The chemistry of life: carbohydrates and lipids

Carbohydrates are large biological molecules, or macromolecules, consisting of carbon (C), hydrogen (H), and oxygen (O) atoms, usually with a hydrogen:oxygen atom ratio of 2:1 (as in water).

The empirical formula $C_m(H_2O)_n$ (where m could be different from n, m normally > than 3).

Carbohydrates include both sugars and polymers of sugars.

Monosaccharides are the most basic units of carbohydrates. Depending on the number of carbon atoms, several types of monosaccharides can be distinguished.

Glucose, fructose, galactose and other sugars that have six carbons are called **hexoses**.

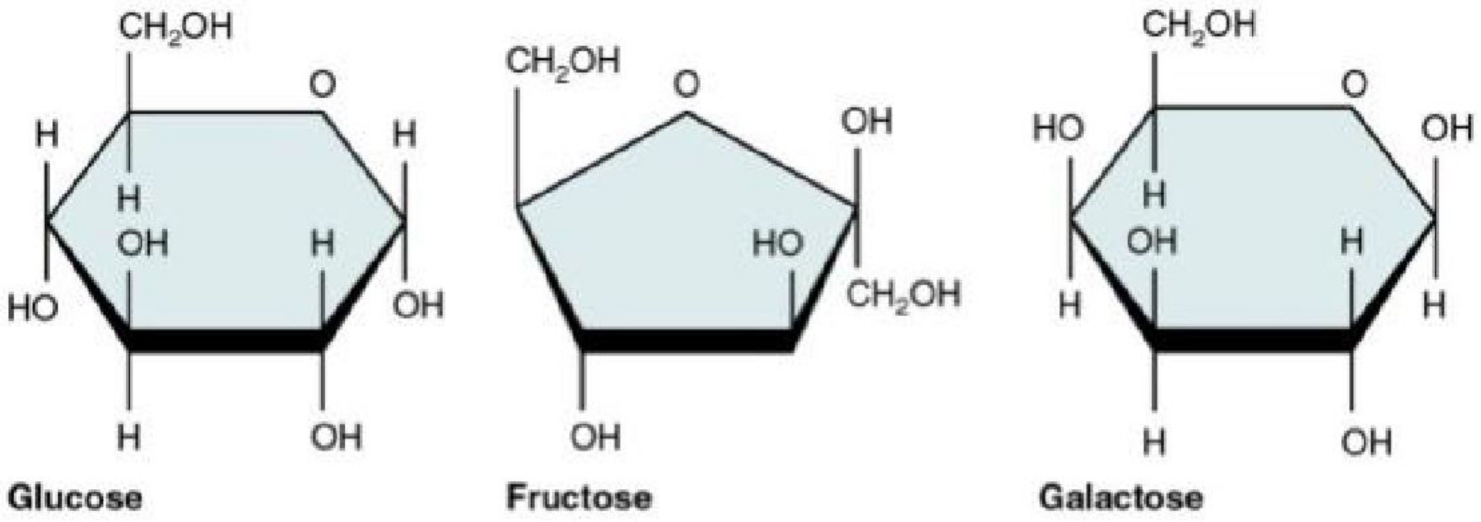
Trioses (three-carbon sugars) and **pentoses** (five-carbon sugars) are also common. The most important pentoses are ribose and deoxyribose.

Monosaccharides are major nutrients for cells.

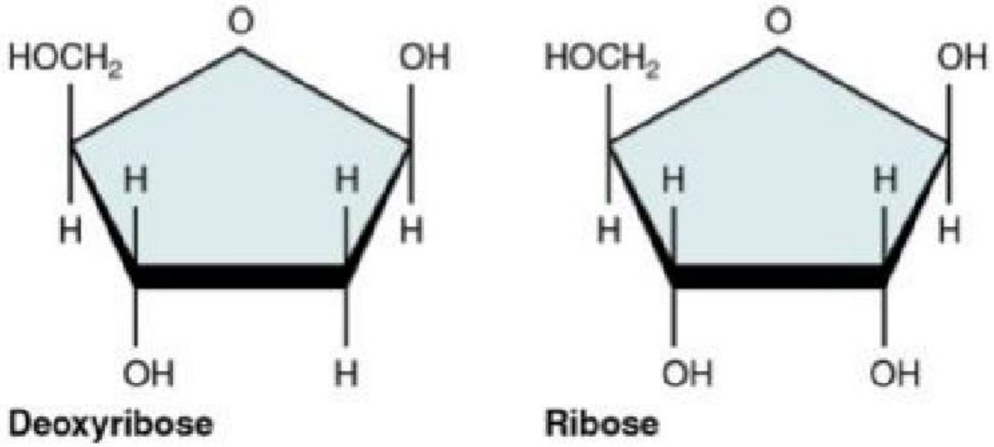
In the process known as cellular respiration, cells extract energy in a series of reactions starting with glucose molecules.

Simple-sugar molecules are not only a major fuel for cellular work, but their carbon skeletons also serve as raw material for the synthesis of other types of small organic molecules, such as amino acids (mostly ribose and deoxyribose) and fatty acids.

Sugar molecules that are not immediately used in these ways are generally incorporated as monomers into disaccharides or polysaccharides.

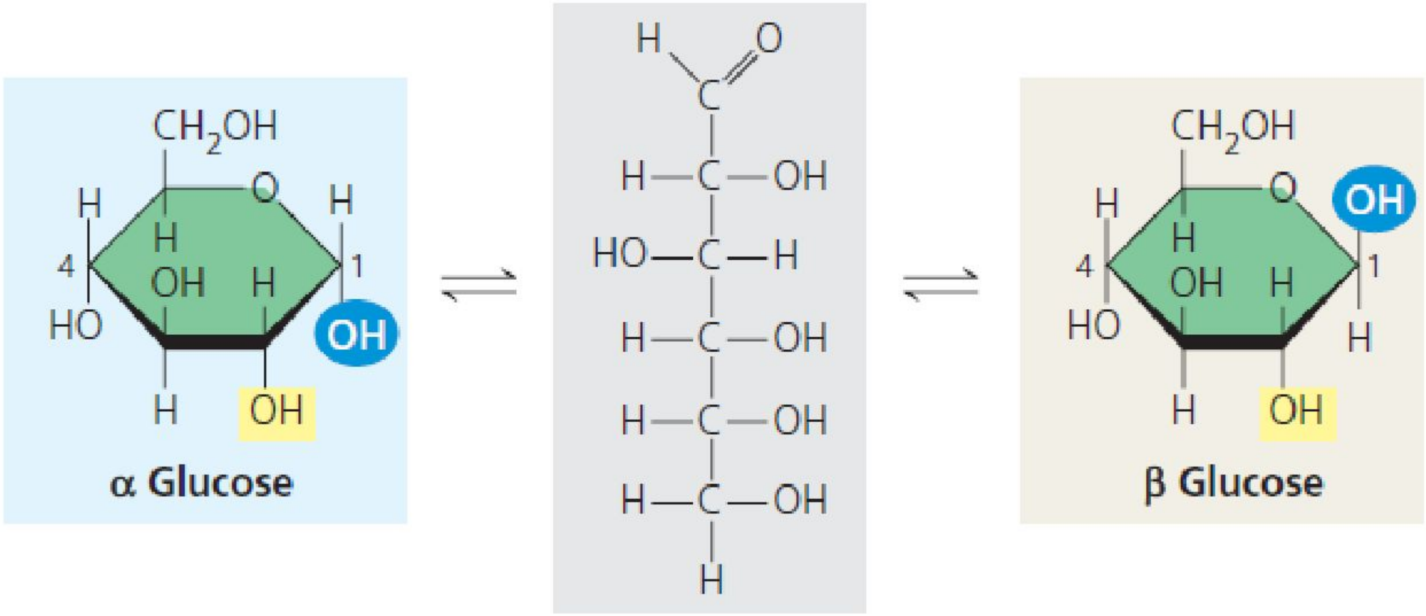


(a) Hexoses



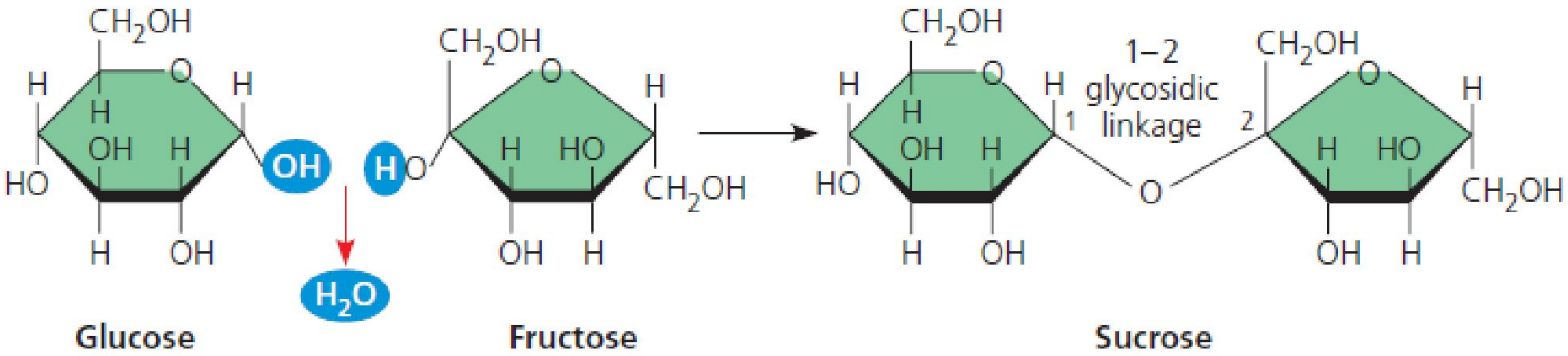
(b) Pentoses

(a) α and β glucose ring structures. These two interconvertible forms of glucose differ in the placement of the hydroxyl group (highlighted in blue) attached to the number 1 carbon.



The difference is based on the fact that there are actually two slightly different ring structures for glucose. When glucose forms a ring, the hydroxyl group attached to the number 1 carbon is positioned either below or above the plane of the ring. These two ring forms for glucose are called alpha (α) and beta (β), respectively. In starch, all the glucose monomers are in the α configuration (see Figure). In contrast, the glucose monomers of cellulose are all in the β configuration, making every glucose monomer "upside down" with respect to its neighbours. Compounds that have the same numbers of atoms of the same elements but different structures and hence different properties are called isomers.

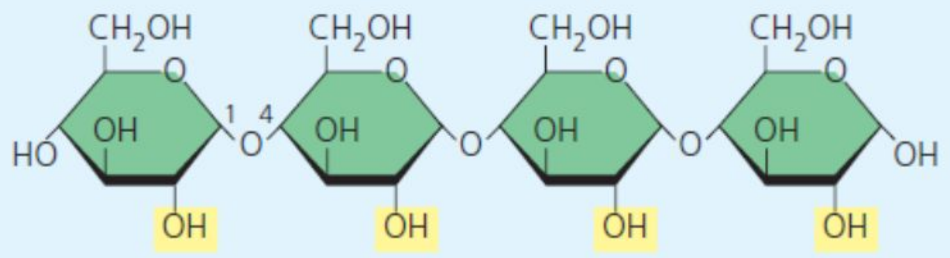
Disaccharides consist of two monosaccharides joined by a **glycosidic linkage**, a covalent bond formed between two monosaccharides by a dehydration reaction. For example, maltose is a disaccharide formed by the linking of two molecules of glucose. The most prevalent disaccharide is sucrose, which is table sugar. Its two monomers are glucose and fructose. Lactose, the sugar present in milk, is another disaccharide, in this case a glucose molecule joined to a galactose molecule. The functions of disaccharides are similar to those of monosaccharides.



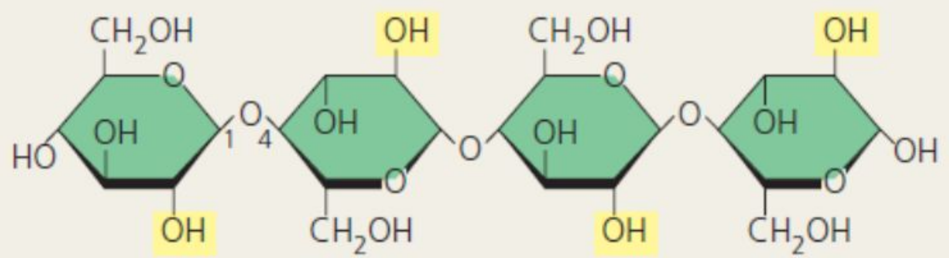
Polysaccharides are macromolecules, polymers with a few hundred to a few thousand monosaccharides joined by glycosidic linkages. Some polysaccharides serve as storage material, hydrolyzed as needed to provide sugar for cells. Other polysaccharides serve as building material for structures that protect the cell or the whole organism. The architecture and function of a polysaccharide are determined by its sugar monomers and by the positions of its glycosidic linkages.

