# Block I. Biological Chemistry

# Unit4: Carbohydrates I

## 4.1- OBJECTIVES

After reading this unit you will be able to understand-

- What are carbohydrates?
- Structure, sources and the basis of their classification
- Regulation of metabolism

## 4.2- INTRODUCTION

Carbohydrates are the most abundant and important class of organic matter found on earth because of their extensive roles in all forms of life.They comprise one of the four major classes of biomolecules along with proteins, nucleic acids, and lipids.

Carbohydrates constitute a versatile class of molecules. Energy from the sun netted by green plants, algae, and some bacteria during photosynthesis is stored in the form of carbohydrates. They are the metabolic pioneers of virtually all other biomolecules and their oxidation is the central energy-yielding pathway in most nonphotosynthetic cells that sustains life. They play significant roles such as:

- Carbohydrates serve as *energy stores, fuels, and metabolic intermediates.*
- Ribose and deoxyribose sugars form part of the *structural framework of RNA and DNA.*
- Insoluble carbohydrate polymers are *structural elements in the cell walls of bacteria, plants and* in the connective tissues of animals. Interestingly, cellulose, the main constituent of plant cell walls, is one of the most abundant organic compounds in the biosphere.
- Complex carbohydrate polymers are covalently *linked to many proteins and lipids* [Carbohydrates linked to lipid molecules, or glycolipids, are common components of biological membranes. Proteins covalently linked to carbohydrates are called glycoproteins. There two classes of biomolecules, together are called as glycoconjugates]. These glycoconjugates, play key roles in mediating interactions among cells by acting as signals that determine the intracellular location or metabolic fate of these molecules and maintains the interactions between cells and other elements in the cellular environment. Recognition events are important in normal cell growth, fertilization, transformation of cells, and other processes.

All of these functions are made possible by the tremendous *structural diversity* possible within this class of molecules and other chemical characteristics as follows:

(1) The existence of at least one and often two or more asymmetric centers
(2) The ability to exist either in linear or ring structures
(3) The capacity to form polymeric structures via *glycosidic* bonds
(4) The potential to form multiple hydrogen bonds with water or other molecules in their environment.

## 4.3- STRUCTURE

Carbohydrates are polyhydroxy aldehydes or ketones, or substances that yield such compounds on hydrolysis. Many, but not all, carbohydrates have the empirical formula $(CH_2O)_n$ , some also contain nitrogen, phosphorus, or sulfur.

### 4.3.2 CLASSIFICATION

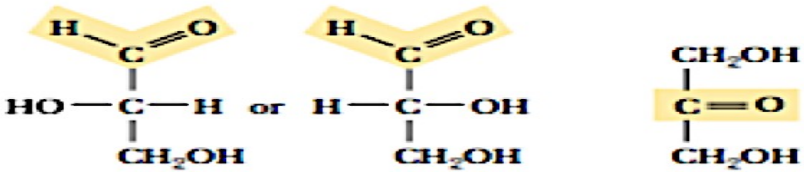
Carbohydrates are generally classified into three major classes: monosaccharides (and their derivatives), oligosaccharides, and polysaccharides (the word "saccharide" is derived from the Greek sakcharon, meaning "sugar"). The monosaccharides are also called simple sugars and have the formula $(CH_2O)_n$, consist of a single polyhydroxy aldehyde or ketone unit. The most abundant monosaccharide in nature is the six-carbon sugar D-glucose, sometimes referred to as dextrose. Monosaccharides more than four carbons tend to have cyclic structures. Monosaccharides cannot be broken down into smaller sugars under mild conditions.

Oligosaccharides originate their name from the Greek word *oligo,* meaning "few," and consist of two to ten simple sugar molecules joined by characteristic linkages called glycosidic bonds. Disaccharides are common in nature, and trisaccharides also occur frequently. In cells, most oligosaccharides consisting of three or more units do not occur as free entities but are joined to nonsugar molecules (lipids or proteins) as glycoconjugates.

As name suggests, polysaccharides are polymers of the simple sugars and their derivatives contains more than 20 or so monosaccharide units and some have hundreds or thousands of units. They may be either linear such as cellulose or branched polymers such as glycogen and may contain hundreds or even thousands of monosaccharide units. Their molecular weights range up to 1 million or more.

### 4.3.3 MONOSACCHARIDES: STRUCTURE AND NOMENCLATURE

Monosaccharides consist typically of three to seven carbon atoms and are described either as **aldoses** or **ketoses,** depending on whether the molecule contains an aldehyde function or a ketone group. They are important fuel molecules as well as building blocks for nucleic acids. The smallest monosaccharides, for which $n = 3$ is, glyceraldehyde (aldose), and dihydroxyacetone (ketose) (Figure 1). Monosaccharides with four, five, six, and seven carbon atoms in their backbones are called, respectively, tetroses, pentoses, hexoses, and heptoses. There are aldoses and ketoses of each of these chain lengths: aldotetroses and ketotetroses, aldopentoses and ketopentoses, and so on.

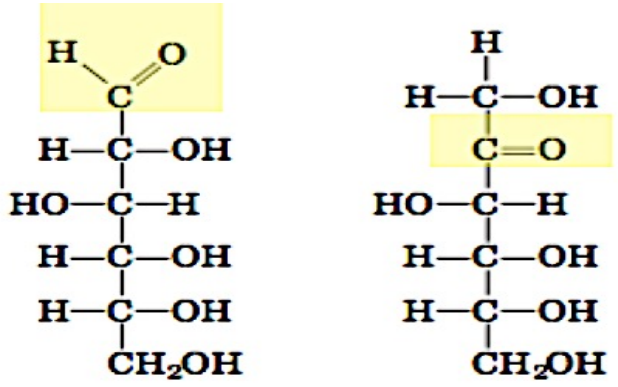



**L-Isomer** **D-Isomer**

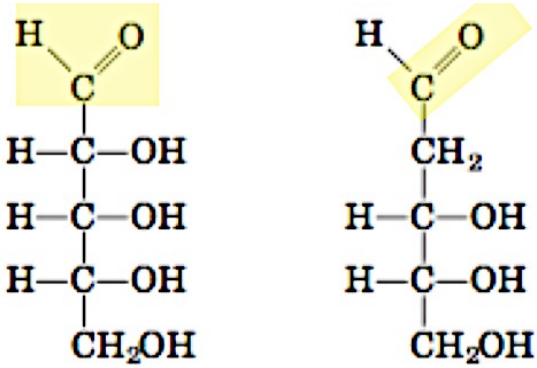
**GLYCERALDEHYDE** **DIHYDROXYACETONE**

**Figure 1 Structure of a simple aldose (glyceraldehyde) and a simple ketose (dihydroxyacetone)**

The hexoses, which include the aldohexose D-glucose and the ketohexose D-fructose (Fig. 2A), are the most common monosaccharides in nature. The aldopentoses D-ribose and 2-deoxy-D-ribose are components of nucleotides and nucleic acids (Fig. 2B). Nevertheless, sugars from all these classes are important in metabolism.



(A) **D-Glucose (aldohexose) D-Fructose (ketohexose)**



(B) **D-Ribose (aldopentose) 2-Deoxy-D-ribose (aldopentose)**

**Figure 2 (A)** Two common hexoses. **(B)** The pentose components of nucleic acids.

**4.3.3.1 Monosaccharides Have Asymmetric Centers**

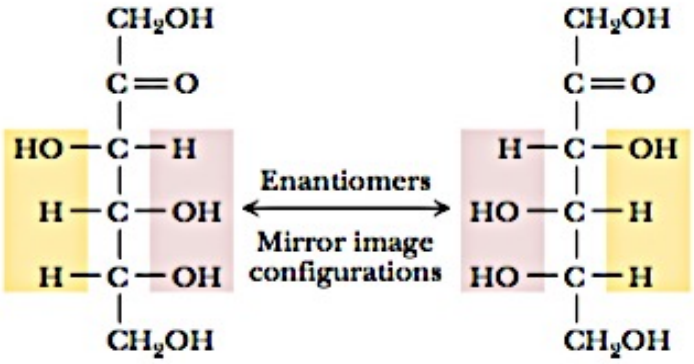
All the monosaccharides except dihydroxyacetone contain one or more asymmetric (chiral) carbon atoms and thus occur in optically active isomeric forms. The simplest aldose, glyceraldehyde, contains one chiral center (the middle carbon atom) and therefore has two different optical isomers (D-Glyceraldehyde and L-Glyceraldehyde), or enantiomers (Fig. 1). By convention, one of these two forms is designated theDisomer, the other the L isomer. To represent three-dimensional sugar structures on paper, we often use Fischer projection formulas (Fig. 7–2) in which atoms are joined to an asymmetric carbon atom by horizontal bonds project out of the plane of the paper, toward the reader (you); vertical bonds project behind the plane of the paper, away from the reader (you).

Generally, a molecule with n chiral centers can have $2^n$stereoisomers. Glyceraldehyde has $2^1$= 2 stereoisomers.

For monosaccharides with two or more asymmetric carbons, the prefix D or L refers to the

configuration of the highest numbered asymmetric carbon (the asymmetric carbon most distant from the carbonyl carbon). A monosaccharide is designated D if the hydroxyl group on the highest numbered asymmetric carbon is drawn to the right in a Fischer projection, as in D - glyceraldehyde (Figure 1).

