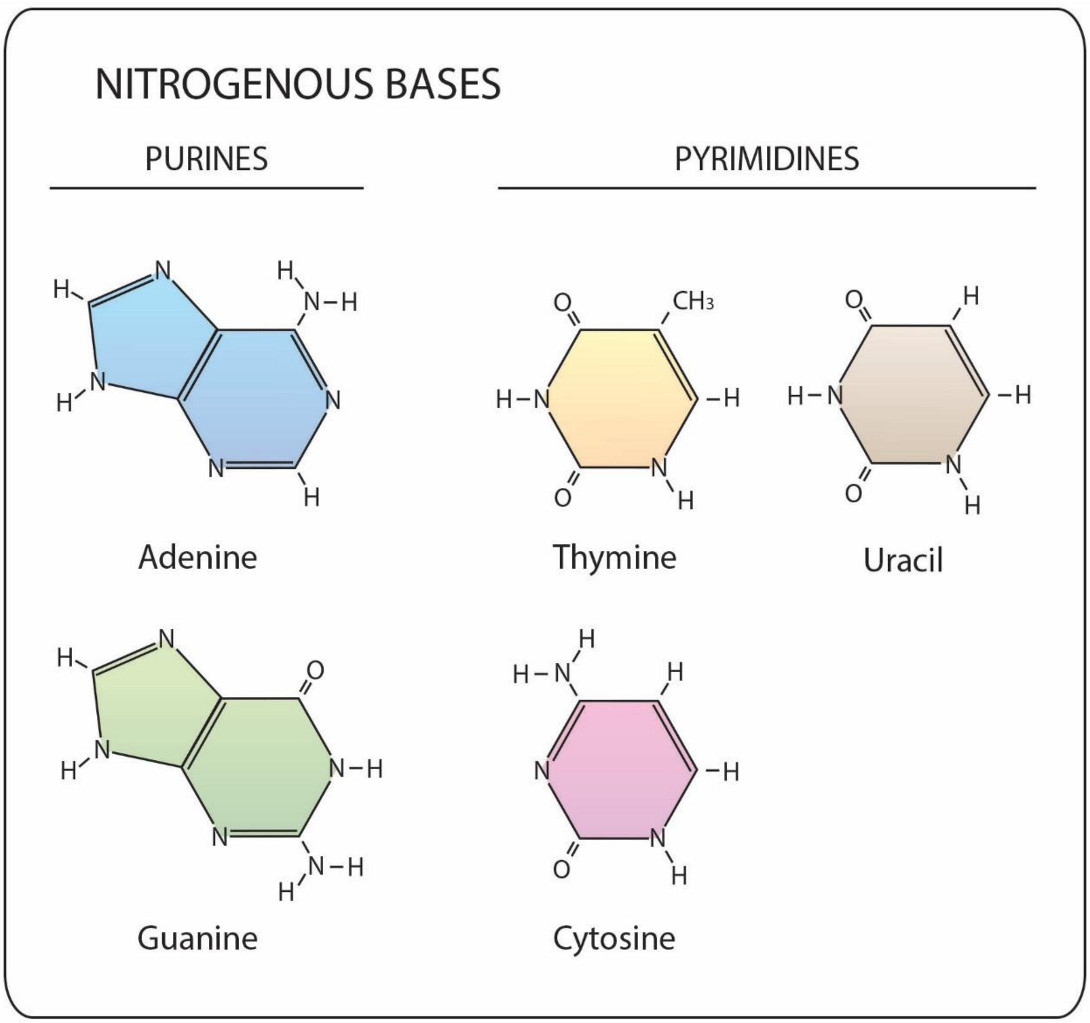


Figure 3-7 © 2018 David G. Ward, PhD

Ribose Nucleotides

The ribose nucleotides are composed of **ribose**, a nitrogenous base, and phosphate(s). The nitrogenous bases used are adenine, guanine, uracil, or cytosine. Ribose nucleotides function as **high energy compounds** and also as the building blocks for **ribonucleic acid** (RNA). The structures of the high energy compounds adenosine triphosphate (ATP) and guanosine triphosphate (GTP) are shown in Figure 3-8.