Both plants and animals store sugars for later use in the form of storage polysaccharides. Plants store **starch**, a polymer of glucose monomers, as granules within cellular structures known as plastids, which include chloroplasts. Synthesizing starch enables the plant to stockpile surplus glucose. Because glucose is a major cellular fuel, starch represents stored energy. The sugar can later be withdrawn from this carbohydrate "bank" by hydrolysis, which breaks the bonds between the glucose monomers. Animals store a polysaccharide called **glycogen**, a polymer of glucose which is extensively branched. Humans and other vertebrates store glycogen mainly in liver and muscle cells. Hydrolysis of glycogen in these cells releases glucose when the demand for sugar increases. This stored fuel cannot sustain an animal for long, however. In humans, for example, glycogen stores are depleted in about a day unless they are replenished by consumption of food. This is an issue of concern in low-carbohydrate diets.

Organisms build strong materials from structural polysaccharides. For example, the polysaccharide called **cellulose** is a major component of the tough walls that enclose plant cells. Like starch, cellulose is a polymer of glucose, but the glycosidic linkages in these two polymers differ. The differing glycosidic linkages in starch and cellulose give the two molecules distinct three-dimensional shapes. Whereas certain starch molecules are largely helical, a cellulose molecule is straight. Cellulose is never branched, and some hydroxyl groups on its glucose monomers are free to hydrogen-bond with the hydroxyls of other cellulose molecules lying parallel to it. Another important structural polysaccharide is chitin, the carbohydrate used by arthropods (insects, spiders, crustaceans, and related animals) to build their exoskeletons. An exoskeleton is a hard case that surrounds the soft parts of an animal. Pure chitin is leathery and flexible, but it becomes hardened when encrusted with calcium carbonate, a salt. Chitin is also found in many fungi, which use this polysaccharide rather than cellulose as the building material for their cell walls. Chitin is similar to cellulose, with β linkages, except that the glucose monomer of chitin has a nitrogen-containing appendage.



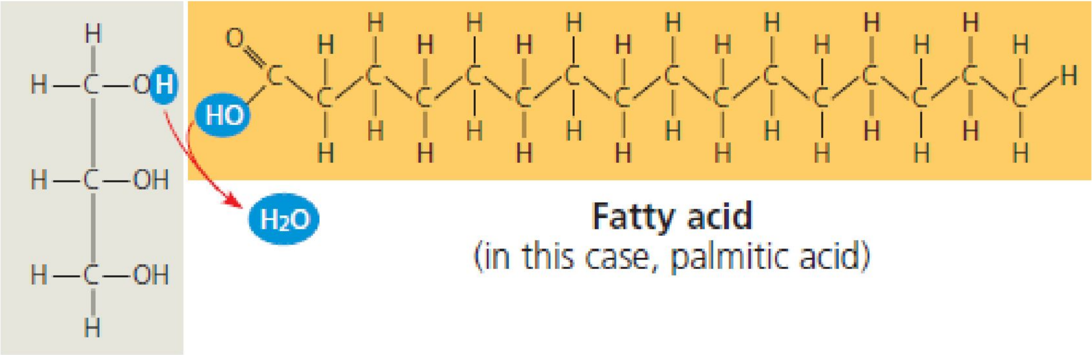
(b) Starch: 1–4 linkage of α glucose monomers. All monomers are in the same orientation. Compare the positions of the —OH groups highlighted in yellow with those in cellulose (c).



(c) Cellulose: 1–4 linkage of β glucose monomers. In cellulose, every β glucose monomer is upside down with respect to its neighbors.

Lipids are the one class of large biological molecules that does not include true polymers, and they are generally not big enough to be considered macromolecules. The compounds called lipids are grouped together because they share one important trait: They mix poorly, if at all, with water. The hydrophobic behavior of lipids is based on their molecular structure. Although they may have some polar bonds associated with oxygen, lipids consist mostly of hydrocarbon regions. Lipids are varied in form and function. The most biologically important types of lipids: fats, phospholipids, and steroids.

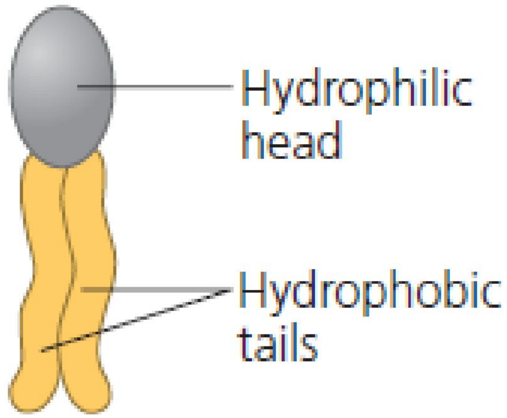
A **fat** is constructed from two kinds of smaller molecules: glycerol and fatty acids. Glycerol is an alcohol; each of its three carbons bears a hydroxyl group. A **fatty acid** has a long carbon skeleton, usually 16 or 18 carbon atoms in length. The carbon at one end of the skeleton is part of a carboxyl group, the functional group that gives these molecules the name fatty acid. The resulting fat, also called a triacylglycerol, thus consists of three fatty acids linked to one glycerol molecule. (Still another name for a fat is *triglyceride*). The major function of fats is energy storage.



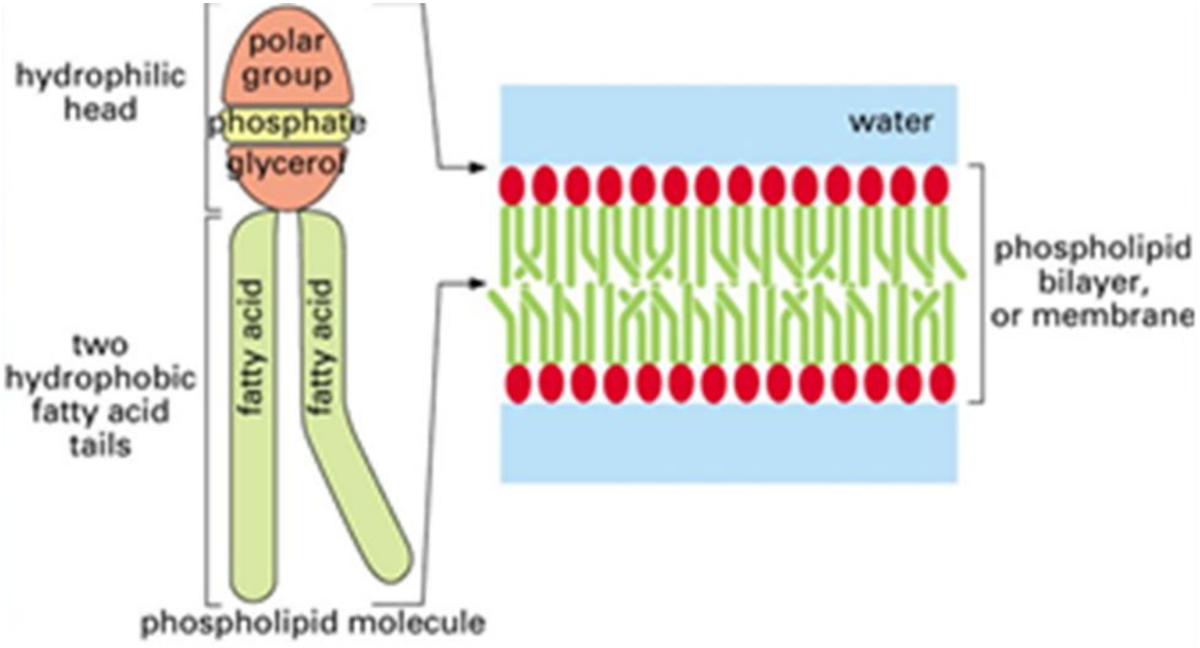
Dehydration reaction in the synthesis of a fat

Structural scheme of triacylglycerol

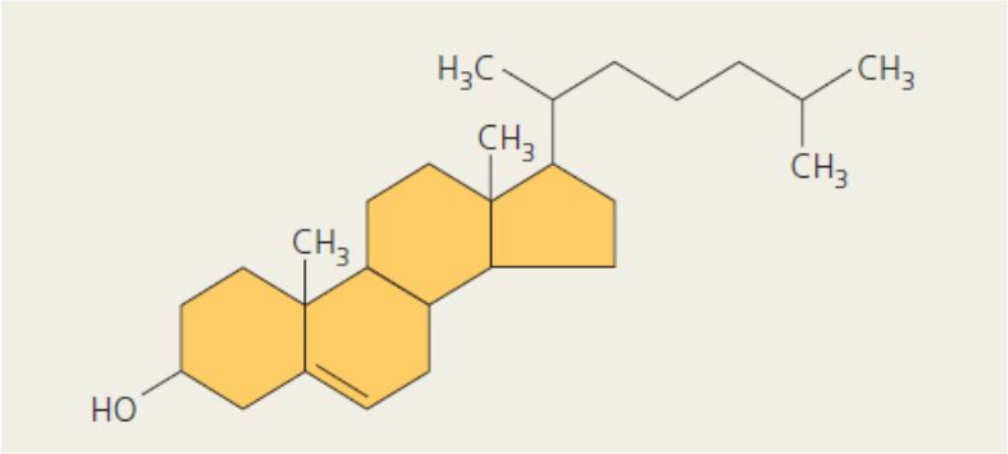
Phospholipids. A phospholipid is similar to a fat molecule but has only two fatty acids attached to glycerol rather than three. The third hydroxyl group of glycerol is joined to a phosphate group, which has a negative electrical charge in the cell. Additional small molecules, which are usually charged or polar, can be linked to the phosphate group to form a variety of phospholipids. Phospholipids are the main component of cell membranes.



(c) Phospholipid symbol



Steroids are lipids characterized by a carbon skeleton consisting of four fused rings. Different steroids, such as cholesterol and the vertebrate sex hormones, are distinguished by the particular chemical groups attached to this ensemble of rings (see Figure). **Cholesterol** is a crucial molecule in animals. It is a common component of animal cell membranes and is also the precursor from which other steroids are synthesized. In vertebrates, cholesterol is synthesized in the liver and obtained from the diet. A high level of cholesterol in the blood may contribute to atherosclerosis.



▲ **Figure 5.14 Cholesterol, a steroid.** Cholesterol is the molecule from which other steroids, including the sex hormones, are synthesized. Steroids vary in the chemical groups attached to their four interconnected rings (shown in gold).

Biological molecule	Composition	Function	Examples
Carbohydrates 1. Monosaccharide 2. Disaccharide 3. Polysaccharides			
Lipids 1. Fats 2. Phospholipids 3.Steroids			

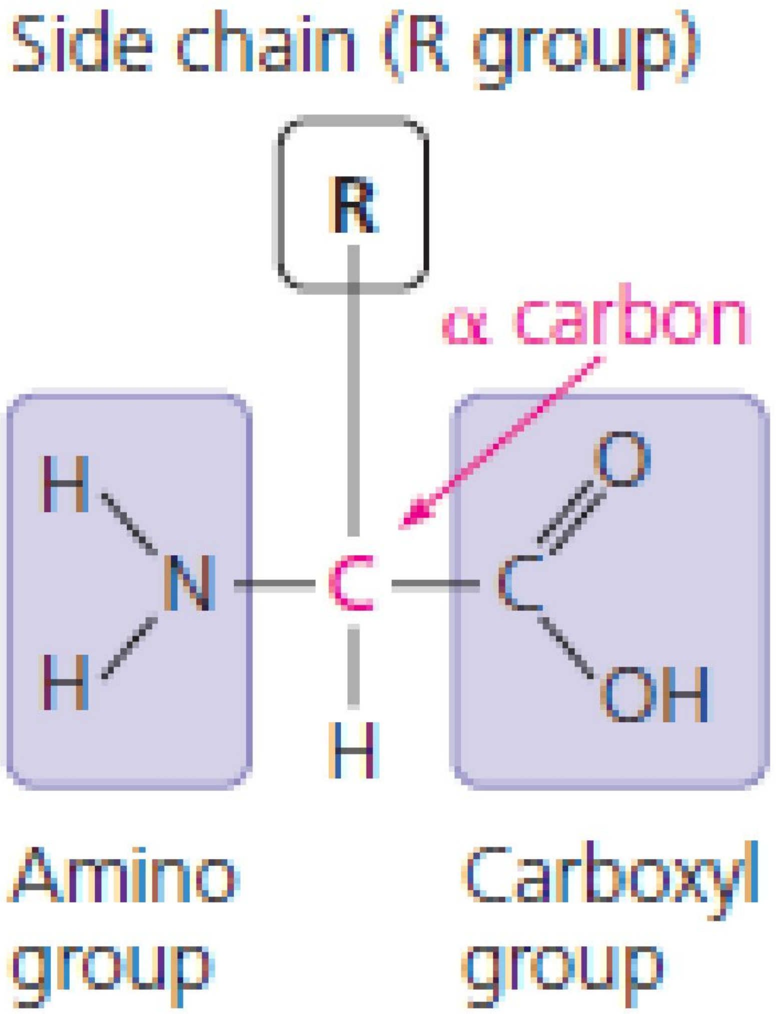
The chemistry of life: proteins and nucleic acids

A protein is a biologically functional molecule that consists of one or more polypeptides, each folded and coiled into a specific three-dimensional structure.