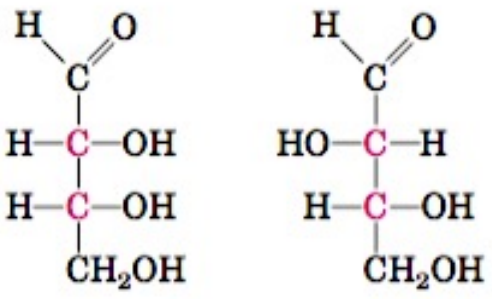
**Note that the designation D or L merely relates the configuration of a given molecule to that of glyceraldehyde and does not specify the sign of rotation of plane-polarized light. If the sign of optical rotation is to be specified in the name, the Fischer convention of D or L designations may be used along with a (plus) or (minus) sign.*




**D-FructoseL-fructose**

**Figure 3 D-Fructose and,L-fructose, an enantiomeric pair.**

The four and five-carbon ketoses are designated by inserting "ul" into the name of a corresponding aldose; for example, D-ribulose is the ketopentose corresponding to the aldopentose D-ribose. The keto- hexoses are named otherwise: for example, fructose and sorbose. According to convention, the D- and L-forms of a monosaccharide are *mirror images* of each other, as shown in Figure 3 for fructose. Stereoisomers that are mirror images of each other are called **enantiomers,** or sometimes *enantiomeric pairs.* For molecules that possess two or more chiral centers, more than two stereoisomers can exist. Pairs of isomers that have opposite configurations at one or more of the chiral centers but that are not mirror images of each other are called **diastereomers** or diastereomeric pairs (Fig.4 A). Two sugars that differ in configuration at only one chiral center are described as **epimers.** For exampleD-glucose and D-mannose are epimers (Fig. 4 B)




**(A) D-Erythrose** **D-Threose**

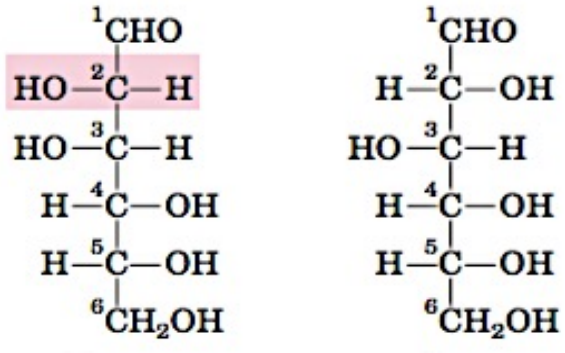



**Figure 4 (A) Diastereomeric pair (B) Epimeric pair (epimer at C-2)**

### 4.3.3.2 Cyclic Structures and Anomeric Forms

Fischer projections are useful for presenting the structures of particular monosaccharides and their stereoisomers, but they ignore one of the most interesting facets of sugar structure—*the ability to form cyclic structures with formation of an additional asymmetric center.* In aqueous solution, aldotetroses and all monosaccharides with five or more carbon atoms in the backbone occur predominantly as cyclic (ring) structures in which the carbonyl group forms a covalent bond with the oxygen of a hydroxyl group along the chain. The formation of these ring structures is the result of a general reaction between alcohols and aldehydes or ketones to form derivatives called hemiacetals or hemiketals (Fig. 5), which contain an additional asymmetric carbon atom and thus can exist in two stereoisomeric forms. The British carbohydrate chemist Sir Norman Haworth showed that the linear form of glucose (and other aldohexoses) could undergo an *intramolecular* reaction to form a *cyclic hemiacetal.* The resulting six-membered, oxygen-containing ring is similar to *pyran* and is designated a pyranose. The reaction is catalyzed by acid ($H^+$) or base ($OH^-$) and is readily reversible. The systematic names for the two ring forms of D-glucose are α-D-glucopyranose and β-D-glucopyranose.

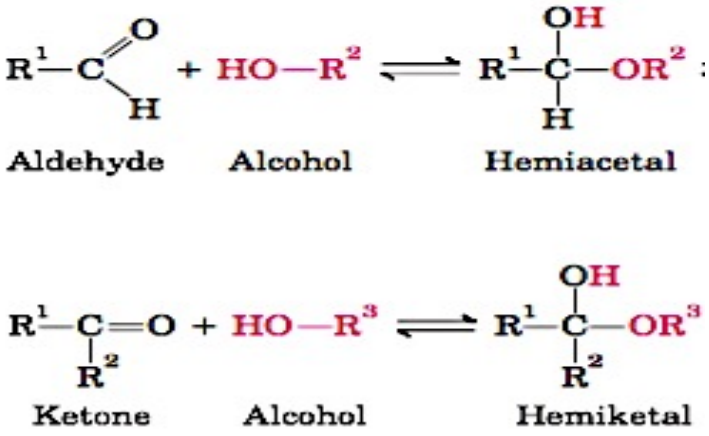



**Figure 5 Formations of Hemiacetals and Hemiketals**

Aldohexoses also exist in cyclic forms having five- membered rings, which, because they resemble the five- membered ring compound furan, are called furanoses. However, the six-membered aldopyranose ring is much more stable than the aldofuranose ring and predominates in aldohexose solutions. Only aldoses having five or more carbon atoms can form pyranose rings.

Isomeric forms of monosaccharides that differ only in their configuration about the hemiacetal or hemiketal carbon atom are called anomers. The hemiacetal (or carbonyl) carbon atom is called the anomeric carbon. α and β anomers of D-glucose interconvert in aqueous solution by a process called mutarotation. Thus, a solution of α-D-glucose and a solution of β-D-glucose eventually form identical equilibrium mixtures having identical optical properties. Mutarotation involves interconversion of α and β forms of the monosaccharide with intermediate formation of the linear aldehyde or ketone (Fig 6 & 7).

Ketohexoses also occur in and anomeric forms. In these compounds the hydroxyl group at C-5 (or C-6) reacts with the keto group at C-2, forming a furanose (or pyranose) ring containing a hemiketal linkage. D-Fructose readily forms the furanose ring (Fig. 7); the more common anomer of this sugar in combined forms or in derivatives is β-D-fructofuranose.

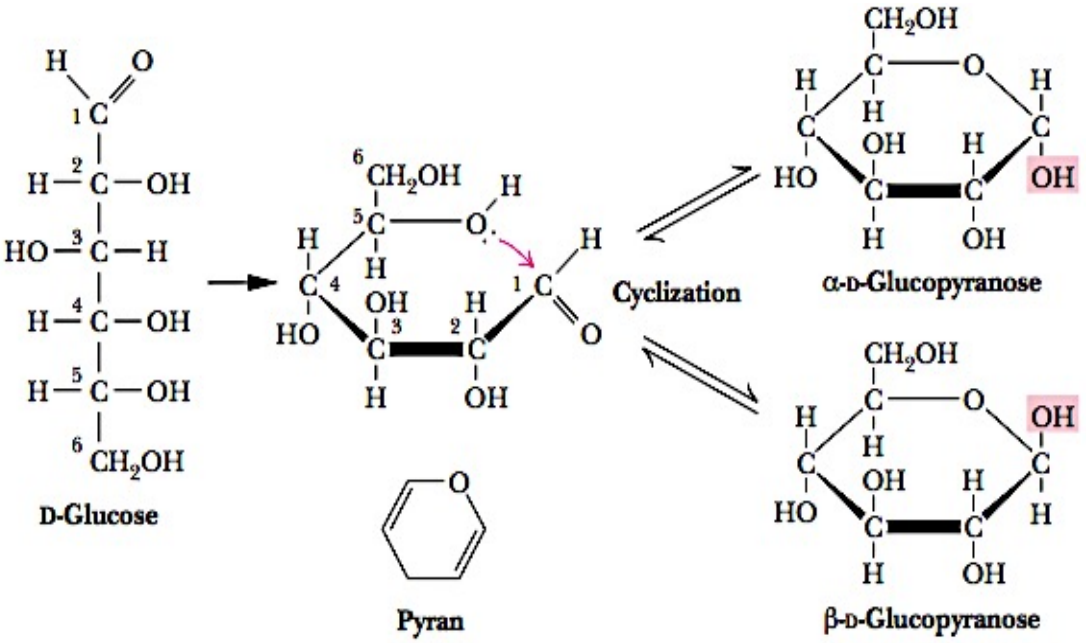
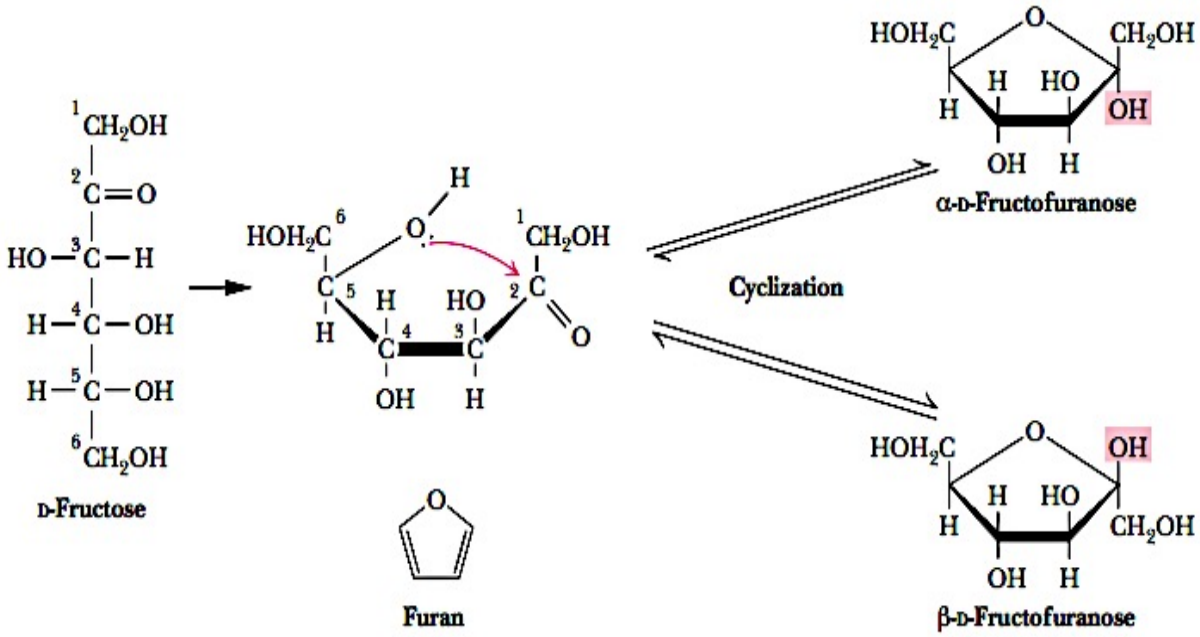



**Figure 6 Formation of the two cyclic forms of D-glucose.**




**HAWORTH PROJECTION FORMULAS**

**Figure 7 Formation of the two cyclic forms of D-Fructose.**

### 4.3.3.3 Haworth Projections

**Haworth projections,** represent pyranose and furanose structures as hexagonal and pentagonal rings lying perpendicular to the plane of the paper, with thickened lines indicating the side of the ring closest to the reader. Such **projections, that** are now widely used to represent saccharide structures (Figures 6 and 7), show substituent groups extending either above or below the ring.