- Adenosine Triphosphate (ATP) is composed of Adenine, ribose, and 3 phosphate groups
- Guanosine Triphosphate (GTP) is composed of Guanine, ribose, and 3 phosphate groups

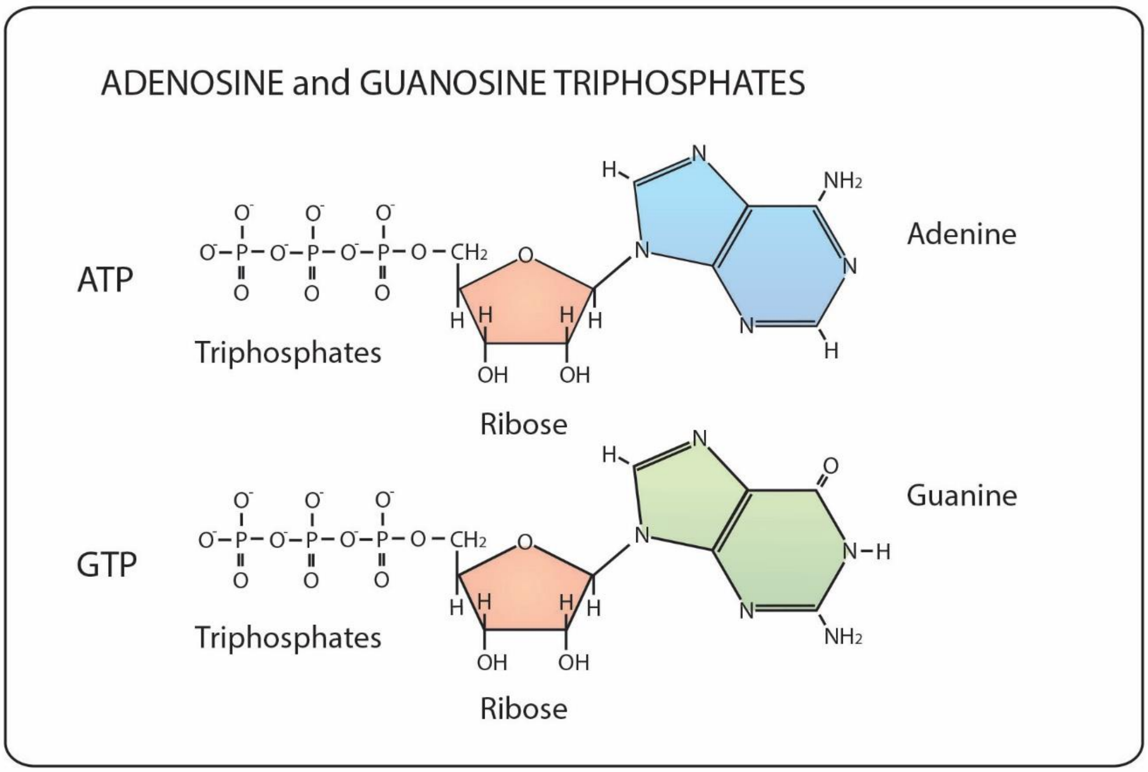


Figure 3-8 © 2007 David G. Ward, PhD

Functions of ATP and GTP are considered further in later chapters, especially in Chapters 4, 5, 6, 7, 9,11, and 23

Deoxyribose Nucleotides

The Deoxyribose nucleotides are composed of **deoxyribose**, a nitrogenous base and phosphate(s), and form the building blocks for **deoxyribonucleic acid** (DNA). The nitrogenous base is adenine, guanine, thymine, or cytosine.

Nucleic Acids

Nucleic acids are chains of either ribose nucleotides or deoxyribose nucleotides. Nucleic acids are linked by phosphodiester bonds between the hydroxyl group of the 3rd carbon of the sugar (3') and the phosphate group of the 5th carbon of the sugar of the adjacent nucleotide (5'). Nucleic acids are synthesized in only one direction by adding nucleotides to the 3' end of a strand.

- 3' (3 prime) is the -OH of the third carbon of the sugar molecule.
- 5' (5 prime) is the - PO_4^{3-} of the fifth carbon of the sugar molecule.

The structure of a short segment of **ribonucleic acid** (RNA) is shown in Figure 3-9. RNA usually takes the form of a single strand. Make a special note that the nitrogenous bases in RNA are adenine, guanine, uracil, and cytosine.