Polypeptides are polymers of amino acids. An amino acid is an organic molecule possessing both an amino group and a carboxyl group (see Figure). The side chain (R group) may be as simple as a hydrogen atom, as in the amino acid glycine, or it may be a carbon skeleton with various functional groups attached, as in glutamine.

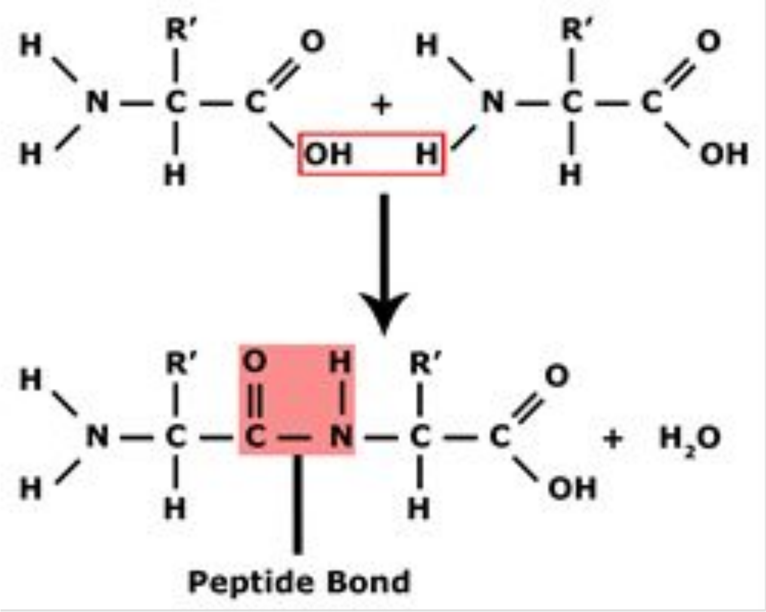
Despite the great diversity of proteins, they are all unbranched polymers constructed from the same set of 20 amino acids. Proteins account for more than 50% of the dry mass of most cells, and they are instrumental in almost everything organisms do.

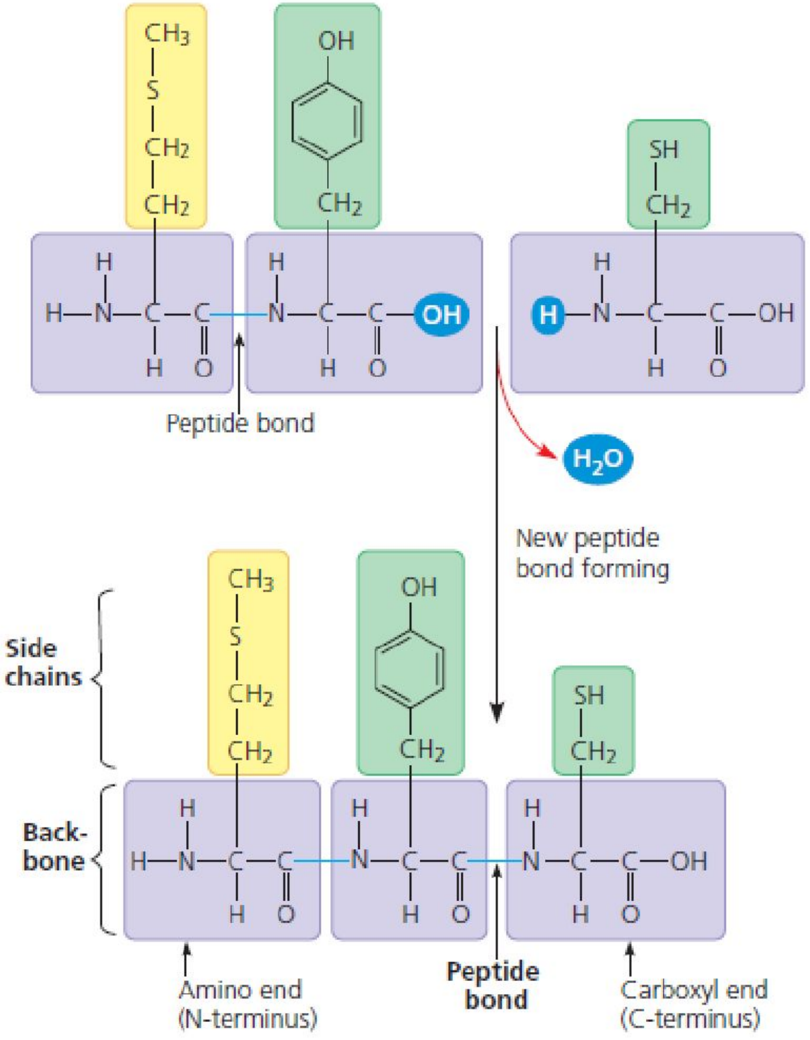
Some proteins speed up chemical reactions (enzymes), while others play a role in defense, storage, transport, cellular communication, regulation, movement, or structural support.



Peptide bond. Read the text below, draw the scheme of a polypeptide chain and mark the peptide bond (for more read Campbell et al. 2009:80-81).

When two amino acids are positioned so that the carboxyl group of one is adjacent to the amino group of the other, they can become joined by a dehydration reaction, with the removal of a water molecule. The resulting covalent bond is called a **peptide bond**. Repeated over and over, this process yields a polypeptide, a polymer of many amino acids linked by peptide bonds. Polypeptides range in length from a few amino acids to a thousand or more. Each specific polypeptide has a unique linear sequence of amino acids.



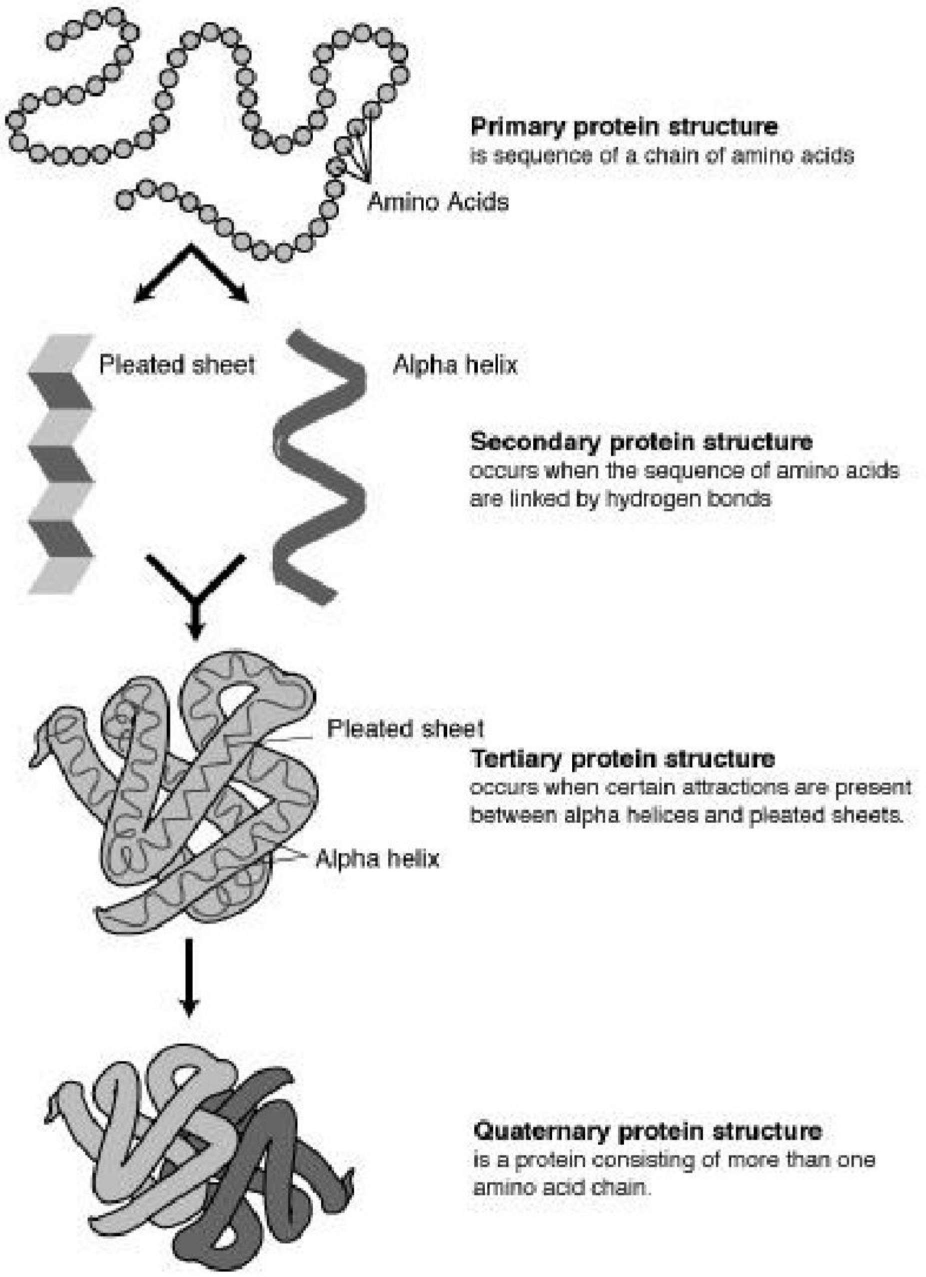


▲ **Figure 5.17 Making a polypeptide chain.** Peptide bonds are formed by dehydration reactions, which link the carboxyl group of one amino acid to the amino group of the next. The peptide bonds are formed one at a time, starting with the amino acid at the amino end (N-terminus). The polypeptide has a repetitive backbone (purple) to which the amino acid side chains (yellow and green) are attached.

Levels of protein structure

All proteins share three superimposed levels of structure, known as primary, secondary, and tertiary structure. A fourth level, quaternary structure, arises when a protein consists of two or more polypeptide chains.

The **primary structure** of a protein is a linked series of amino acids with a unique sequence. The primary structure is held together by covalent bonds such as peptide bonds, which are made during the process of protein biosynthesis or translation. The precise primary structure of a protein is determined not by the random linking of amino acids, but by inherited genetic information.