The rules previously mentioned for assignment of α- and β-configurations can be applied to Haworth projection formulas. For the D-sugars, the anomeric hydroxyl group is below the ring in the α-anomer and above the ring in the β-anomer. For L-sugars, the opposite relationship holds.

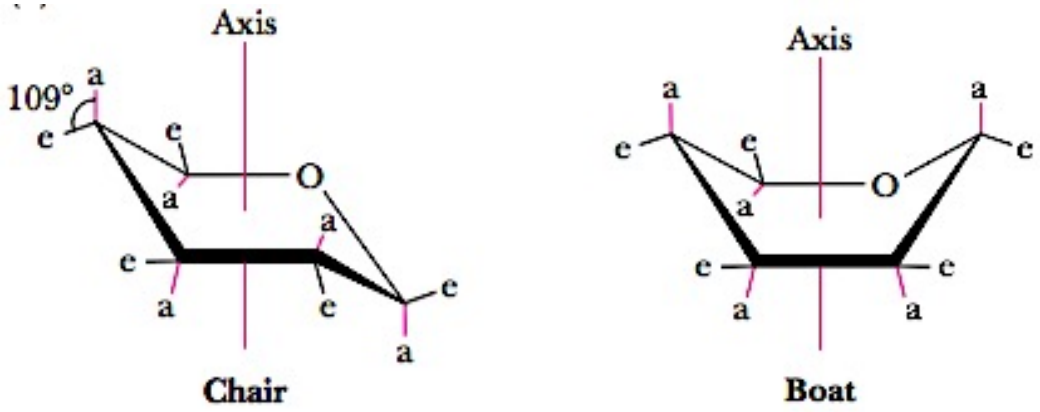
Although Haworth projections are convenient for display of monosaccharide structures, they do not accurately portray the conformations of pyranose and furanose rings. Given C-C-C tetrahedral bond angles of 109° and C-O-C angles of 111°, neither pyranose nor furanose rings can adopt true planar structures. Instead, they take on puckered conformations, and in the case of pyranose rings, the two favored structures are the **chair conformation** and the **boat conformation (**Fig 8A). The ring substituents in these structures can be **equatorial,** which means approximately coplanar with the ring, or **axial,** that is, parallel to an axis drawn through the ring as shown. Two general rules dictate the conformation to be adopted by a given saccharide unit.

(1) Bulky substituent groups on such rings are more stable when they occupy equatorial positions rather than axial positions.

(2) Chair conformations are slightly more stable than boat conformations.

For a typical pyranose, such as β-D-glucose, there are two possible chair conformations (Figure 9B). Interestingly, of all the D-aldohexoses, β-D-glucose is the only one that can adopt a conformation with all its bulky groups in an equatorial position. With this advantage of stability, β-D-glucose is the most widely occurring organic group in nature and the central hexose in carbohydrate metabolism.

**(A)**




**a = axial bond e = equatorial bond**

**(B)**

**Figure 8** (A) Chair and boat conformations of a pyranose sugar. (B) Two possible chair conformations of β-D-glucose.

**4.3.3.4 Derivatives of Monosaccharides**

***Sugar Acids***

Sugars with free anomeric carbon atoms are rationally good reducing agents and reduce hydrogen peroxide, ferricyanide, certain metals and other oxidizing agents, resulting in the conversion of the sugar to a **sugar acid.**

Monosaccharides can be oxidized enzymatically at C-6, yielding **uronic acids,** such as **D-glucuronic** and **L-iduronic** acids (Figure9). L-Iduronic acid is similar to D-glucuronic acid, except for having an opposite configuration at C-5. Oxidation at both C-1 and C-6 produces **aldaric acids,** such as **D-glucaric acid.**

### *Sugar Alcohols*

**Sugar alcohols** can be prepared by the mild reduction of the carbonyl groups of aldoses and ketoses. Sugar alcohols, or **alditols,** are designated by the addition of *-itol* to the name of the parent sugar (Figure 10). The alditols are linear molecules that cannot cyclize in the manner of aldoses. Nonetheless, alditols are characteristically sweet tasting, and **sorbitol, mannitol,** and **xylitol** are widely used to sweeten sugarless gum and mints.

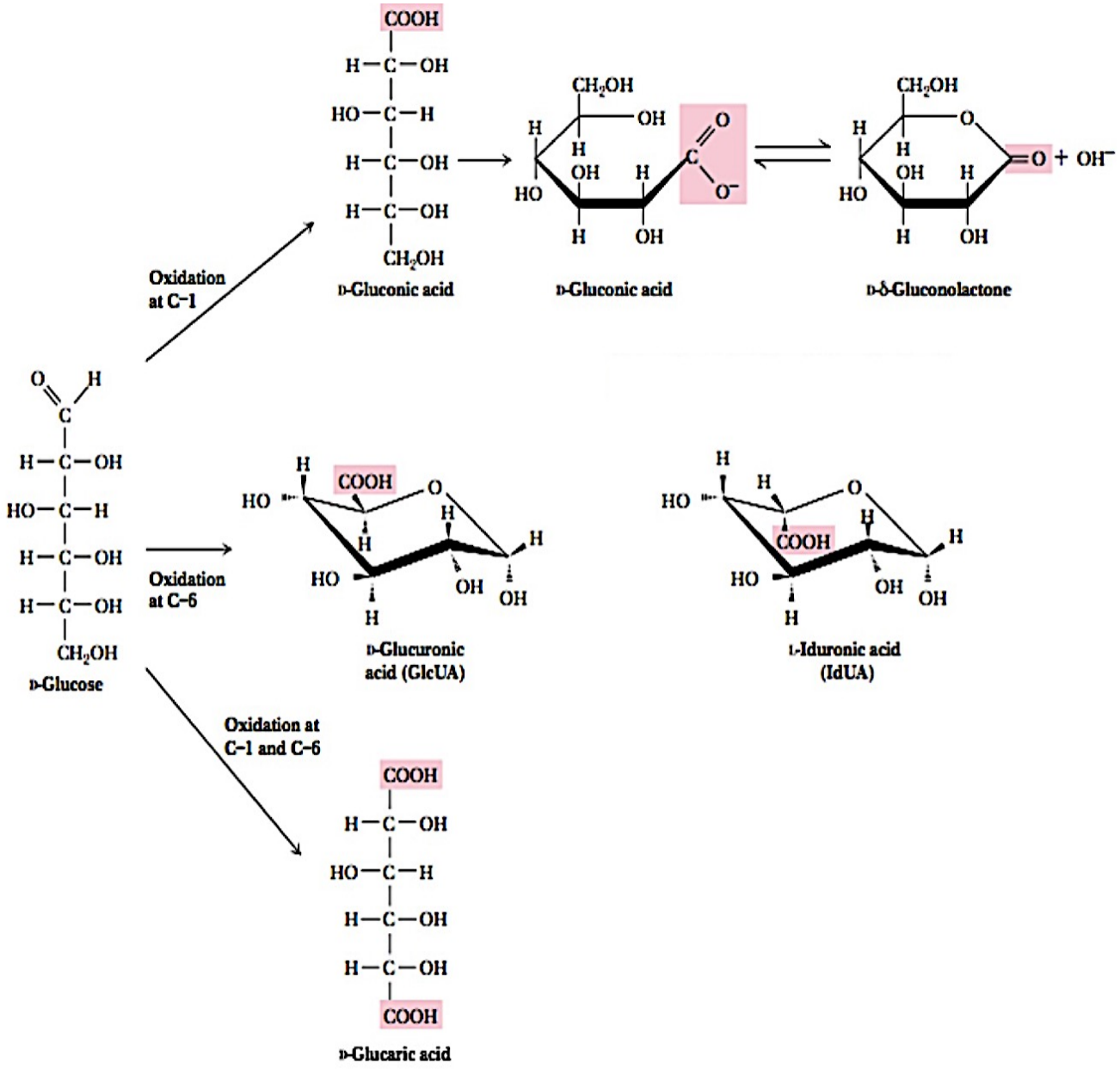
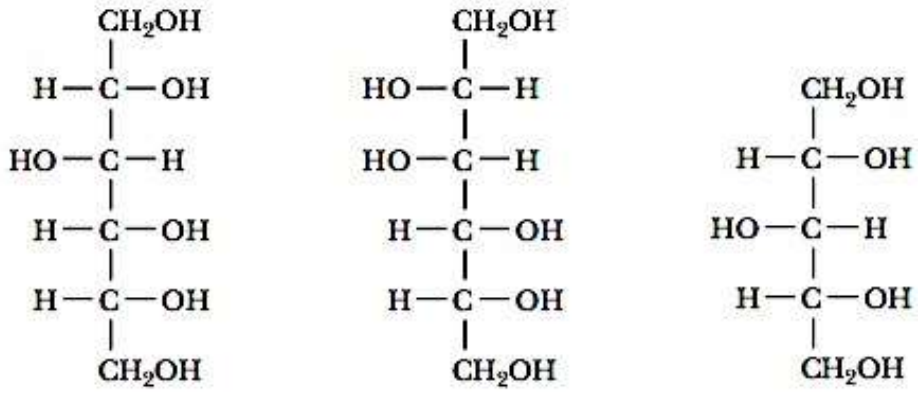