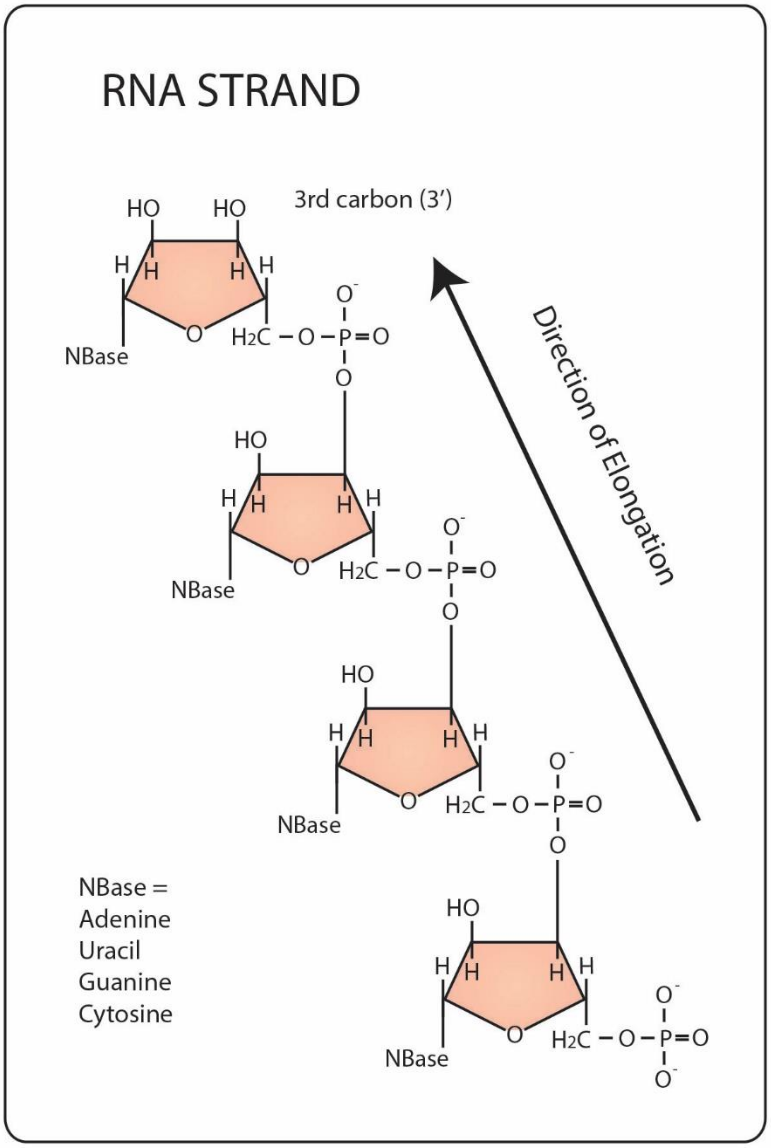