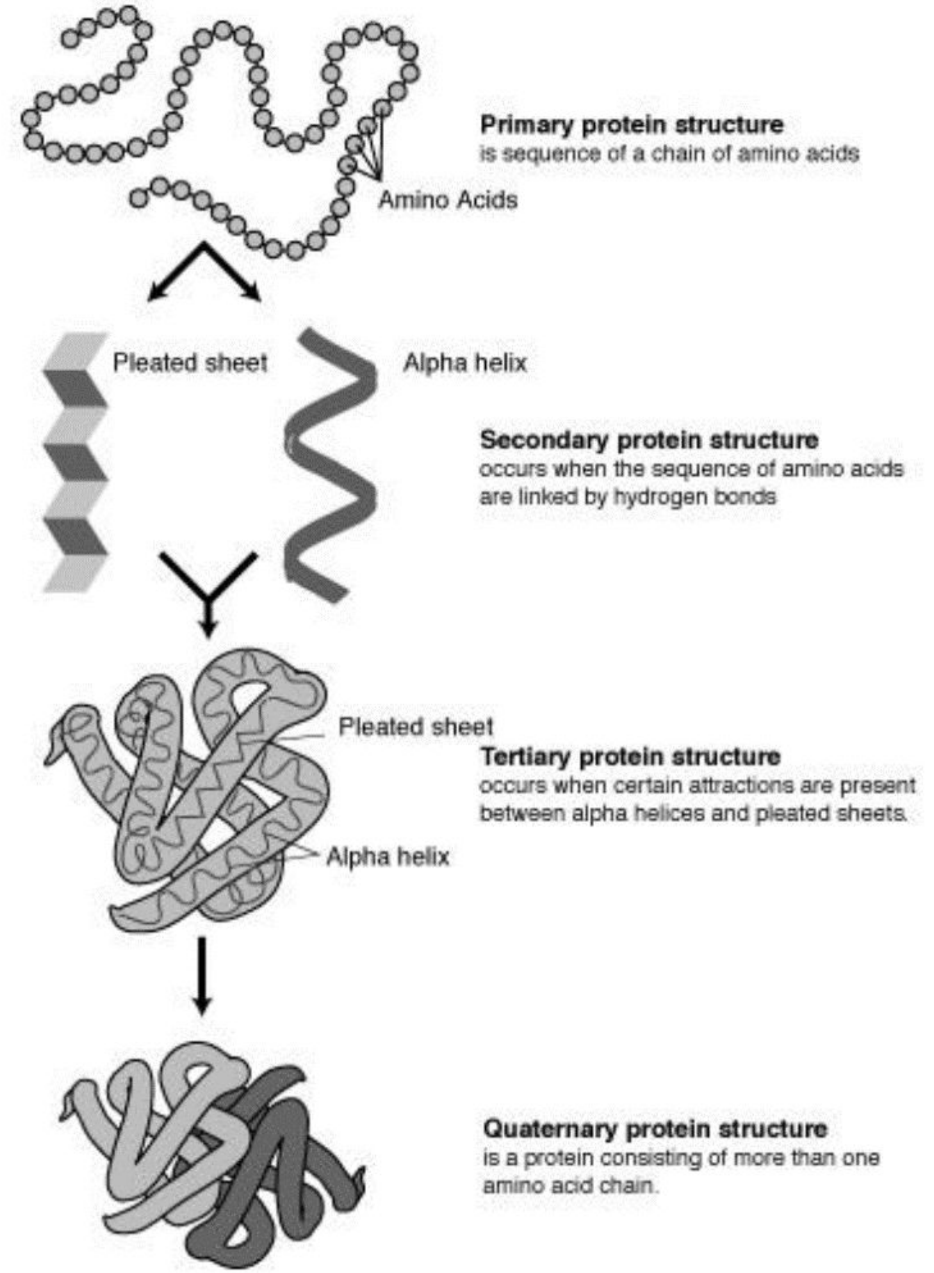


Most proteins have segments of their polypeptide chains repeatedly coiled or folded in patterns that contribute to the protein's overall shape. These coils and folds, collectively referred to as **secondary structure**, are the result of hydrogen bonds between the repeating constituents of the polypeptide backbone (not the amino acid side chains).

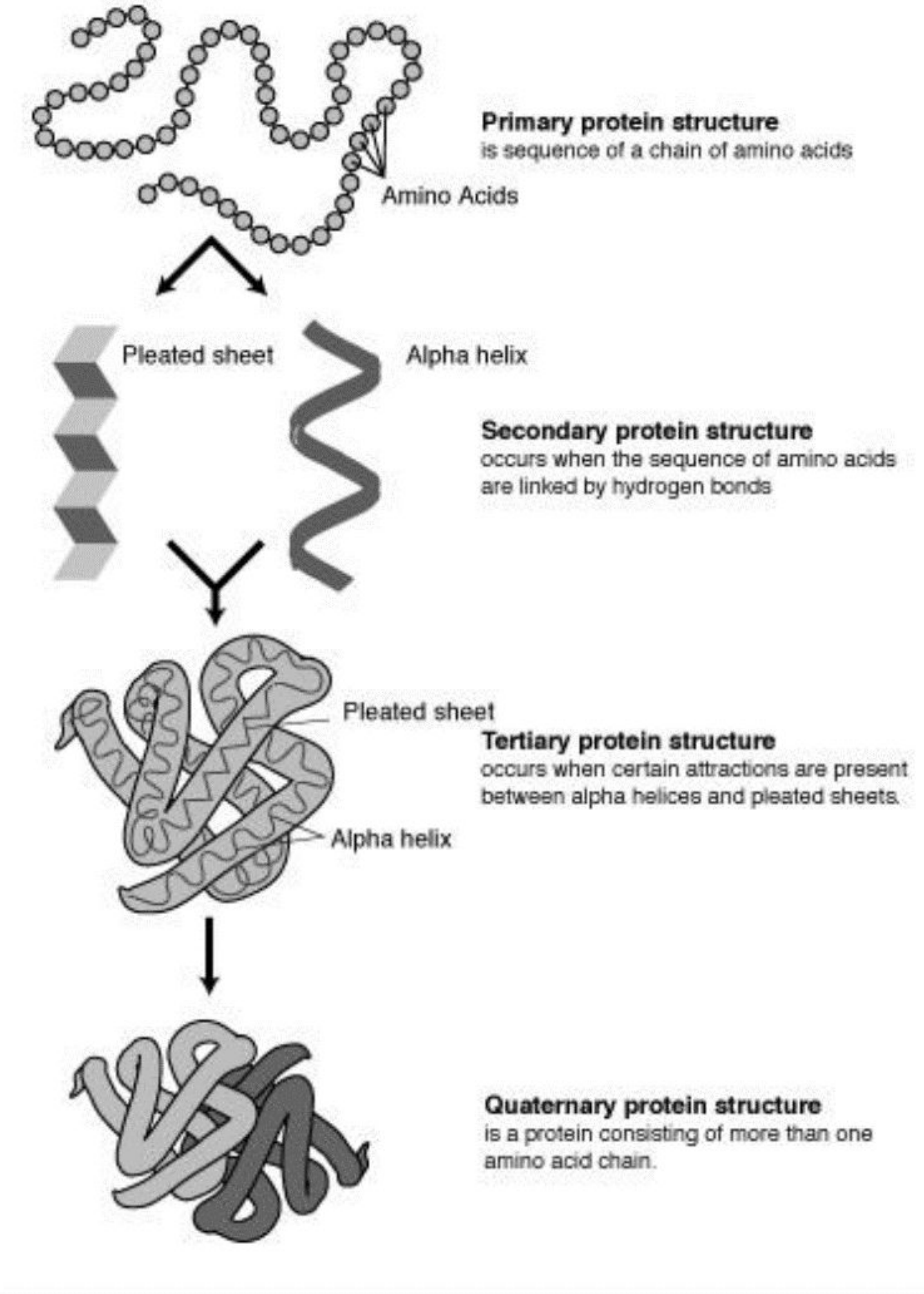
Within the backbone, the oxygen atoms have a partial negative charge, and the hydrogen atoms attached to the nitrogens have a partial positive charge (Figure); therefore, hydrogen bonds can form between these atoms.

One such secondary structure is the ***α-helix***, a delicate coil held together by hydrogen bonding between every fourth amino acid, shown above.

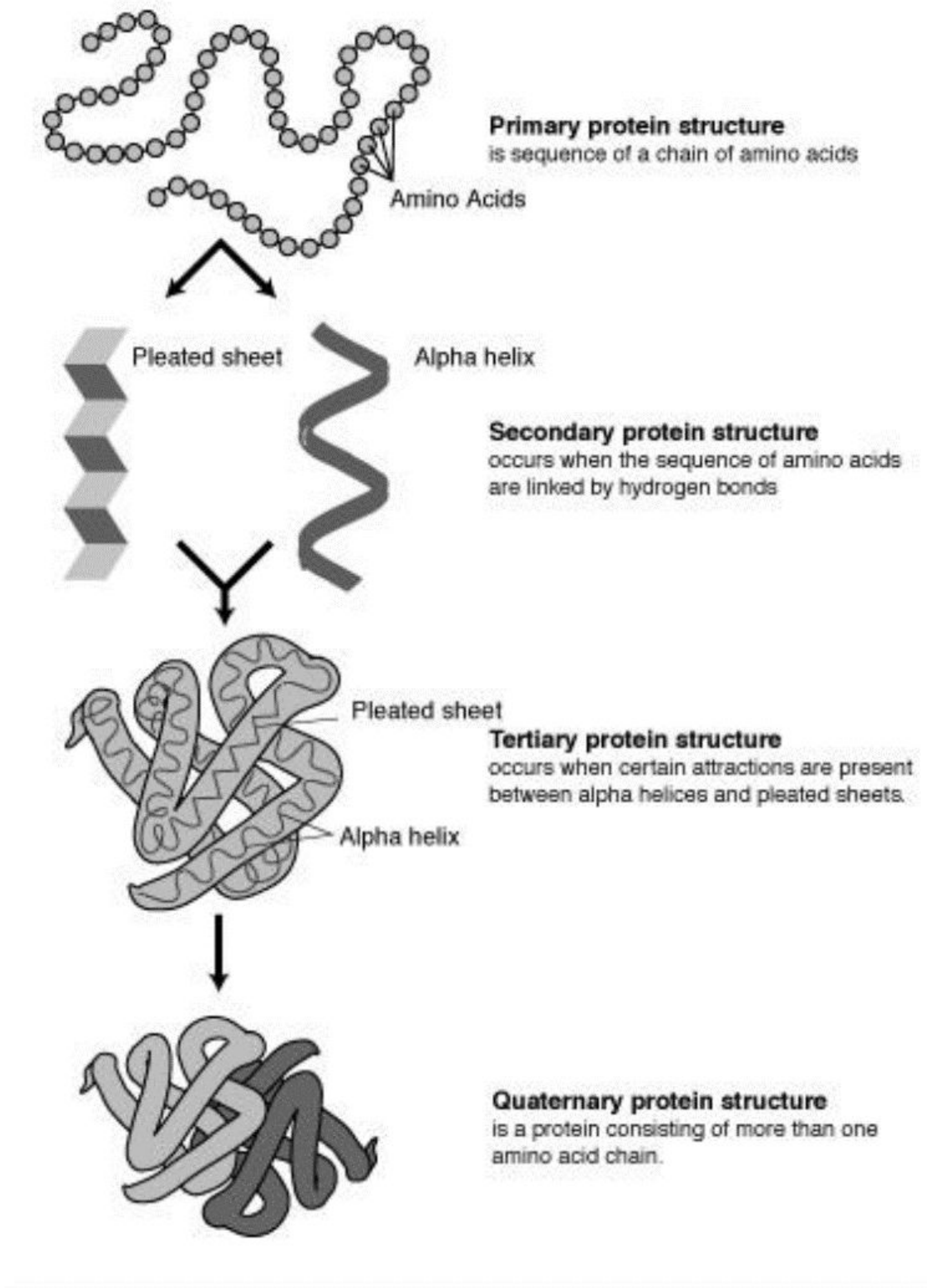
The other main type of secondary structure is the **β-*pleated sheet***. In this structure two or more strands of the polypeptide chain lying side by side (called β-strands) are connected by hydrogen bonds between parts of the two parallel polypeptide backbones.



Tertiary structure refers to the three-dimensional structure of a single, double, or triple bonded protein molecule. The alpha-helixes and beta pleated-sheets are folded into a compact globular structure. While secondary structure involves interactions between backbone constituents, tertiary structure is the overall shape of a polypeptide resulting from interactions between the side chains (R groups) of the various amino acids. The folding is driven by the non-specific hydrophobic interactions, the burial of hydrophobic residues from water, but the structure is stable only when the parts of a protein domain are locked into place by specific tertiary interactions, such as salt bridges, hydrogen bonds, and the tight packing of side chains and disulfide bonds.



Some proteins consist of two or more polypeptide chains aggregated into one functional macromolecule. **Quaternary structure** is the arrangement of multiple folded protein or coiling protein molecules in a multi-subunit complex. The quaternary structure is stabilized by the same non-covalent interactions and disulfide bonds as the tertiary structure. The examples are collagen and hemoglobin.