**Figure 9 Oxidation of Monosaccharides**

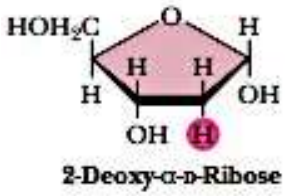


**D-Glucitol (sorbitol)** **D-Mannitol** **D-Xylitol**

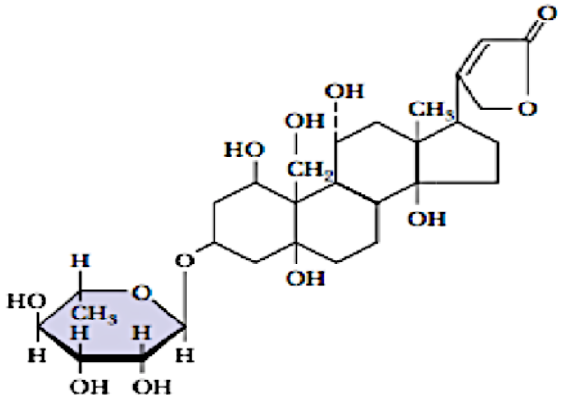
**Figure 10 Structures of some sugar alcohols**

***Deoxy Sugars***

The **deoxy sugars** are monosaccharides with one or more hydroxyl groups replaced by hydrogens. 2-Deoxy-**D**-ribose (Figure 11), whose systematic name is 2-deoxy-**D**-erythropentose, is a constituent of DNA in all livingbeings. Deoxy sugars also occur frequently in glycoproteins and polysaccharides.**L**-Fucose and **L**-rhamnose, both 6-deoxy sugars, are components of some cell walls, and rhamnose is a component of **ouabain,** a highly toxic *cardiac glycoside* found in the bark and root of the ouabain tree.



**2-Deoxy-α-D-Ribose**



**Ouabain**

**Figure 11** Deoxy sugars and ouabain. Hydrogen atoms highlighted in red show "deoxy" positions.

***Sugar Esters***

Phosphate esters of glucose, fructose, and other monosaccharides are important metabolic intermediates, and the ribose moiety of nucleotides such as ATP and GTP is phosphorylated at the 5' position (Fig 12).

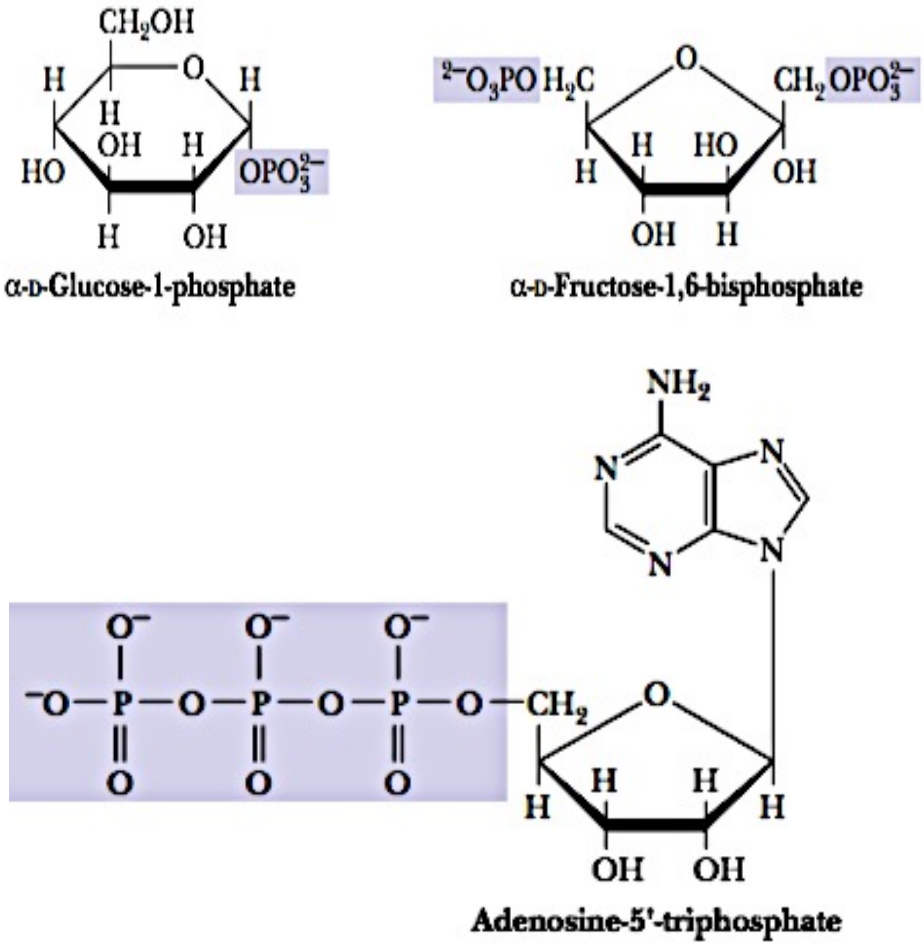


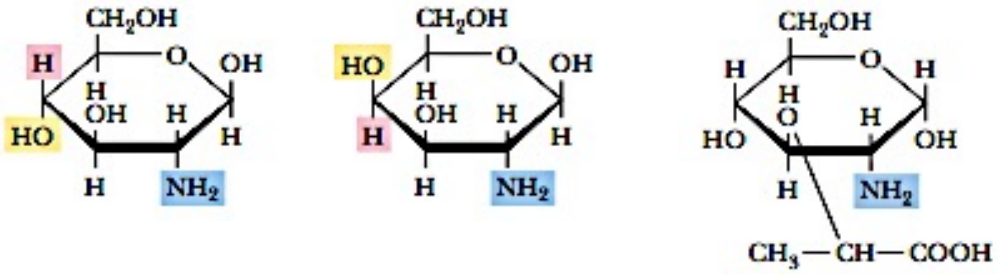

**Figure 12 Sugar esters**

## *Amino Sugars*

**D-Glucosamine**and **D-Galactosamine-**contain an amino group (instead of a hydroxyl group) at the C-2 position (Figure 13). They are found in many oligo- and polysaccharides, including *chitin,* a polysaccharide in the exoskeletons of crustaceans and insects.

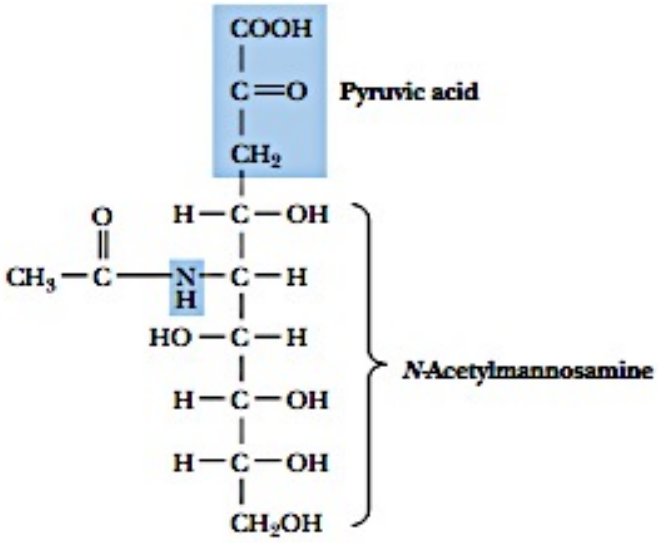
**Muramic acid** and **Neuraminic acid-** components of polysaccharides of cell membranes of higher organisms and also bacterial cell walls are having glucosamines linked to three-carbon acids at the C-1 or C-3 positions. In muramic acid the hydroxyl group of a lactic acid moiety makes an ether linkage to the C-3 of glucosamine. Neuraminic acid (an *ami*ne isolated from *neur*al tissue) forms a C-C bond between the C-1 of *N*- acetylmannosamine and the C-3 of pyruvic acid (Figure13).

**Sialic acids-** The *N*-acetyl and *N*-glycolyl derivatives of neuraminic acid are collectively known as **sialic acids** found widely in bacteria and animal systems.




β-D-Glucosamine β-D-Galactosamine

**Muramic acid**




**N-Acetyl-D-neuraminic acid (NeuNAc)**

**Figure 13 Structure of amino sugars**

***Acetals, Ketals, and Glycosides***

Hemiacetals and hemiketals can react with alcohols in the presence of acid to form **acetals** and **ketals** (Figure 14). This reaction is a type of a *dehydration synthesis.*The pyranose and furanose forms of monosaccharides react with alcohols in the same way to form **glycosides** with retention of the α- and β-configuration at the C-1 carbon. The new bond between the anomeric carbon atom and the oxygen atom of the alcohol is called a **glycosidic bond.** Glycosides are named according to the parent monosaccharide.