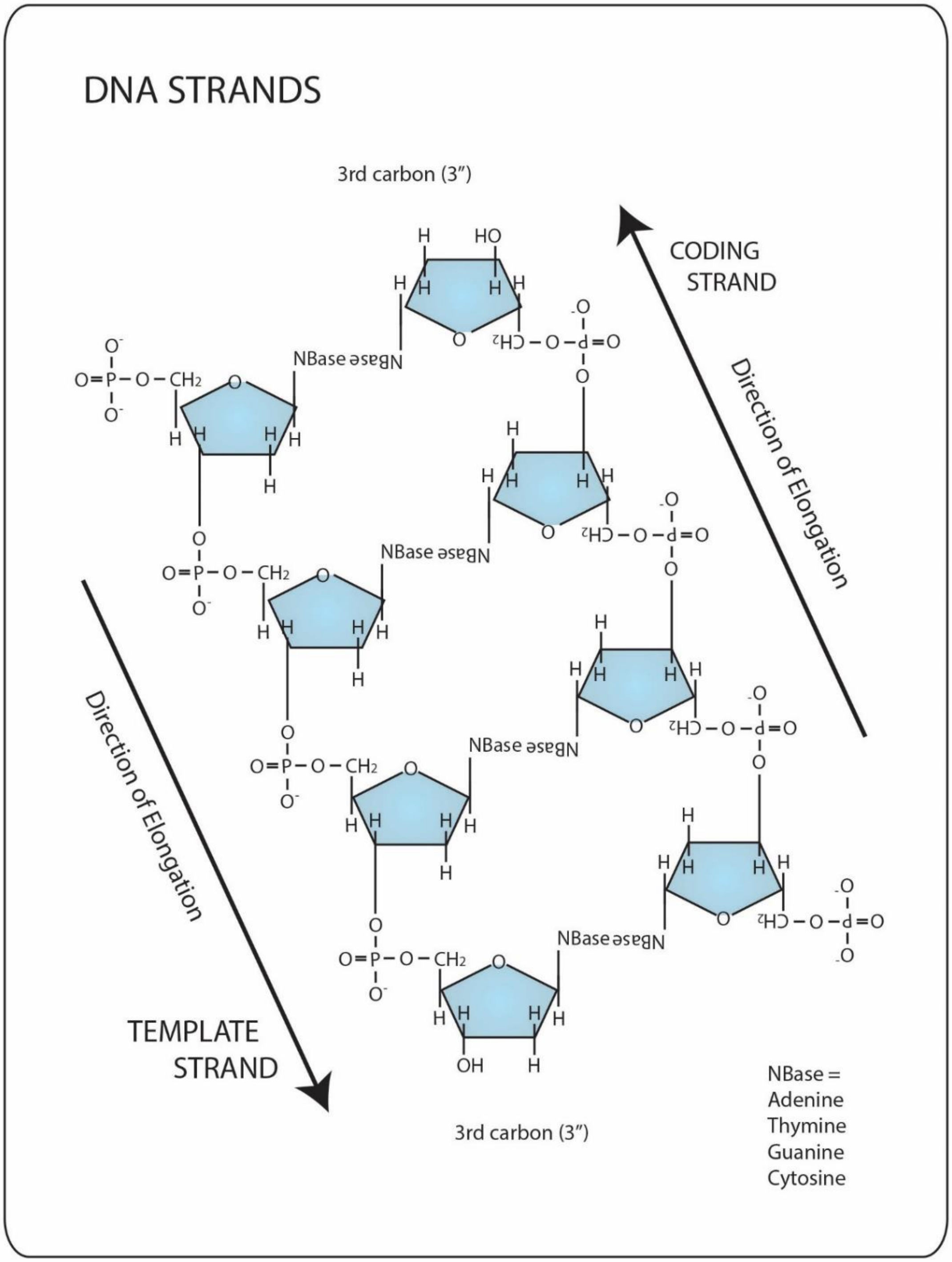