Levels of protein structure

Structure level	Definition	Structural bonds	Scheme
Primary structure			
Secondary structure			
Tertiary structure			
Quaternary structure			

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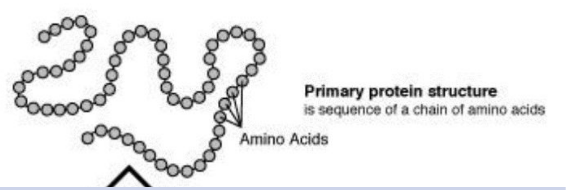
Primary structure	The primary structure of a protein is a linked series of amino acids with a unique sequence.	covalent bonds such as peptide bonds	

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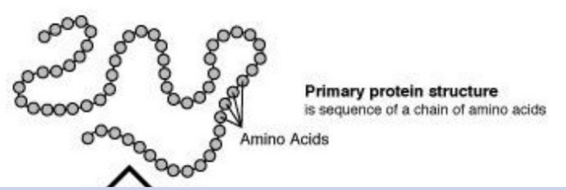
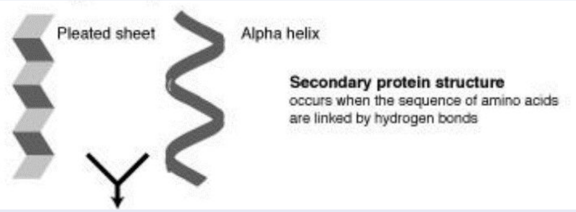
Primary structure	The primary structure of a protein is a linked series of amino acids with a unique sequence.	covalent bonds such as peptide bonds	
Secondary structure	the result of hydrogen bonds between the repeating constituents of the polypeptide backbone. **α-helix**, a delicate coil held together by hydrogen bonding between every fourth amino acid **β-pleated sheet**, two or more strands of the polypeptide chain lying side by side (called β-strands) are connected by hydrogen bonds between parts of the two parallel polypeptide backbones	hydrogen bonds between the repeating constituents of the polypeptide backbone	

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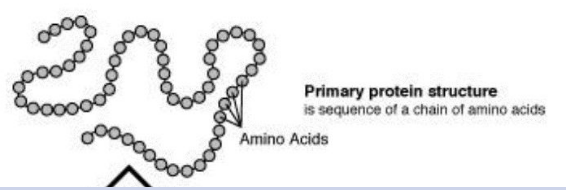
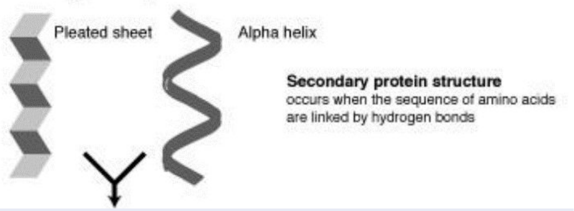
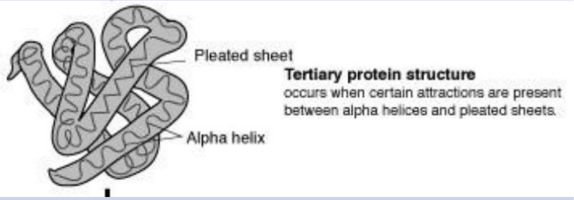
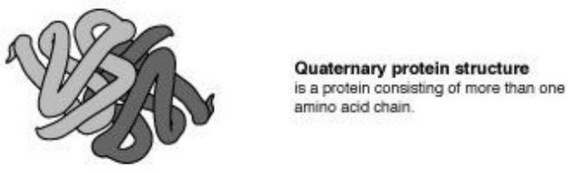
Primary structure	The primary structure of a protein is a linked series of amino acids with a unique sequence.	covalent bonds such as peptide bonds	
Secondary structure	the result of hydrogen bonds between the repeating constituents of the polypeptide backbone. **α-helix**, a delicate coil held together by hydrogen bonding between every fourth amino acid **β-pleated sheet**, two or more strands of the polypeptide chain lying side by side (called β-strands) are connected by hydrogen bonds between parts of the two parallel polypeptide backbones	hydrogen bonds between the repeating constituents of the polypeptide backbone	
Tertiary structure	Tertiary structure refers to the three-dimensional structure of a single, double, or triple bonded protein molecule. tertiary structure is the overall shape of a polypeptide resulting from interactions between the side chains (R groups) of the various amino acids.	the non-specific hydrophobic interactions, such as salt bridges, hydrogen bonds, and the tight packing of side chains and disulfide bonds.	
Quaternary structure			

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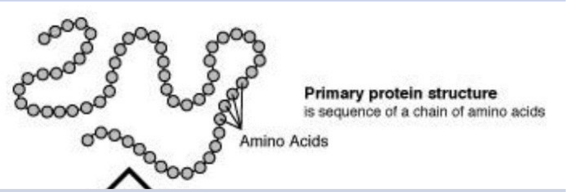
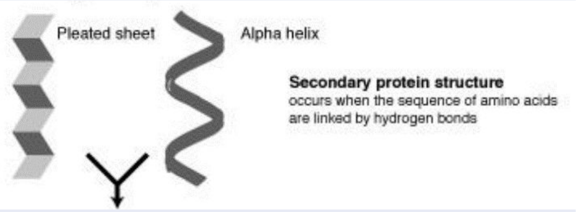
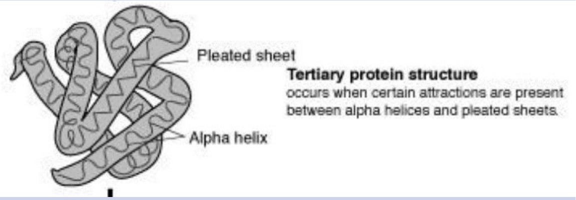
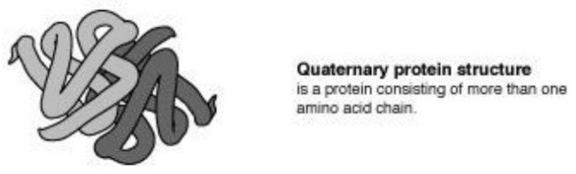
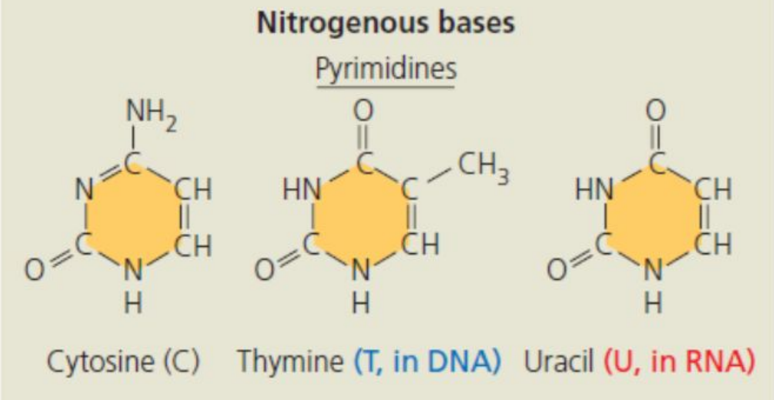
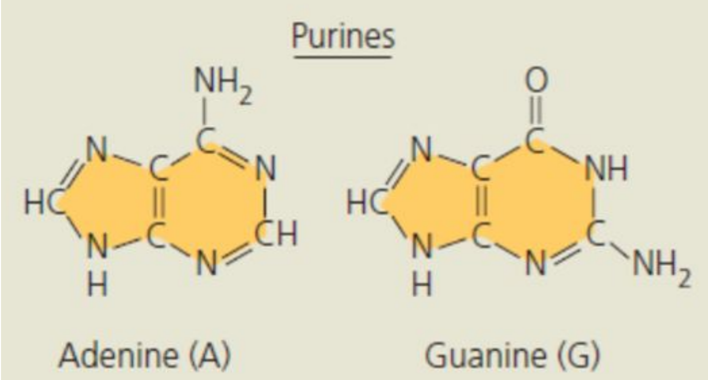
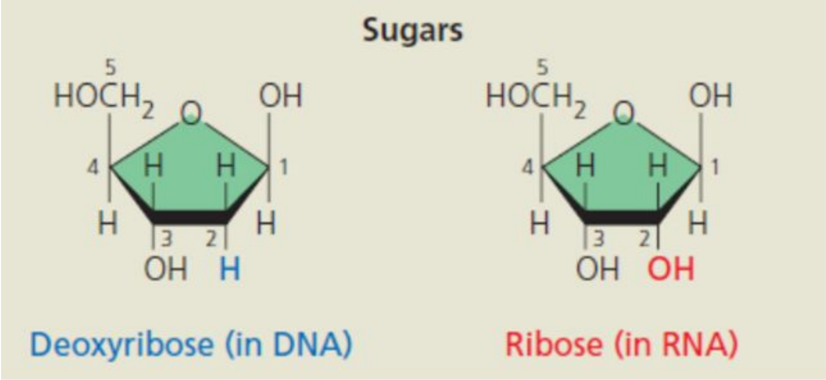
Primary structure	The primary structure of a protein is a linked series of amino acids with a unique sequence.	covalent bonds such as peptide bonds	
Secondary structure	the result of hydrogen bonds between the repeating constituents of the polypeptide backbone. **α-helix**, a delicate coil held together by hydrogen bonding between every fourth amino acid **β-pleated sheet**, two or more strands of the polypeptide chain lying side by side (called β-strands) are connected by hydrogen bonds between parts of the two parallel polypeptide backbones	hydrogen bonds between the repeating constituents of the polypeptide backbone	
Tertiary structure	Tertiary structure refers to the three-dimensional structure of a single, double, or triple bonded protein molecule. tertiary structure is the overall shape of a polypeptide resulting from interactions between the side chains (R groups) of the various amino acids.	the non-specific hydrophobic interactions, such as salt bridges, hydrogen bonds, and the tight packing of side chains and disulfide bonds.	
Quaternary structure	Quaternary structure is the arrangement of multiple folded protein or coiling protein molecules in a multi-subunit complex. The examples are collagen and hemoglobin.	The quaternary structure is stabilized by the same non-covalent interactions and disulfide bonds as the tertiary structure.	

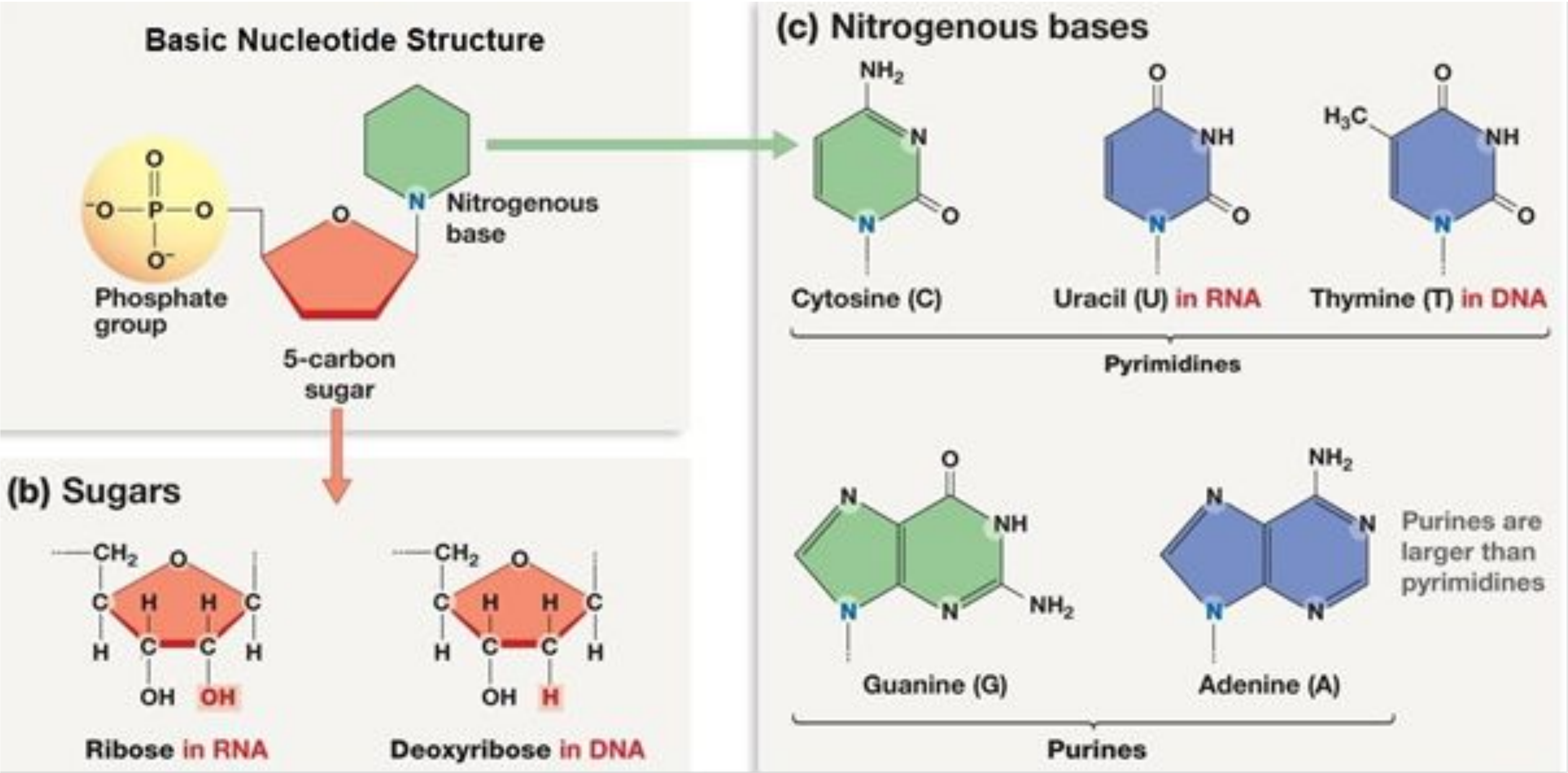
Read the text below, write down the definition of nucleic acids and nucleotides. Draw the scheme of nucleotides and polynucleotides (for more read Campbell et al. 2009:87-89).