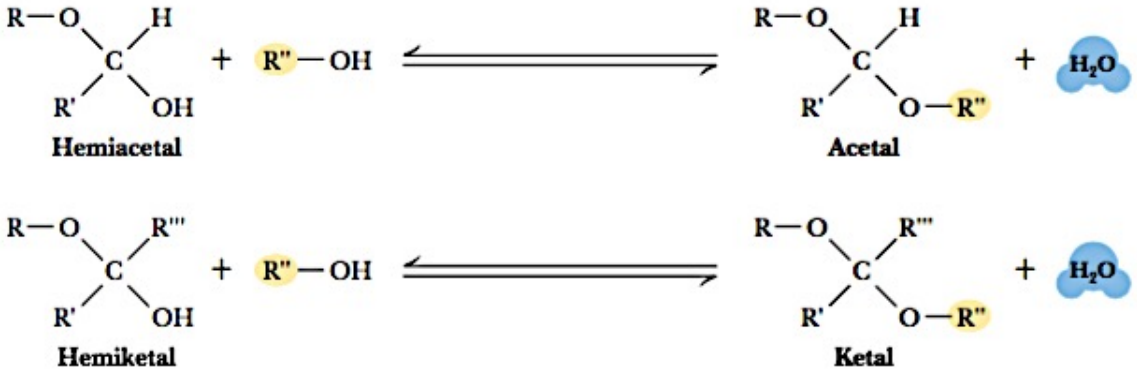



**Figure 14** Formation of acetals and ketals from hemiacetals and hemiketals

### 4.3.4 OLIGOSACCHARIDE: STRUCTURE AND NOMENCLATURE

An **oligosaccharide** (from the Greek olígos, "a few", andsácchar, "sugar") is a saccharidepolymer containing a small number (typically two to ten) of simple sugars (monosaccharides). Monosaccharide units include the hexoses (glucose, fructose, mannose, and galactose) and the pentoses (ribose and xylose).

**Disaccharides**

**Disaccharides are the** simplest oligosaccharides consist of two monosaccharide units linked by a glycosidic bond. The disaccharides commonly found in nature are sucrose, maltose, and lactose. The molecule is a mixed acetal, when a hydroxyl group of one sugar reacts with the anomeric carbon of the other. Except for sucrose, each of these structures possesses one free unsubstituted anomeric carbon atom, and thus each of these disaccharides is a reducing sugar. The end of the molecule containing the free anomeric carbon is called the **reducing end,** and the other end is called the **nonreducing end.** In the case of sucrose, both of the anomeric carbon atoms are substituted, that is, neither has a free -OH group. The substituted anomeric carbons cannot be converted to the aldehyde configuration and thus cannot participate in the oxidation–reduction reactions characteristic of reducing sugars. Thus, sucrose is *not* a reducing sugar.

Maltose, isomaltose, and cellobiose (Figure 15) are all **homodisaccharides** because they each contain only one kind of monosaccharide, namely, glucose. **Maltose** is produced from starch (a polymer of -D-glucose produced by plants) by the action of amylase enzymes and is a component of malt (a substance obtained by allowing grain to soften in water and germinate). The enzyme **diastase,** produced during the germination process, catalyzes the hydrolysis of starch to maltose. Maltose is used in beverages and because it is fermented readily by yeast, it is important in the brewing of beer. In both maltose and cellobiose, the glucose units are **1➔4 linked,** meaning that the C-1 of one glucose is linked by a glycosidic bond to the C-4 oxygen of the other glucose. The only difference between them is in the configuration at the glycosidic bond. Maltose exists in the α- configuration, whereas cellobiose is β. **Isomaltose** is obtained in the hydrolysis of some poly- saccharides (such as dextran), and **cellobiose** is obtained from the acid hydrolysis of cellulose. Isomaltose also consists of two glucose units in a glycosidic bond, but in this case, C-1 of one glucose is linked to C-6 of the other, and the configuration is α.

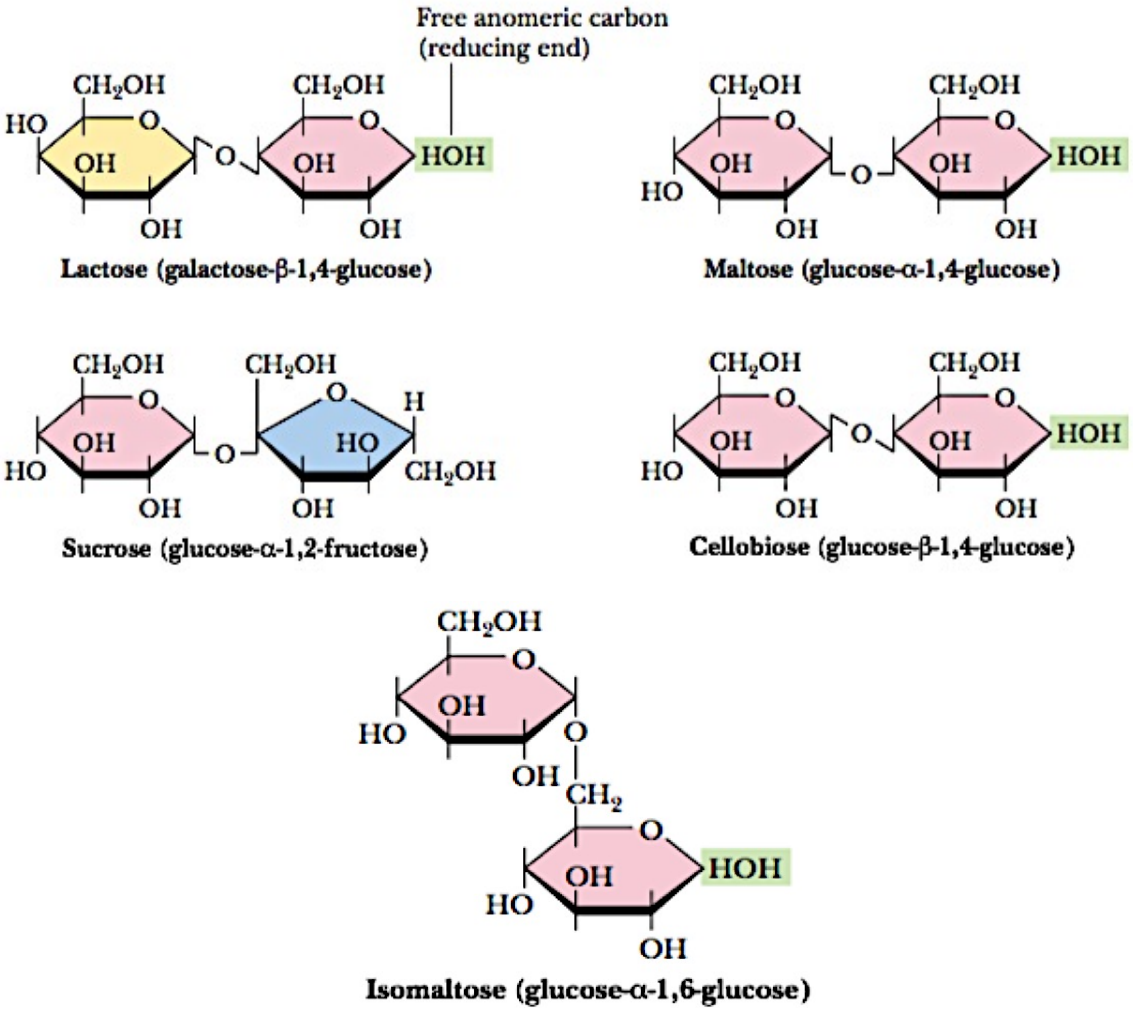



**Figure 15** The structures Disaccharides (*Note: Pink colored ring= Glucose, yellow colored ring= galactose, blue colored ring = fructose)

**Rules of Nomenclature of Disaccharides:**

To name reducing disaccharides several rules are followed. By convention, the name describes the compound with its nonreducing end to the left, and we can "build up" the name in the following order. (1) Give the configuration (α or β) at the anomeric carbon joining the first monosaccharide unit (on the left) to the second. (2) Name the nonreducing residue; to distinguish five- and six-membered ring structures, insert "furano" or "pyrano" into the name. (3) Indicate in parentheses the two carbon atoms joined by the glycosidic bond, with an arrow connecting the two numbers; for example, (1➔**4**) shows that C-1 of the first-named sugar residue is joined to C-4 of the second. (4) Name the second residue. If there is a third residue, describe the second glycosidic bond by the same conventions.

β-**D**-**lactose** (O-β-**D**-Galactopyranosyl-(1➔**4**)**D**-glucopyranose) (Figure 15) is the prime carbohydrate in milk and is of prime nutritional importance to mammals in the early stages of their lives. It is formed from D-galactose and D-glucose via a (1➔**4**) link, and because it has a free anomeric carbon available for oxidation, it is capable of mutarotation and is a reducing

sugar. Its abbreviated name is Gal(β1➔**4**)Glc. It is an interesting peculiarity of nature that lactose cannot be absorbed directly into the bloodstream. It must first be broken down into galactose and glucose by **lactase,** an intestinal enzyme that exists in young, nursing mammals but is not produced in significant quantities in the mature mammal. Most humans, with the exception of certain groups in Africa and northern Europe, produce only low levels of lactase. For most individuals, this is not a problem, but some cannot tolerate lactose and experience intestinal pain and diarrhea upon consumption of milk.

**Sucrose,** in contrast, is a disaccharide of almost universal appeal and tolerance. Produced by many higher plants and commonly known as *table sugar,* it is one of the products of photosynthesis and is composed of fructose and glucose. Sucrose is hydrolyzed by the enzyme **invertase,** and also easily hydrolyzed by dilute acid, apparently because the fructose in sucrose is in the relatively unstable furanose form. Contradictory to maltose and lactose, sucrose contains no free anomeric carbon atom; the anomeric carbons of both monosaccharide units are involved in the glycosidic bond (Fig. 15). Sucrose is therefore a nonreducing sugar. In the abbreviated nomenclature, a double-headed arrow connects the symbols specifying the anomeric carbons and their configurations. For example, the abbreviated name of sucrose is either Glc(α1↔2β)Fru or Fru(β2↔1α )Glc. Although sucrose and maltose are important to the human diet, they are not taken up directly in the body. In a manner similar to lactose, they are first hydrolyzed by **sucrase** and **maltase,** respectively, in the human intestine.