Figure 3-9 © 2007 David G. Ward, PhD

The structure of a short segment of **deoxyribonucleic acid** (DNA) is shown in Figure 3-10. DNA is a double stranded molecule forming a double alpha helix. Make a special note that the nitrogenous bases in DNA are adenine, guanine, thymine, and cytosine. The nucleotides making up the coding strand are organized in the reverse direction of the nucleotides making up the template strand.



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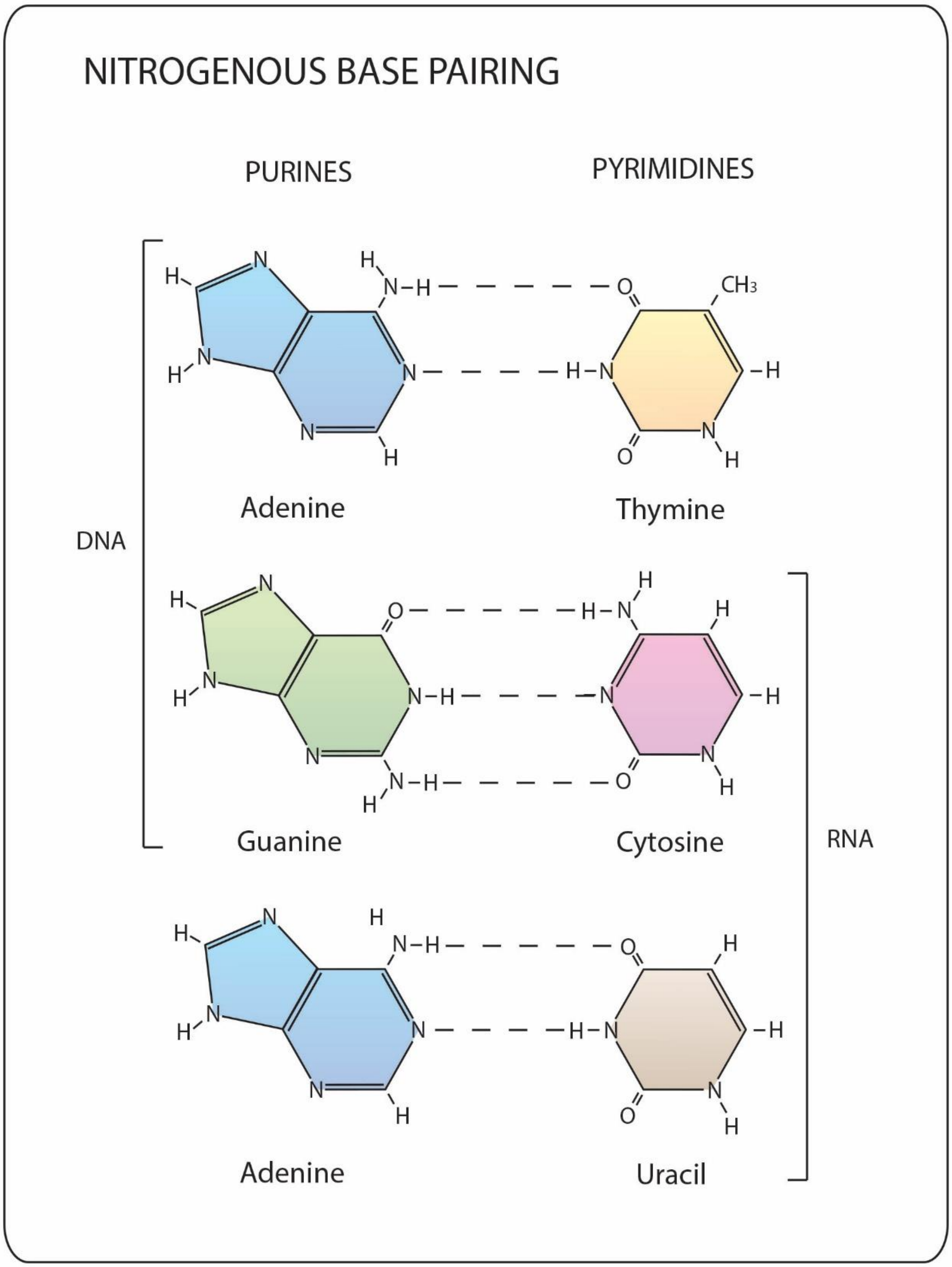
The pairing between the purine and pyrimidine nitrogenous bases is shown in Figure 3-11. Note that the pairing is determined by hydrogen bonds. There are two hydrogen bonds between adenine and thymine (or uracil), and three hydrogen bonds between guanine and cytosine. We explore the role of RNA and DNA in protein synthesis and cell functioning in the next chapter.



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Quiz Yourself

1-5. Matching

A) Anabolic reactions
B) Catabolic reactions

usually use energy 1) _____
assemble molecules 2) _____
break down molecules 3) _____
usually produce energy 4) _____
include dehydration synthesis 5) _____

6-10. Matching

A) Anabolic reactions
B) Catabolic reactions
C) A or B

Oxidation 6) _____
Hydrolysis 7) _____
Phosphorylation 8) _____
Dephosphorylation 9) _____
Dehydration synthesis 10) _____

11-15. Matching

A) Oxidation
B) Hydrolysis
C) Phosphorylation
D) Dephosphorylation
E) Dehydration synthesis

$AB + H_2O \rightarrow A\text{-}OH + BH$ 11) _____
$A\text{-}OH + BH \rightarrow AB + H_2O$ 12) _____
$A + P_i \rightarrow AP_i$ 13) _____
$AP_i \rightarrow A + P_i$ 14) _____
$A + O \rightarrow AO$ 15) _____

16-20. Matching

A) Allosteric control of enzyme
B) Covalent control of enzyme
C) No control of enzyme
D) A or B

Controlled by phosphorylation 16) _____
Can cause inhibition of enzyme 17) _____
Can cause activation of enzyme 18) _____
Controlled by end product of reaction 19) _____
Not affected by phosphorylation or end product concentration 20) _____

Fill in

21. Enzymes act as _______________.

22. Enzymes can be made either of proteins or _______________.

23. _______________ is a common reaction in the breakdown of fats to fatty acids and glycerol.

24. _______________ _______________ is a common reaction in the synthesis of peptides from amino acids.

25. _______________ help an enzyme hold its normal conformation.

Study Questions

1. Explain the role of chemical reactions and enzymes in the functioning of cells.
2. Compare and contrast dehydration synthesis and hydrolysis. Include a description of the role of enzymes.
3. Explain the significance of phosphorylation.
4. Compare and contrast allosteric and covalent regulation, and explain the role of enzymes.
5. Describe the composition of nucleotides; and compare and contrast nucleotides with ATP and GTP.