BIOMOLECULES

CARBOHYDRATES

INTRODUCTION

The name "carbohydrates" was derived from their general formula $C_x (H_2O)_y$, which gives the impression that they are carbon compounds combined with water, resembling hydrates of carbon.

$$xCO_2 + yH_2O \xrightarrow{\text{Sunlight, chlorophyll}} C_x(H_2O)_y + xO_2$$

Carbohydrate

A polyhydroxy compound containing an aldehyde or ketone functional group, either in its free form or as a hemiacetal or acetal, is classified as a carbohydrate.

Carbohydrates are substances with the general formula $C_x (H_2O)_y$, and they were initially named "carbohydrates" because they were observed to have hydrogen and oxygen in the same proportion as in water. However, certain compounds have been identified that exhibit carbohydrate-like chemical behavior but do not adhere to the formula $C_x (H_2O)_y$.

For example, 2-deoxyribose has the molecular formula $C_5H_{10}O_4$.

It's essential to recognize that not all compounds conforming to the formula $C_x (H_2O)_y$, are carbohydrates; some examples include formaldehyde (CH_2O) and acetic acid ($C_2H_4O_2$). Carbohydrates are also commonly referred to as saccharides (derived from the Latin word "Saccharum," meaning sugar) because of the sweet taste exhibited by the simpler members of this class, namely sugars.

CLASSIFICATION OF CARBOHYDRATE

Carbohydrates are categorized into three main classes based on the number of individual sugar units present in their molecular structure.

1. **Monosaccharide:** Monosaccharides are carbohydrates that cannot be further broken down into simpler compounds. Monosaccharides with six carbon atoms are classified as either aldohexoses or ketohexoses.
2. **Oligosaccharides:** Oligosaccharides are carbohydrates that yield between two and ten monosaccharide units upon hydrolysis. They are further subdivided into categories such as disaccharides, trisaccharide's, tetra saccharides, and so on, depending on the number of monosaccharides they yield upon hydrolysis. Disaccharides are the most common among them. In a disaccharide, the two monosaccharide units obtained upon hydrolysis can be either identical or different.

   For example, sucrose, when hydrolyzed, yields one molecule each of glucose and fructose, while maltose produces two glucose molecules.
3. **Polysaccharide:** Polysaccharides are carbohydrates that can be hydrolyzed into numerous monosaccharide molecules.

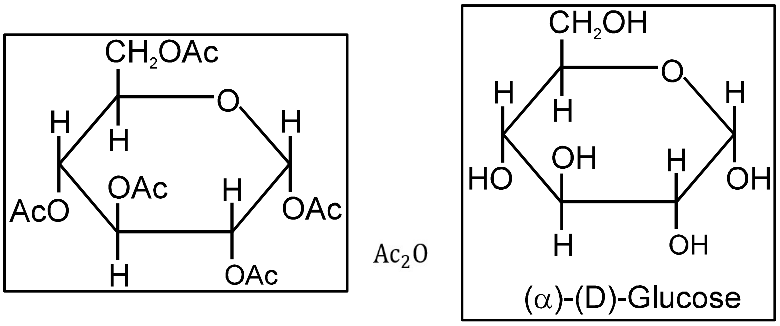
   Examples of polysaccharides include starch, cellulose, and more.

4. Aldohexoses

Their structure has been clarified through the following steps:

I. Examination and determination of molecular weight reveal that the molecular formula of the aldohexoses is $C_6H_{12}O_6$.

II. When subjected to acetic anhydride, aldohexoses yield the penta-acetate, indicating the presence of five hydroxyl groups.



III. Aldohexoses form an oxime when treated with hydroxylamine, or add molecule of HCN to form Cyanohydrin and therefore contain a carbonyl group.

IV. When an aldohexose is oxidised with bromine-water or tolan's reagent or Fehling solution a pentahydroxy-acid of formula $C_6H_{12}O_7$ is obtained. This indicates that the carbonyl group present is an aldehydic group.

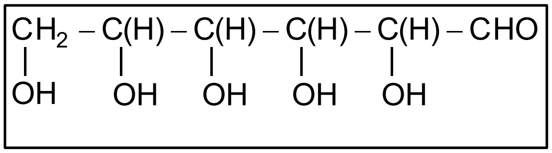
V. When reduced with concentrated hydroiodic acid and red phosphorus at 100°C, aldohexoses give n-hexane. This indicates that the six carbon atoms in an aldohexose are in a straight chain. The above reactions show that structure of aldohexoses is.

VI. Aldohexoses undergo oxime formation when exposed to hydroxylamine or react with HCN to create cyanohydrin, signifying the presence of a carbonyl group.