### 4.3.5 POLYSACCHARIDE: STRUCTURE AND NOMENCLATURE

Polysaccharides, also called glycans, differ from each other in the identity of their recurring monosaccharide units, in the length of their chains, in the types of bonds linking the units, and in the degree of branching. Basically they are of two types:

**Homopolysaccharides**- contains only a single type of monomer. Some serve as storage forms of monosaccharides that are used as fuels (starch and glycogen) other (cellulose and chitin) serve as structural elements in plant cell walls and animal exoskeletons. Homopolysaccharides are often named for the sugar unit they contain, so that glucose homopolysaccharides are called **glucans,** while mannose homopolysaccharides are **mannans.** Other homopolysaccharide names are just as obvious: *galacturonans, arabinans,* and so on. Homopolysaccharides of uniform linkage type are often named by including notation to denote ring size and linkage type.

**Heteropolysaccharides**- contains two or more different kinds of monomer. They provide extracellular support for organisms of all kingdoms (peptidoglycan in the bacterial cell envelope, the extracellular matrix in animal tissues).

Interestingly, polysaccharides include not only those substances composed only of glycosidically linked sugar residues but also molecules that contain polymeric saccharide structures linked via covalent bonds to amino acids, peptides, proteins, lipids, and other structures. The most common constituent of polysaccharides is D-glucose, but D-fructose, D-galactose, L-galactose, D-mannose, L-arabinose, and D-xylose are also common. Common monosaccharide derivatives in polysaccharides include the amino sugars (D-glucosamine and D-galactosamine), their derivatives (*N*-acetylneuraminic acid and *N*-acetylmuramic acid), and simple sugar acids (glucuronic and iduronic acids). Polysaccharides differ not only in the nature of their component monosaccharides but also in the length of their chains and in the amount of chain branching that occurs. Although a given sugar residue has only one anomeric carbon and thus can form only one glycosidic linkage with hydroxyl groups on other molecules, each sugar

residue carries several hydroxyls, one or more of which may be an acceptor of glycosyl substituents. This ability to form branched structures distinguishes polysaccharides from proteins and nucleic acids, which occur only as linear polymers.

### 4.3.6.1 POLYSACCHARIDE FUNCTIONS

- Typically as storage materials, structural components, or protective substances.
- Variety of cellular recognition and intercellular communication events.

### 4.3.6.2 STORAGE POLYSACCHARIDES

The most important storage polysaccharides are starch in plant cells and glycogen in animal cells. Both polysaccharides occur intracellularly as large clusters or granules. Starch and glycogen molecules are heavily hydrated, because they have many exposed hydroxyl groups available to hydrogen bond with water. Most plant cells have the ability to form starch, but it is especially abundant in tubers, such as potatoes, and in seeds.

**It is noteworthy to tell you that** *organisms store carbohydrates in the form of polysaccharides rather than as monosaccharides to lower the osmotic pressure of the sugar reserves. Because osmotic pressures depend only on numbers of molecules, the osmotic pressure is greatly reduced by formation of a few polysaccharide molecules out of thousands (or even millions) of monosaccharide units.*

### STARCH

By far the most common storage polysaccharide in plants is **starch,** which exists in two forms: α**-amylose** and **amylopectin (**Figure 16). Most forms of starch in nature are 10 to 30% α-amylose and 70 to 90% amylopectin. -Amylose is composed of linear chains of **D-**glucose in (1→4) linkages. The chains are of varying length, having molecular weights from several thousand to half a million. The chain has a reducing end and a nonreducing end. Although poorly soluble in water, α-amylose forms micelles in which the polysaccharide chain adopts a helical conformation. Iodine reacts with α-amylose to give a characteristic blue color, resulted from the insertion of iodine into the middle of the hydrophobic amylose helix.

In contrast to α-amylose, amylopectin is a highly branched chain of glucose units (Figure 16). Branches occur in these chains every 12 to 30 residues. The average branch length is between 24 and 30 residues, and molecular weights of amylopectin molecules can range up to 100 million. The linear linkages in amylopectin are (1→4), whereas the branch linkages are (1→6). As is the case for α-amylose, amylopectin forms micellar suspensions in water; iodine reacts with such suspensions to produce a red-violet color.

#### *Glycogen*

The major form of storage polysaccharide in animals is **glycogen.** Glycogen is found mainly in the liver and skeletal muscle. Like amylopectin, glycogen is a polymer of (1→4)-linked subunits of glucose, with (1→6)- linked branches, but glycogen is more extensively branched (on average, every 8 to 12 residues) and more compact than starch. Like amylopectin, glycogen yields a red-violet color with iodine. Glycogen can be hydrolyzed by both α- and β-amylases, yielding glucose and maltose, respectively, as products and can also be hydrolyzed by **glycogen phosphorylase,** an enzyme present in liver and muscle tissue, to release glucose-1-phosphate.

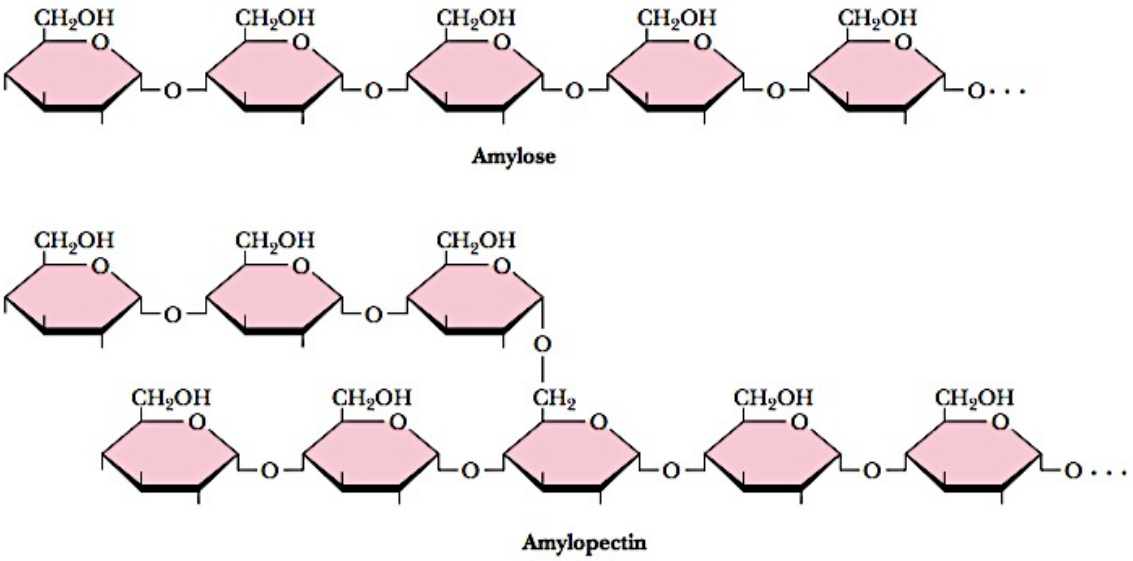



**Figure 16 Amylose and amylopectin, the polysaccharides of starch** [linear linkages are (1→4), but the branches in amylopectin are (1→6)]

Note*: Glycogen has a similar structure but is more highly branched and more compact.

***Dextran***

**Dextrans** are (1→6)-linked polysaccharides of D-glucose with branched chains found in yeast and bacteria (Figure 17). Because the main polymer chain is (1→6) linked, the repeating unit is *isomaltose,* Glc (1→6)-Glc. The branch points may be 1→2, 1→3, or 1→4 in various species. The degree of branching and the average chain length between branches depend on the species and strain of the organism. Bacteria growing on the surfaces of teeth produce extracellular accumulations of dextrans, an important component of *dental plaque.* Synthetic dextrans are frequently used in research laboratories as the support medium for column chromatography of macromolecules.

**Structural polysaccharides**

Cellulose

Cellulose, the most abundant natural polymer is a fibrous, tough, water-insoluble substance, found in the cell walls of plants (stalks, stemsand trunks). Cellulose constitutes much of the mass of wood, and cotton is almost pure cellulose. Cellulose is one of the principal components providing physical structure and strength. Cellulose also has its delicate side, as *Cotton* woven fibers make some of our most comfortable clothing fabrics, is almost pure cellulose. Like amylose and the main chains of amylopectin and glycogen, the cellulose molecule is a linear, unbranched homopolysaccharide, of D-glucose units. But there is a very important difference: in cellulose the glucose residues have the β configuration (Fig. 18), whereas in amylose, amylopectin, and glycogen the glucose is in the α configuration. The glucose residues in cellulose are linked by β (1→4) glycosidic bonds, in contrast to the α (1→4) bonds of amylose, starch, and glycogen. This difference gives cellulose and amylose very different structures and physical properties.