Nucleic acids are macromolecules that exist as polymers called **polynucleotides**. There two main types of nucleic acids deoxyribonucleic acid (DNA) and ribonucleic acid (RNA). As indicated by the name, each polynucleotide consists of monomers called **nucleotides**. A nucleotide, in general, is composed of three parts: a nitrogencontaining (nitrogenous) base, a five-carbon sugar (a pentose), and one or more phosphate groups **(Figure)**. In a polynucleotide, each monomer has only one phosphate group. The portion of a nucleotide without any phosphate groups is called a *nucleoside*. Each nitrogenous base has one or two rings that include nitrogen atoms. There are two families of nitrogenous bases: pyrimidines and purines. A pyrimidine has one six-membered ring of carbon and nitrogen atoms. The members of the pyrimidine family are cytosine (C), thymine (T), and uracil (U). Purines are larger, with a six-membered ring fused to a five-membered ring. The purines are adenine (A) and guanine (G). The specific pyrimidines and purines differ in the chemical groups attached to the rings. Adenine, guanine, and cytosine are found in both DNA and RNA; thymine is found only in DNA and uracil only in RNA. In DNA the sugar is **deoxyribose**; in RNA it is **ribose** (see the previous lesson).





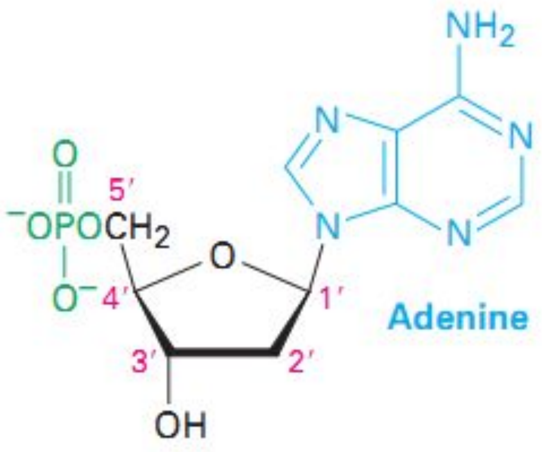




Basic Nucleotide Structure
O
-O—P—O
O-
Phosphate group
O
N
Nitrogenous base
5-carbon sugar
(b) Sugars
CH2
O
C
H
H
C
H
C
C
H
OH
OH
Ribose in RNA
CH2
O
C
H
H
C
H
C
C
H
OH
H
Deoxyribose in DNA
(c) Nitrogenous bases
NH2
N
O
N
Cytosine (C)
O
NH
O
N
Uracil (U) in RNA
O
H3C
NH
O
N
Thymine (T) in DNA
Pyrimidines
O
N
NH
N
N
NH2
Guanine (G)
NH2
N
N
N
N
Adenine (A)
Purines are larger than pyrimidines
Purines

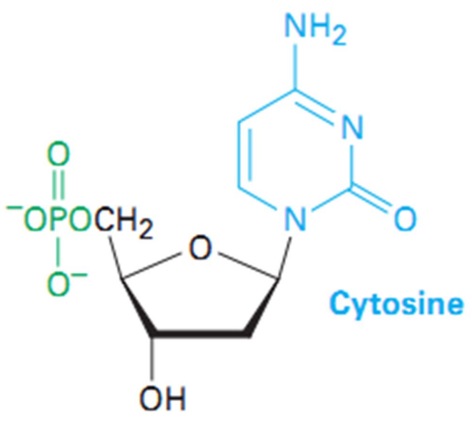
deoxyribonucleotide

A



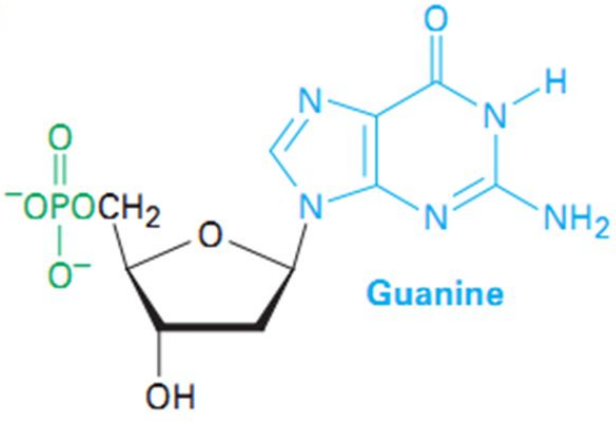
2′-Deoxyadenosine 5′-phosphate

C



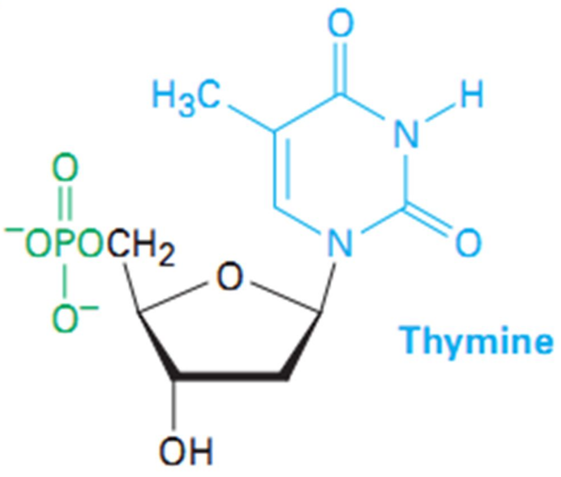
2′-Deoxycytidine 5′-phosphate

G



2′-Deoxyguanosine 5′-phosphate

T



Thymidine 5′-phosphate

Bases attached to a sugar is called **nucleoside**.

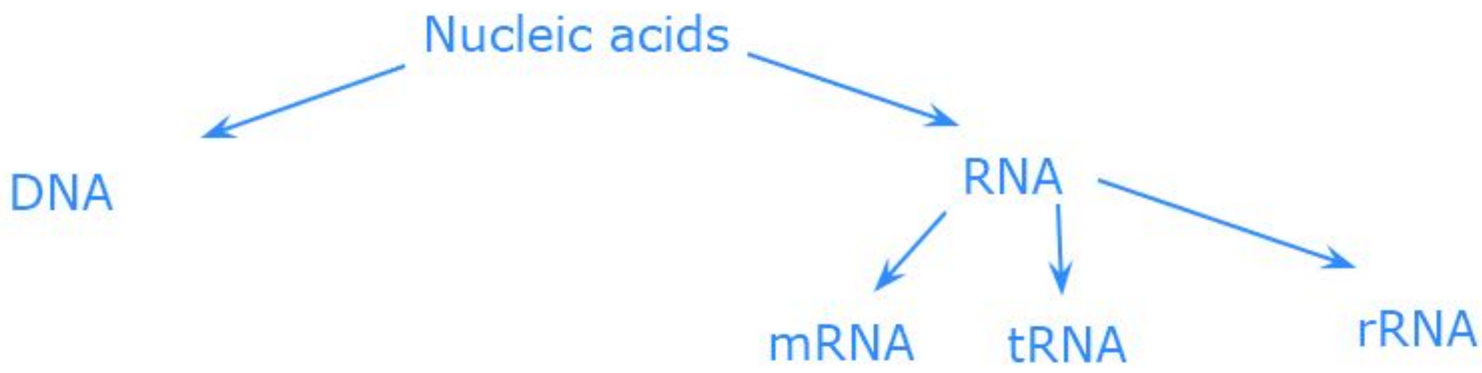
Sugar + phosphate + base = **nucleotide.**