VII. Oxidizing an aldohexose with bromine-water, Tollen's reagent, or Fehling's solution results in the formation of a pentahydroxy-acid with the formula $C_6H_{12}O_7$, confirming the presence of an aldehydic group within the carbonyl group.

VIII. Reduction of aldohexoses with concentrated hydroiodic acid and red phosphorus at 100°C yields n-hexane, indicating that the six carbon atoms in an aldohexose are arranged in a straight chain.

These reactions collectively elucidate the structure of aldohexoses.

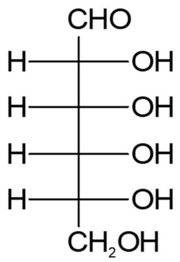


$$\underset{\mathrm{OH}}{\underset{|}{\mathrm{CH_2}}}-\underset{\mathrm{OH}}{\underset{|}{\mathrm{C(H)}}}-\underset{\mathrm{OH}}{\underset{|}{\mathrm{C(H)}}}-\underset{\mathrm{OH}}{\underset{|}{\mathrm{C(H)}}}-\underset{\mathrm{OH}}{\underset{|}{\mathrm{C(H)}}}-\mathrm{CHO}$$

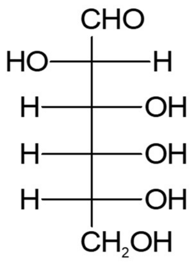
Due to four asymmetric carbon atoms, there are sixteen optical isomers.

or Eight pairs of enantiomers. (8D-variety & 8L- variety).

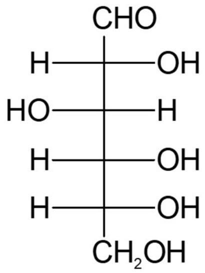
D-variety of them are as follows



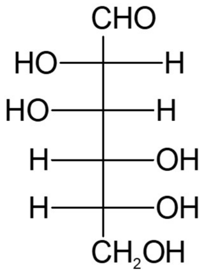
D(+)-allose
(VII)



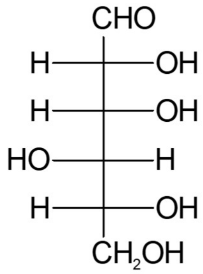
D(+)-altrose
(VIII)



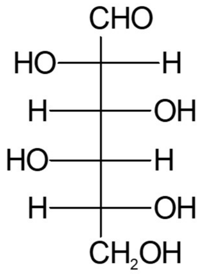
D(+)-glucose
(IX)



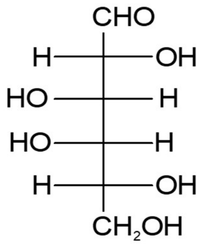
D(+)-mannose
(X)



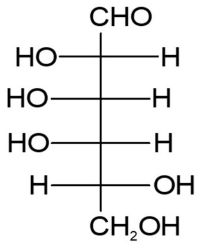
D(–)-gulose
(XI)



D(–)-idose
(XII)



D(+)-galactose
(XIII)



D(+)-talose
(XIV)
(XII)

Note:

1. D-aldohexoses shown above have epimoric / diastereomeric relationship with each other
2. D-aldohexoses can be either dextro (+) or laevo (-)

Aldoses:

Monosaccharides containing aldehyde group are called aldoses.

Ketoses:

Monosaccharides containing ketonic group are called ketoses.

Photosynthesis

$$6CO_2 + 6H_2O + 18\text{ ATP} \xrightarrow{\text{Sunlight, chlorophyll}} C_6H_{12}O_6 + 6O_2$$

Cellular Respiration

$$C_6H_{12}O_6 + 6O_2 \xrightarrow{\text{enzymes}} 6CO_2 + 6H_2O + 38\text{ ATP (36 ATP net gain)}$$

Classification and structure of carbohydrates

Carbohydrates are compounds characterized by their polyhydroxy aldehyde and ketone nature, as well as their ability to break down into polyhydroxy aldehydes and ketones.

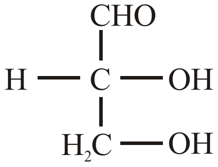
The most basic carbohydrates are referred to as **sugars** or **saccharides,** a term derived from the Latin word "Saccharum," meaning sugar. Carbohydrates can be categorized into three main groups: **monosaccharides, oligosaccharides**, and **polysaccharides.**

General characteristic of monosaccharides

Here are the salient features of monosaccharides:

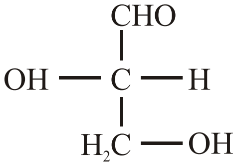
1. Monosaccharides are universally soluble in water because of the presence of hydrogen bonding between their various OH groups and the adjacent water molecules.
2. Monosaccharides possess a sweet taste and, when heated, tend to undergo charring, emitting the aroma reminiscent of burning sugar.
3. Monosaccharides exhibit optical activity, a property attributed to the presence of chiral carbon atoms.
4. The chemical attributes of monosaccharides stem from their OH groups and the carbonyl group, which can be either aldehydic or ketonic in nature.