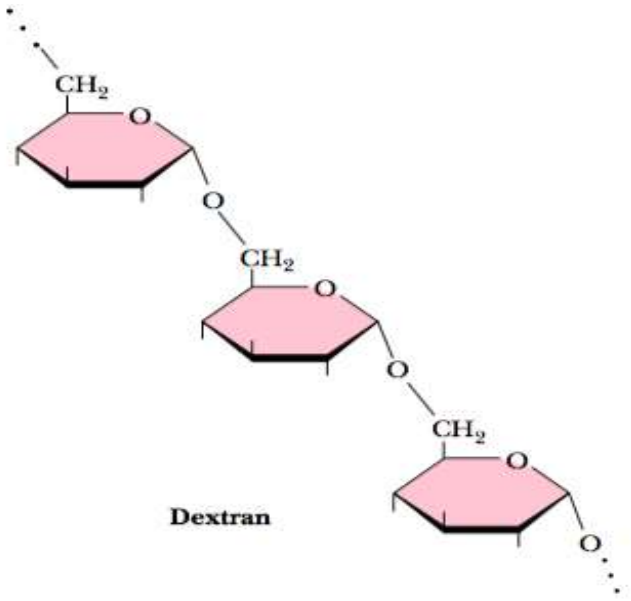



**Figure 17**The structure of Dextran

The α(1→4)-linkage sites of amylose are naturally bent, conferring a gradual turn to the polymer chain, which results in the helical conformation whereas the most stable conformation about the β (1→4) linkage involves alternating 180° flips of the glucose units along the chain so that the chain adopts a fully extended conformation, referred to as an **extended ribbon.** Juxtaposition of several such chains permits efficient interchain hydrogen bonding, the basis of much of the strength of cellulose. The flattened sheets of the chains lie side by side and are joined by hydrogen bonds and are laid on top of one another in a way to give strength and stability to a wall. Cellulose is extremely resistant to hydrolysis, whether by acid or by the digestive tract amylases. Consequently, most animals (including humans) cannot digest cellulose to any significant degree. Ruminant animals (cattle, deer, giraffes, and camels) are an exception because bacteria that live in the rumen secrete the enzyme **cellulase,** a β-glucosidase effective in the hydrolysis of cellulose. The resulting glucose is then metabolized in a fermentation process to the benefit of the host animal. Termites similarly digest cellulose because their digestive tracts also contain bacteria that secrete cellulase.

**Chitin**

Chitin, earth's second most abundant carbohydrate polymer (after cellulose) is ahomopolysaccharide that is similar to cellulose, both in its biological function and its primary, secondary, and tertiary structure, is **chitin.** Chitin is present in the cell walls of fungi and is the fundamental material in the exoskeletons of crustaceans, insects, and spiders. The structure of chitin, an extended ribbon, is identical to cellulose, except that the -OH group on each C-2 is replaced by N-acetylglucosamine (-NHCOCH3), so that the repeating units are *N-acetyl-D-glucosamines* in β (1→4)linkage. Like cellulose (Figure 18), the chains of chitin form extended ribbons (Figure 19) and pack side by side in a crystalline, strongly hydrogen-bonded form. One

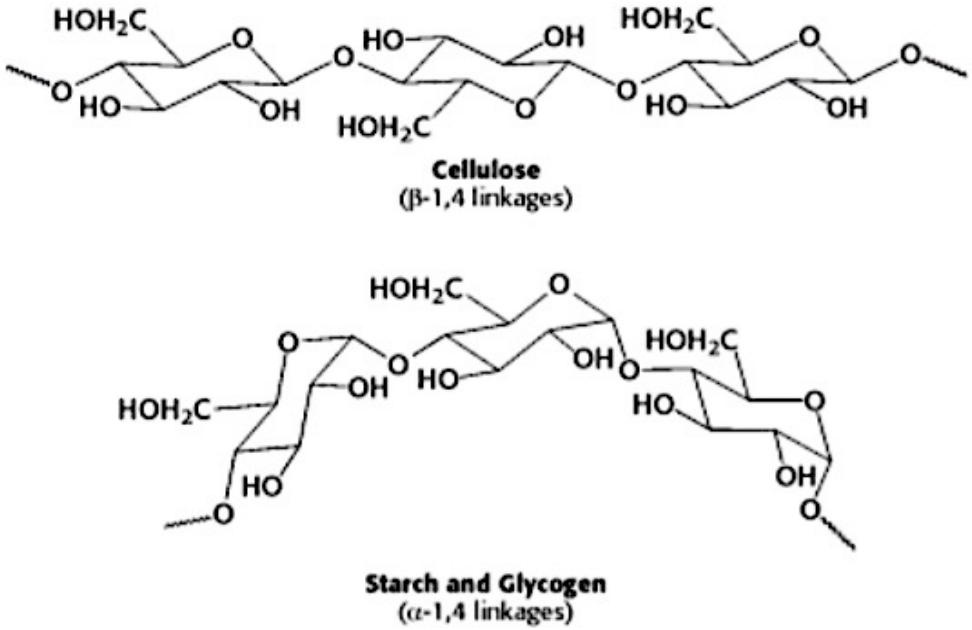



**Figure 18 Cellulose, with** β (1→4) **glycosidic linkages, can adopt a fully extended conformation**, which are optimal for structural purposes. The α (1→4) linkages (starch & Glycogen) favor bent structures, which are more suitable for storage.

significant difference between cellulose and chitin is whether the chains are arranged in parallel (all the reducing ends together at one end of a packed bundle and all the nonreducing ends together at the other end) or **antiparallel** (each sheet of chains having the chains arranged oppositely from the sheets above and below). Natural cellulose seems to occur only in parallel arrangements. Chitin, however, can occur in three forms, sometimes all in the same organism. α-*Chitin* is an all-parallel arrangement of the chains, whereas β-*chitin* is an antiparallel arrangement. In δ-*chitin,* the structure is thought to involve pairs of parallel sheets separated by single antiparallel sheets.

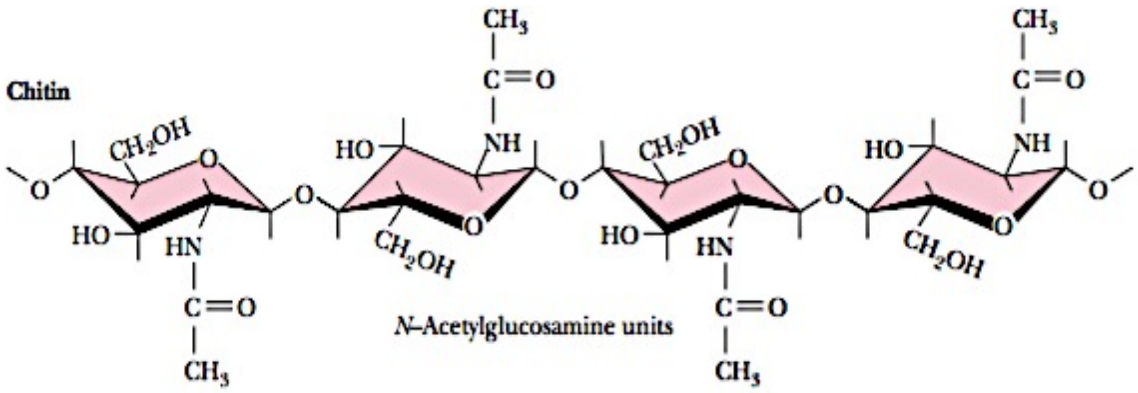
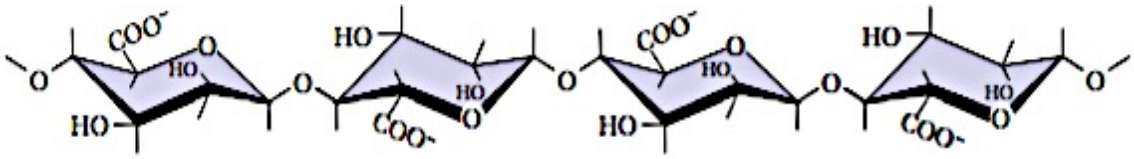



**Figure 19 A short segment of chitin**

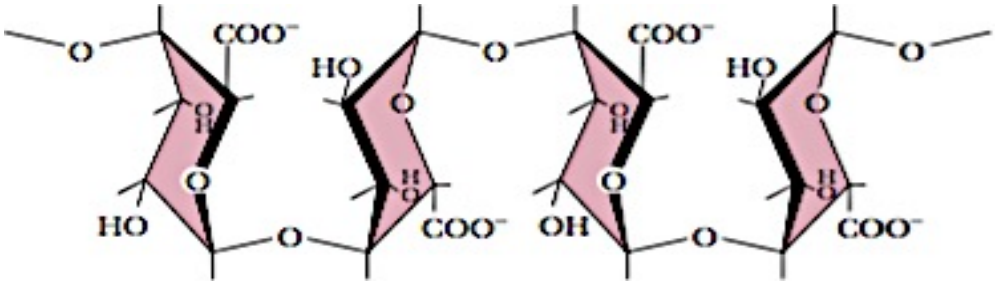
Chitin's availability and abundance offer opportunities for industrial and commercial applications. Chitin-based coatings can extend the shelf life of fruits, and a chitin derivative that binds to iron atoms in meat has been found to slow the reactions that cause rancidity and flavor loss. Without such a coating, the iron in meats activates oxygen from the air, forming reactive free radicals that attack and oxidize polyunsaturated lipids, causing most of the flavor loss associated with rancidity. Chitin-based coatings coordinate the iron atoms, preventing their interaction with oxygen.

## *Alginates*

**Alginate**, is an anionicpolysaccharide distributed widely in the cell walls of brown algae *(Phaeophyceae)*, where through binding with water it forms a viscous gum.These polysaccharides have extended ribbon structures that bind metal ions, particularly calcium, in their structure. These include **poly (β-D-mannuronate)** and **poly (α-L-guluronate) (figure 20)** which are (1→4) linked chains formed from **β-***mannuronic acid* and **α-L-***guluronic acid,* respectively. Both of these homopolymers are found together in most marine alginates, although mixed chains containing both monomer units are also found. The conformation of poly **(β-D-**mannuronate) is similar to that of cellulose. Alginate absorbs water quickly, which makes it useful as an additive in dehydrated products such as slimming aids, and in the manufacture of paper and textiles. It is also used for waterproofing and fireproofing fabrics, in the food industry as a thickening agent for drinks, ice cream and cosmetics, and as a gelling agent for jellies.