DNA only : Tymine, 2-deoxyribose

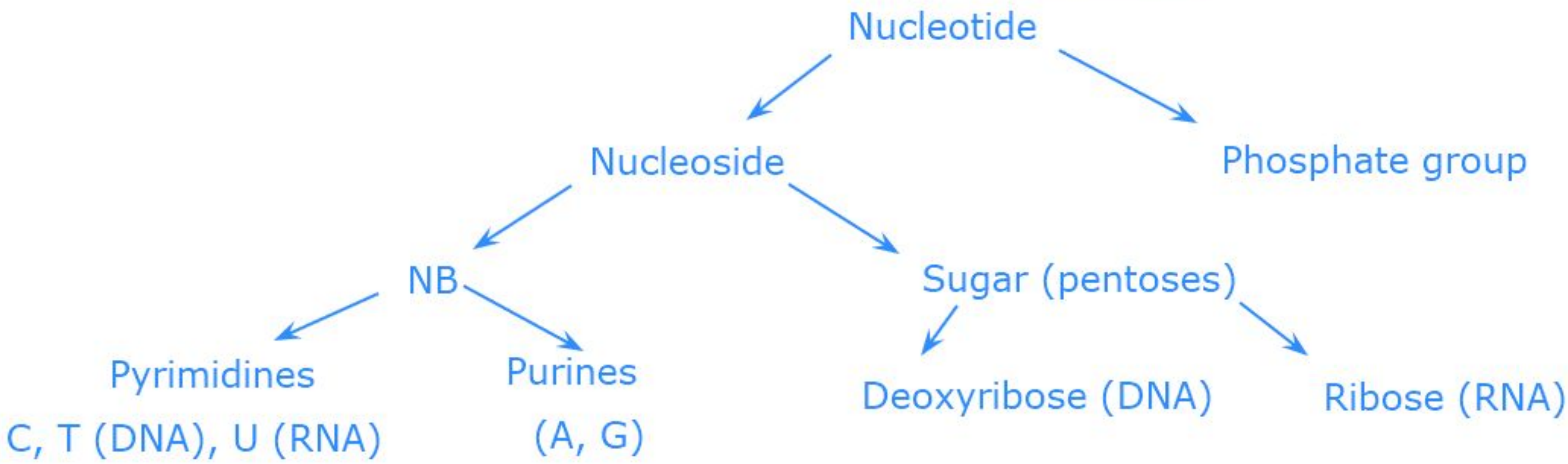
RNA only : Uracil, ribose

DNA and RNA : adenine, guanine, cytosine

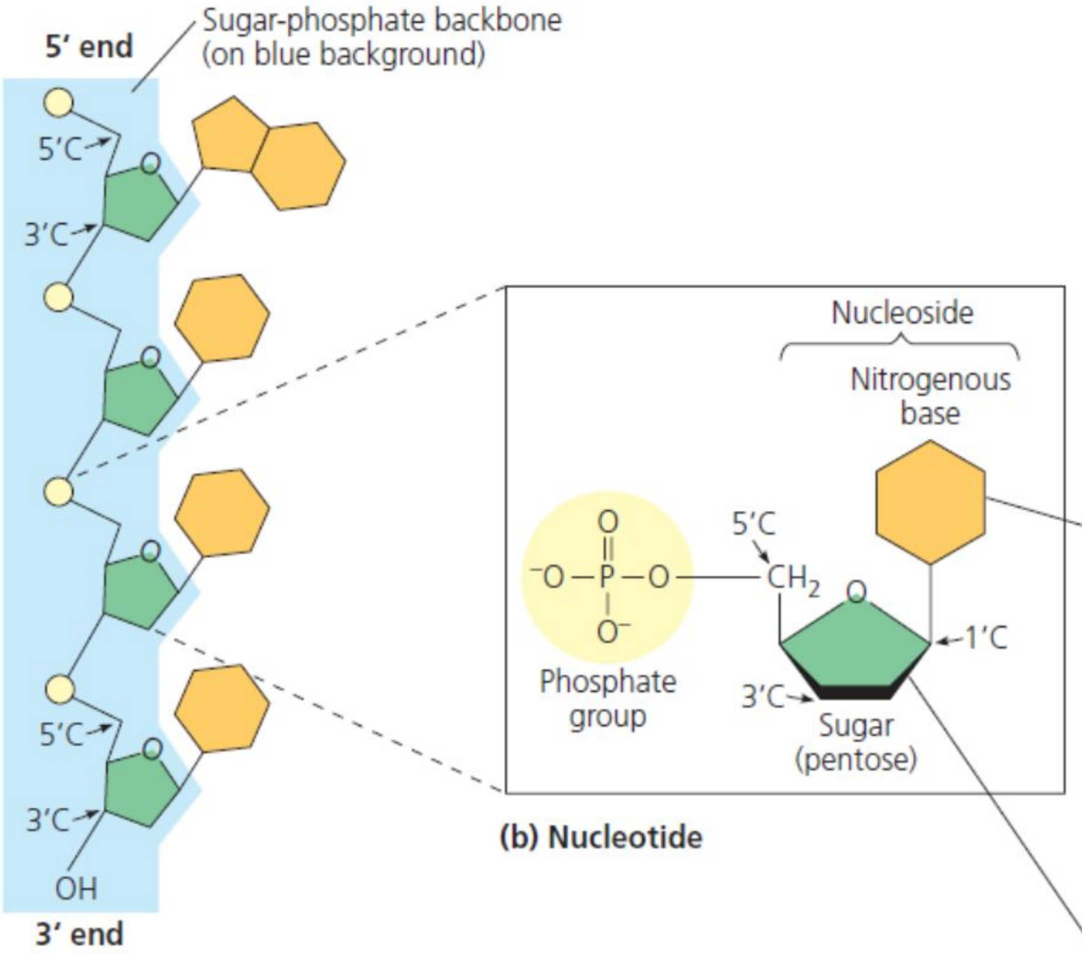
Types of NA



The structure of nucleotide



Adjacent nucleotides are joined by a phosphodiester linkage, which consists of a phosphate group that links the sugars of two nucleotides. This bonding results in a backbone with a repeating pattern of sugar-phosphate units (see Figure). (Note that the nitrogenous bases are not part of the backbone.) The two free ends of the polymer are distinctly different from each other. One end has a phosphate attached to a 5'carbon, and the other end has a hydroxyl group on a 3' carbon; we refer to these as the 5' end and the 3' end, respectively. RNA molecules usually exist as single polynucleotide chains. In contrast, DNA molecules have two polynucleotides, or "strands," that spiral around an imaginary axis, forming a **double helix.** The sequence of bases along a DNA (or mRNA) polymer is unique for each gene and provides very specific information to the cell. The main function of DNA is to store genetic information in cells, whereas RNA performs various function during gene expression (protein synthesis) including carrying instruction from DNA to ribosomes.



According to the Watson-Crick model of a DNA molecule consists of **two** polynucleotide chains forming a **double helix** with diameter of 1.8 - 2.0 nm. At **each turn** of the helix are **ten base pairs**.

The **sugar– phosphate** backbone runs along the **outside** of the helix, and the amine bases hydrogen bond to one another on the inside. Both major and minor grooves are visible.

Two polynucleotide strands are **antiparallel** to each other, so direction of phosphodiester formation is opposite: **one chain is 5' - 3' end** and the other of 3' – 5' end.

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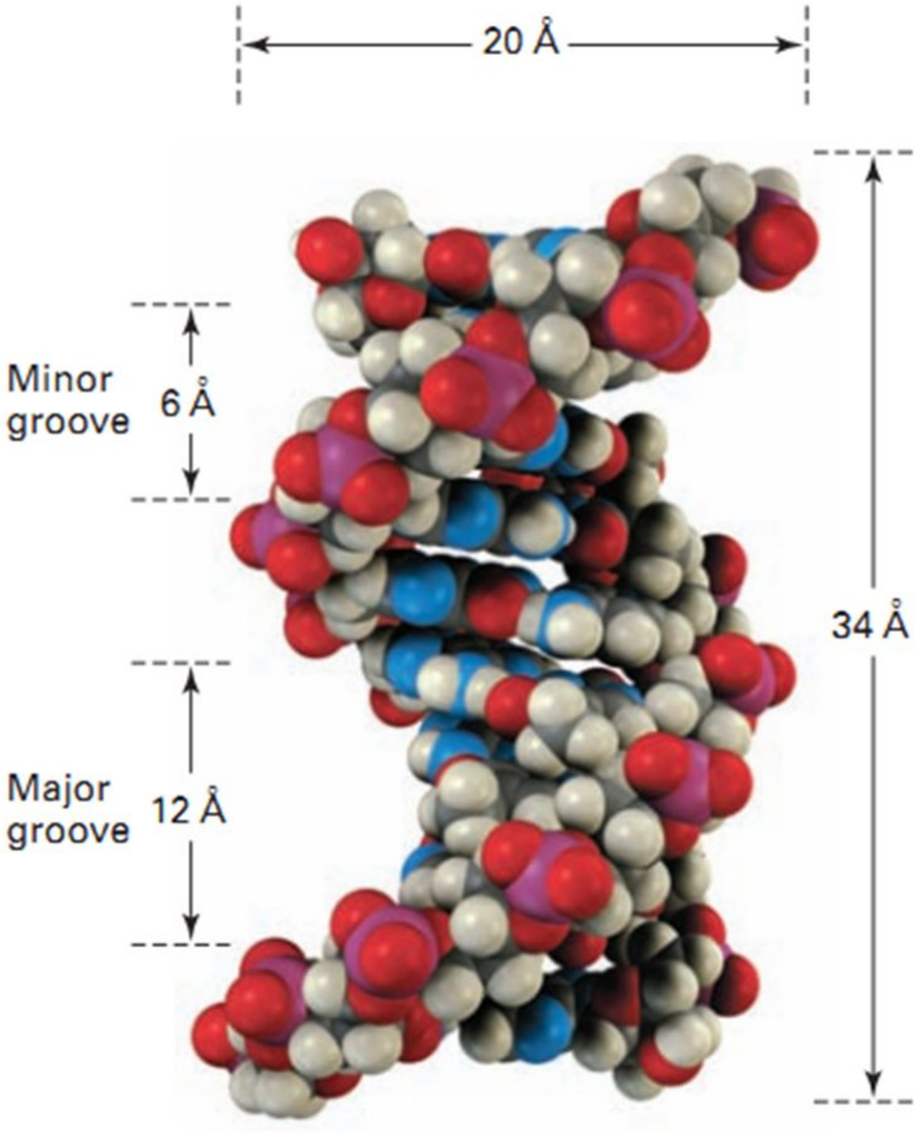
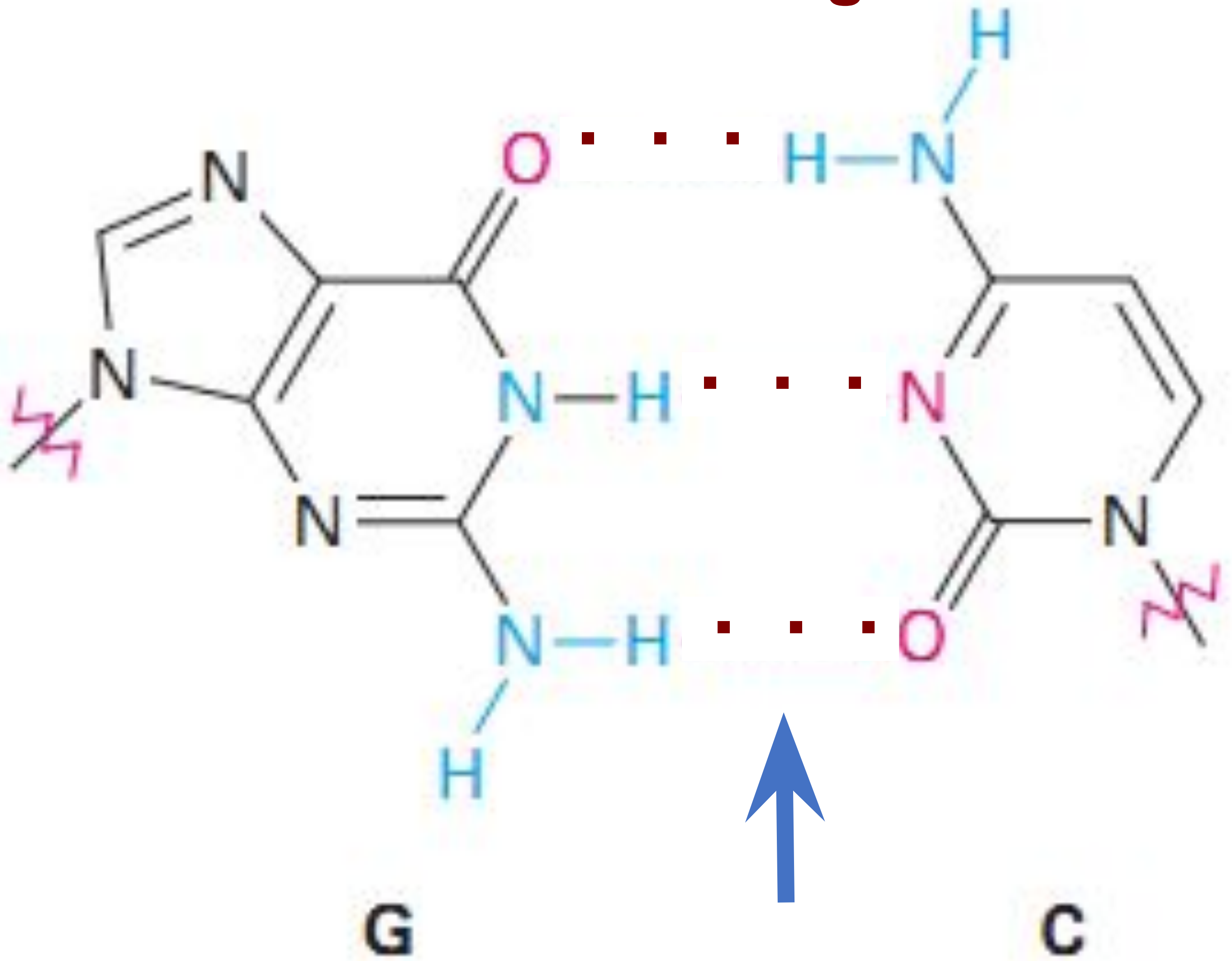


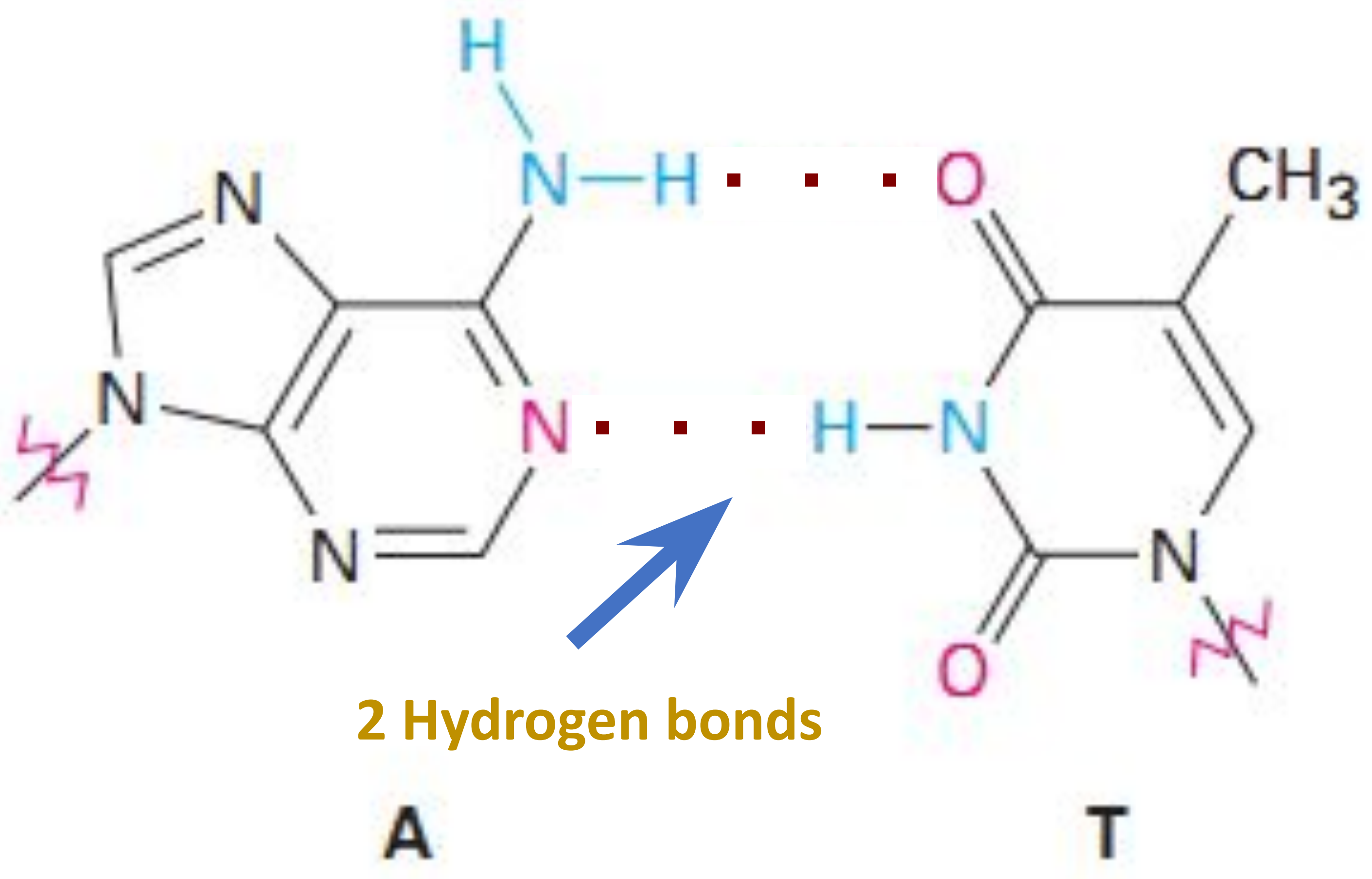
DNA double helix fragment in space-filling