**poly (β-D-mannuronate)**



**poly (α-L-guluronate)**

**Figure 20 Structure of Alginates**

### *Agarose*

An important polysaccharide mixture isolated from marine red algae (*Rhodophyceae*) is agar, a mixture of sulfated heteropolysaccharides made up of D-galactose and an L-galactose derivative ether-linked between C-3 and C-6 (Fig. 21). The two major components of agar are the unbranched polymer agarose (Mr ~120,000) and a branched component, agaropectin. The

three-dimensional structure of agarose is a double helix with a threefold screw axis. The central cavity is large enough to accommodate water molecules. Agarose and agaropectin readily form gels containing large amounts (up to 99.5%) of water. Agarose can be processed to remove most of the charged groups, yielding a material (trade name Sepharose) useful for purification of macromolecules in gel exclusion chromatography.

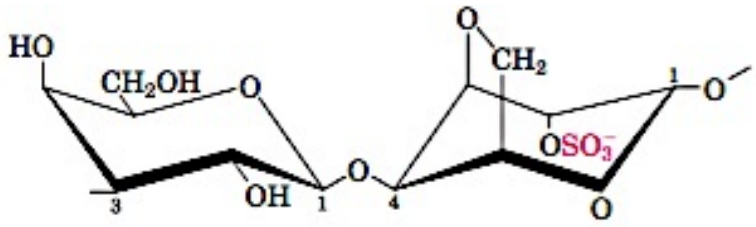



**Figure 21 Structure of Agarose**

It is interesting to note that the rigid component of bacterial cell walls is a heteropolymer of alternating β (1→4)-linked N-acetylglucosamine and N-acetylmuramic acid residues. The linear polymers lie side by side in the cell wall, cross-linked by short peptides, the exact structure of which depends on the bacterial species. The peptide cross-links weld the polysaccharide chains into a strong sheath that envelops the entire cell and prevents cellular swelling and lysis due to the osmotic entry of water.

***Glycosaminoglycans***

The extracellular matrix is composed of an interlocking meshwork of heteropolysaccharides and fibrous proteins such as collagen, elastin, fibronectin, and laminin. These heteropolysaccharides known as **glycosaminoglycans** and are involved in a variety of extracellular (and sometimes intracellular) functions. They consist of linear chains of repeating disaccharides (figure 22) in which one of the monosaccharide units is an amino sugar (either N-acetylglucosamine or N-acetyl- galactosamine) the other is in most cases a uronic acid (usually D-glucuronic or L-iduronic acid) and one (or both) of the monosaccharide units contains at least one negatively charged sulfate or carboxylate group. The combination of sulfate groups and the carboxylate groups of the uronic acid residues gives glycosaminoglycans a very high density of negative charge. To minimize the repulsive forces among neighboring charged groups, these molecules assume an extended conformation in solution. The specific patterns of sulfated and nonsulfated sugar residues in glycosaminoglycans provide for specific recognition by a variety of protein ligands that bind electrostatically to these molecules. **Heparin,** with the highest net negative charge of the disaccharides, is a natural anticoagulant substance. It binds strongly to *antithrombin III* (a protein involved in terminating the clotting process) and inhibits blood clotting. **Hyaluronate** molecules may consist of as many as 25,000 disaccharide units, with molecular weights of up to 107. Hyaluronates are important components of the vitreous humor in the eye and of *synovial fluid,* the lubricant fluid of joints in the body. The **chondroitins** and **keratan sulfate** are found in tendons, cartilage, and other connective tissue, whereas **dermatan sulfate,** as its name implies, is a component of the extracellular matrix of skin. Glycosaminoglycans are fundamental constituents of *proteoglycans* (discussed below).

### 4.3.7. Glycoconjugates: Proteoglycans, Glycoproteins, and Glycolipids

In addition to their imperative roles as stored fuels and as structural materials polysaccharides and oligosaccharides are information carriers:

They serve as target labels for some proteins and as facilitators of specific cell-cell interactions and interactions between cells and the extracellular matrix. Specific carbohydrate containing molecules act in cell-cell recognition and adhesion, cell migration during development, blood clotting, the immune response, and wound healing. In most of these cases, the informational carbohydrate is covalently joined to a protein or a lipid to form a glycoconjugate, which is the biologically active molecule.

**Proteoglycans**

These are macromolecules of the cell surface or extracellular matrix in which one or more glycosaminoglycan chains are joined covalently to a membrane protein or a secreted protein. The glycosaminoglycan moiety commonly forms the greater fraction (by mass) of the proteoglycan molecule, dominates the structure, and is often the main site of biological activity. In many cases the biological activity is the provision of multiple binding sites, rich in opportunities for hydrogen bonding and electrostatic interactions with other proteins of the cell surface or the extracellular matrix. Proteoglycans are major components of connective tissue such as cartilage, in which many noncovalent interactions with other proteoglycans, proteins, and glycosaminoglycans provide strength and toughness. These molecules act as tissue organizers, influence the development of specialized tissues, mediate the activities of various growth factors, and regulate the extra- cellular assembly of collagen fibrils.

**Glycoproteins**

These have one or several oligosaccharides of variable complexity joined covalently to a protein. They are found on the outer face of the plasma membrane, in the extracellular matrix, and in the blood. Inside cells they are found in specific organelles such as golgi complexes, secretory granules, and lysosomes. The oligosaccharide portions of glycoproteins are less monotonous than the glycosaminoglycan chains of proteoglycans; they are rich in information, forming highly specific sites for recognition and high-affinity binding by other proteins.

**Glycolipids**

These are membrane lipids in which the hydrophilic head groups are oligosaccharides, which, as in glycoproteins, act as specific sites for recognition by carbohydrate-binding proteins. Gangliosides are membrane lipids of eukaryotic cells in which the polar head group, the part of the lipid that forms the outer surface of the membrane, is a complex oligosaccharide containing sialic acid and other monosaccharide residues. Some of the oligosaccharide moieties of gangliosides, such as those that determine human blood groups, are identical with those found in certain glycoproteins, which therefore also contribute to blood group type determination.

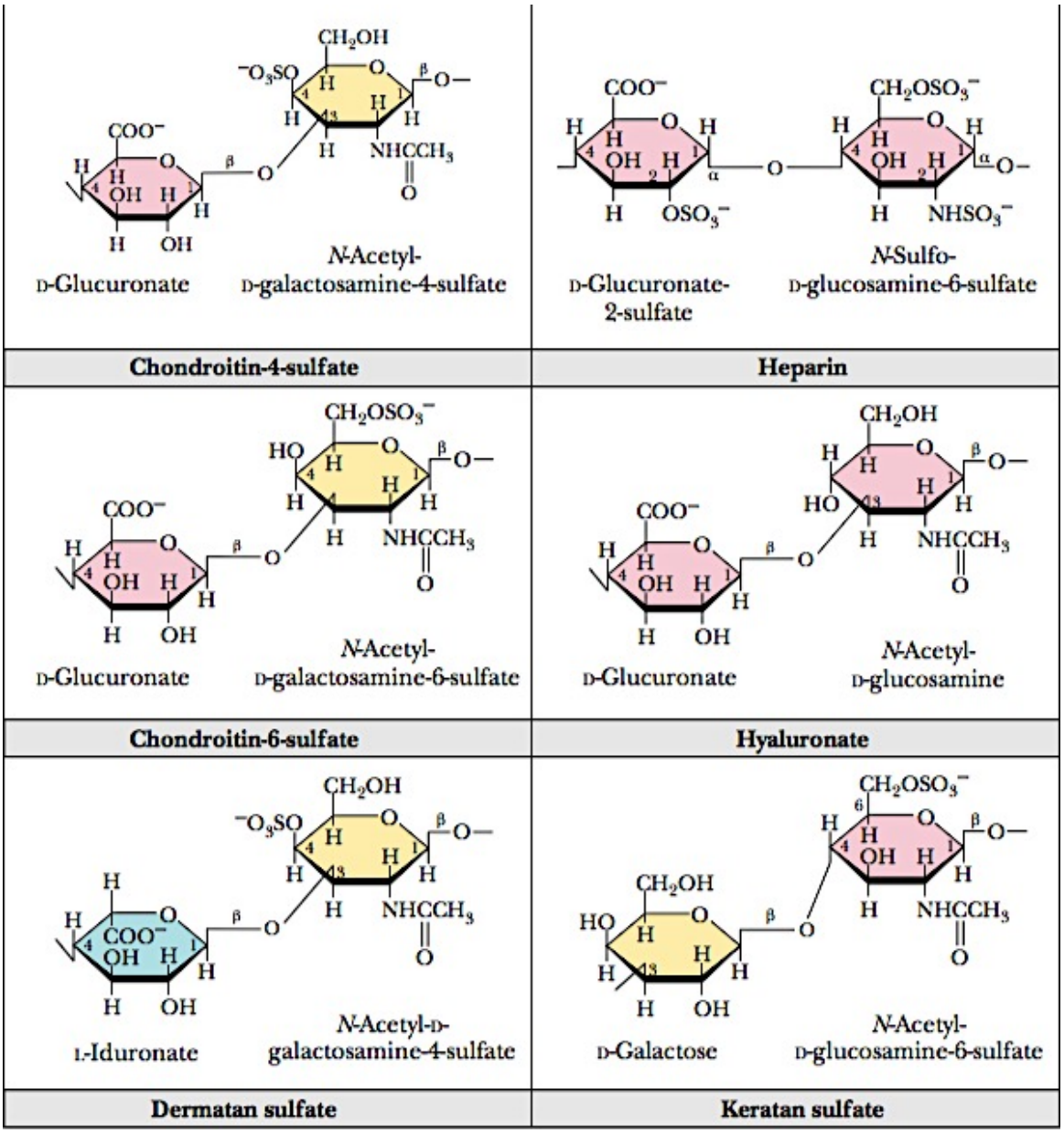



**Figure 22 Glycosaminoglycans**