Base Pairing



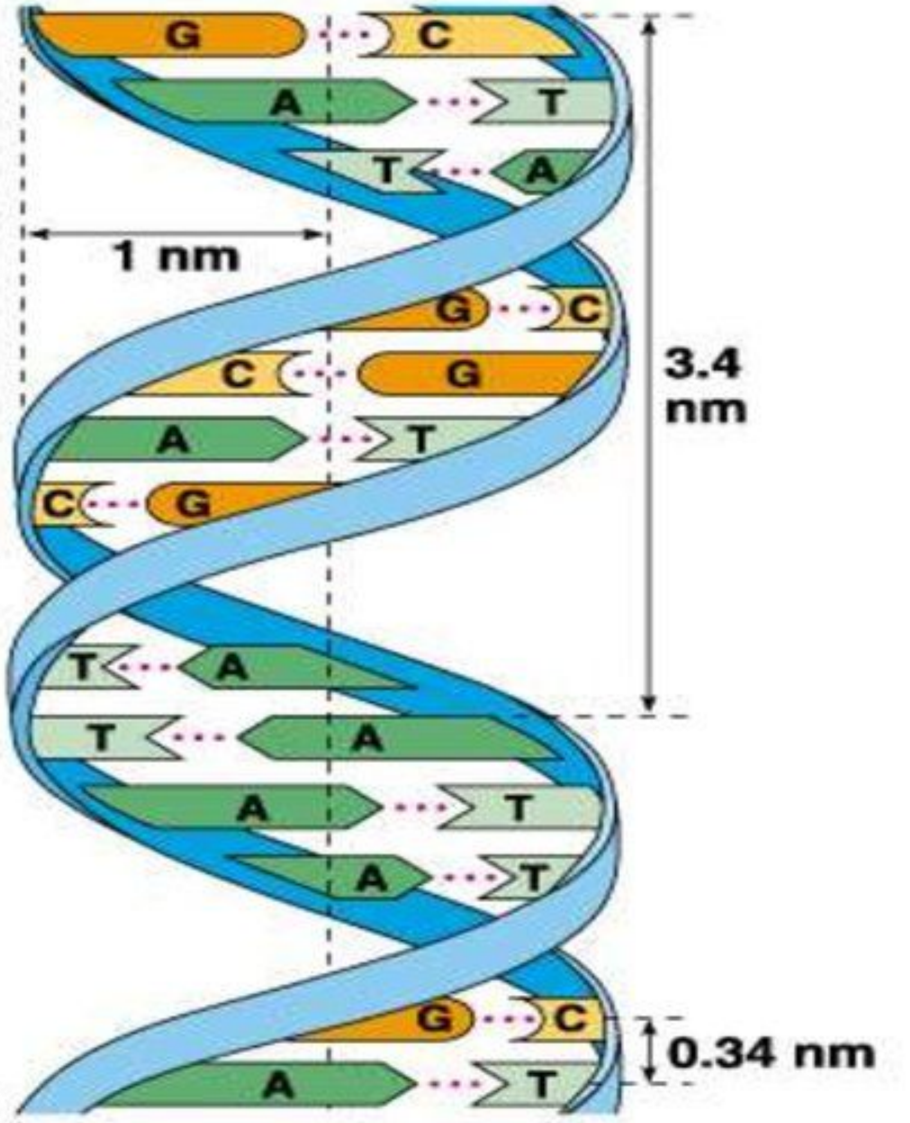
3 Hydrogen bonds

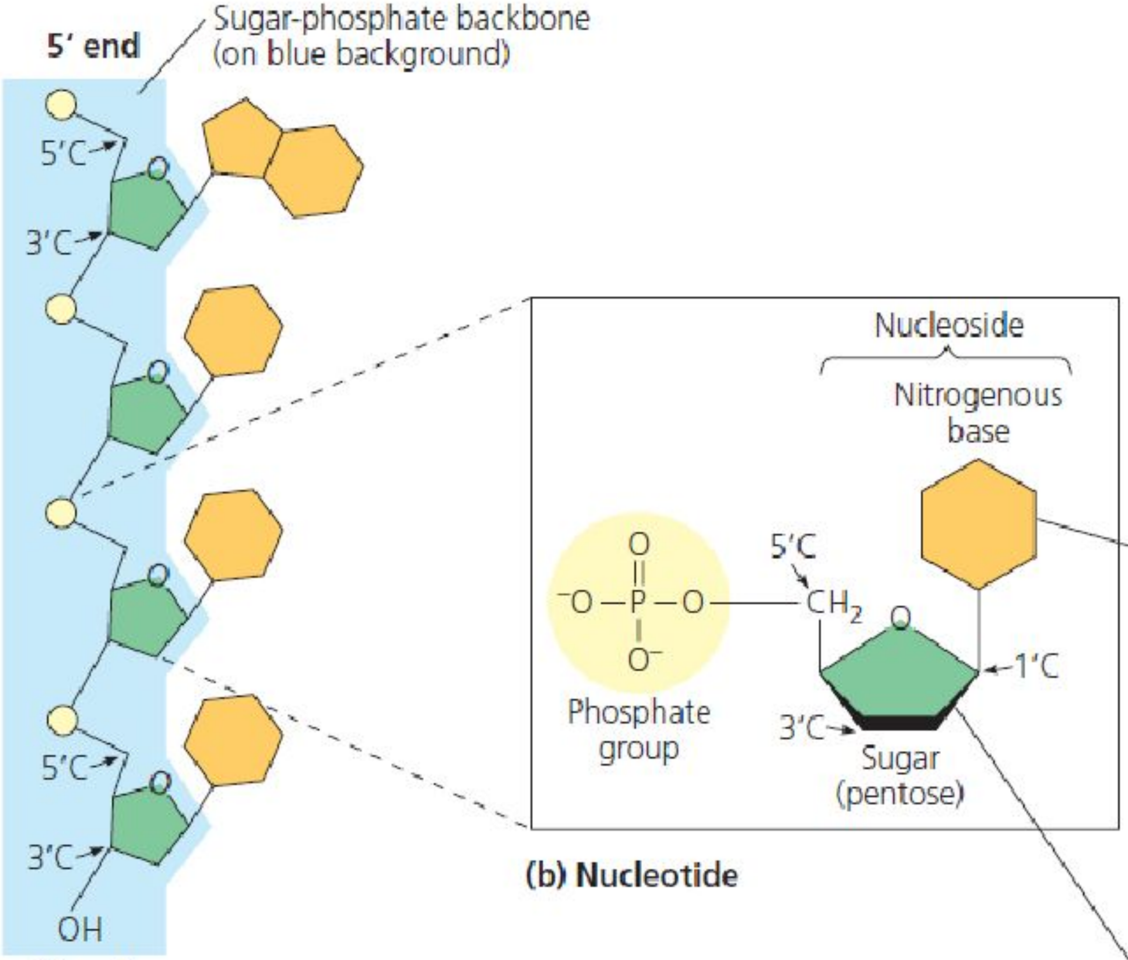
Base Pairing



Chargaff principles:

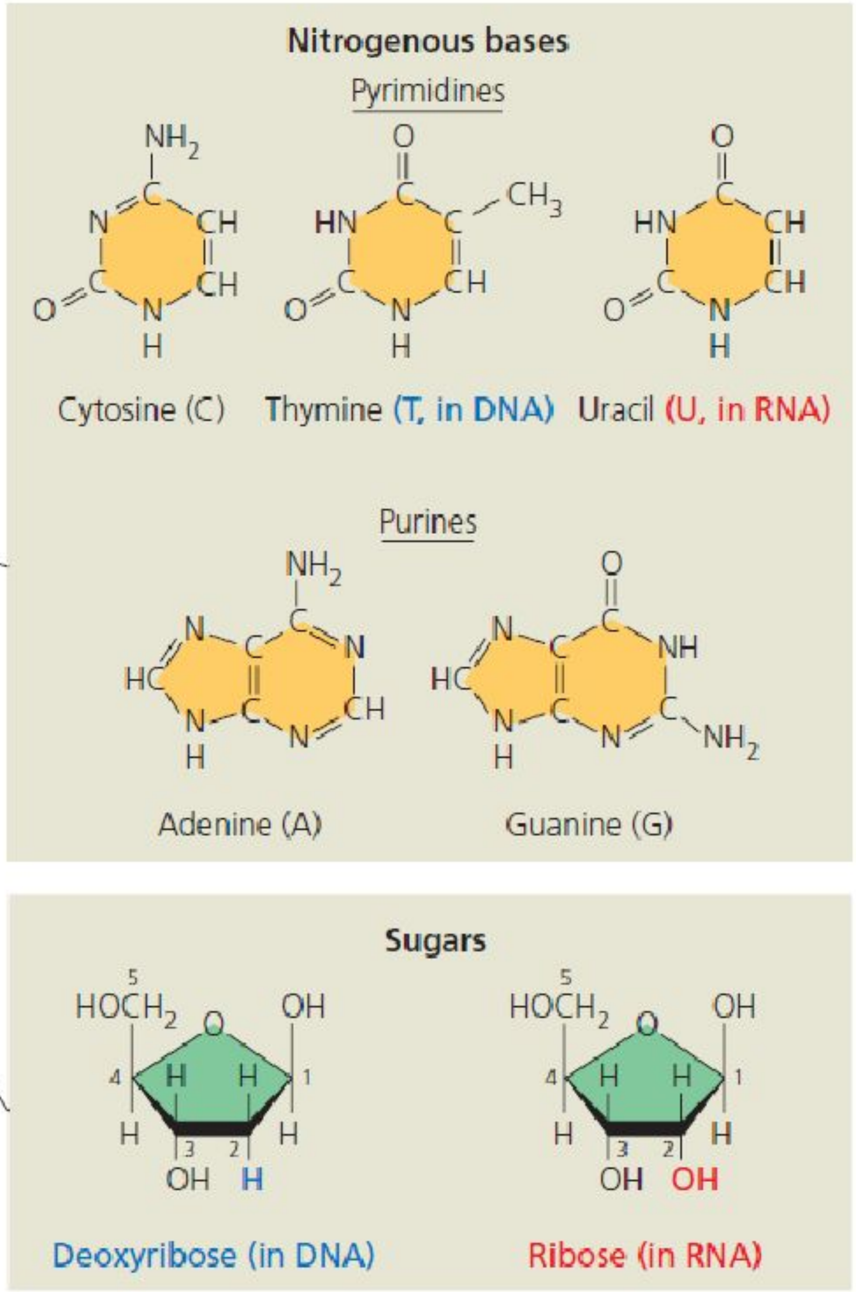
- **A** always pairs with **T** in DNA.
- **C** also pairs with **G** in DNA.
- The amount of A is equal to the amount of T, same for C and G.
-
- A+C = T+G





(a) Polynucleotide, or nucleic acid

(b) Nucleotide



(c) Nucleoside components

▲ **Figure 5.26 Components of nucleic acids. (a)** A polynucleotide has a sugar-phosphate backbone with variable appendages, the nitrogenous bases. **(b)** A nucleotide monomer includes a nitrogenous base, a sugar, and a phosphate group. Without the phosphate group, the structure is called a nucleoside. **(c)** A nucleoside includes a nitrogenous base (purine or pyrimidine) and a five-carbon sugar (deoxyribose or ribose).

Biological molecule	Composition	Function	Examples
Proteins			
Nucleic acids 1. DNA 2. RNA			