For example, glyceraldehyde contains a single asymmetric carbon atom, indicated by an asterisk, allowing it to exist in two optically active forms known as the D-form and the L-form. These two forms are unmistakable mirror images and cannot be superimposed, making them enantiomers.



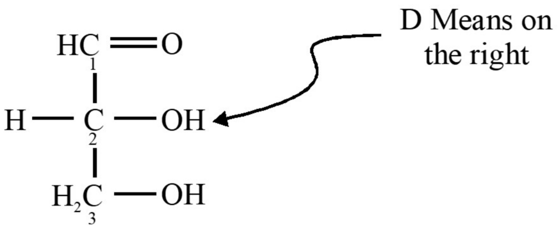
$$\begin{array}{ccc} & CHO & \\ & | & \\ H - & C & - OH \\ & | & \\ & H_2C & - OH \end{array}$$

D-Glyceraldehyde

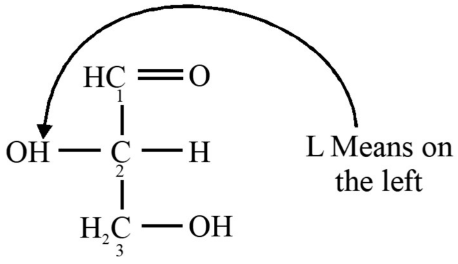


$$\begin{array}{ccc} & CHO & \\ & | & \\ OH - & C & - H \\ & | & \\ & H_2C & - OH \end{array}$$

L-Glyceraldehyde

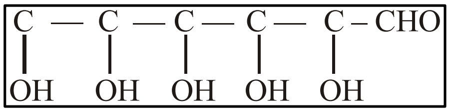


D-Glyceraldehyde



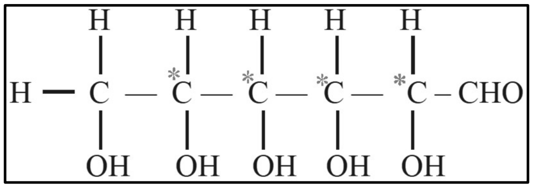
L-Glyceraldehyde

Synthetic synthesis has yielded all four isomers. D-erythrose and L-erythrose are enantiomers, which means they are mirror images of each other. They exhibit identical optical rotation magnitudes, albeit in opposite directions. A combination of equal proportions of these two isomers forms a racemic mixture, wherein plane-polarized light would pass through the solution without any alteration.



$$\begin{array}{ccccc} C - & C - & C - & C - & C - CHO \\ | & | & | & | & | \\ OH & OH & OH & OH & OH \end{array}$$

To satisfy the tetravalency of the five carbon atoms by providing hydrogen atoms, we can attribute the following structure (open chain) to glucose, with an asterisk (*) denoting an asymmetric carbon atom.



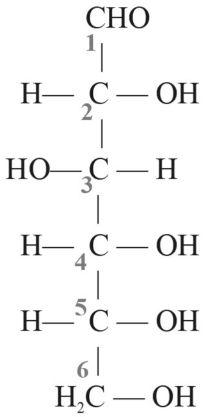
$$\begin{array}{cccccc} & H & H & H & H & H \\ & | & | & | & | & | \\ H - & C - & \overset{*}{C} - & \overset{*}{C} - & \overset{*}{C} - & \overset{*}{C} - CHO \\ & | & | & | & | & | \\ & OH & OH & OH & OH & OH \end{array}$$

GLUCOSE

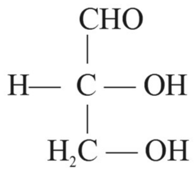
Glucose stands as the most prevalent monosaccharide and is often referred to as dextrose. This nomenclature is due to its primarily occurring in nature as optically active dextrorotatory isomers. Glucose functions as a potent reducing agent, capable of reducing both Fehling's solution and ammoniacal silver nitrate solution. Upon heating with sodium hydroxide, an aqueous glucose solution undergoes a browning reaction. This sugar, known as dextrose, is commonly found in natural sources such as grapes, honey, cane sugar, starch, and cellulose.

Configuration of Glucose:

Given that the structure described above contains four asymmetric carbon atoms, marked with asterisks, it can exist in a total of $2^4 = 16$ different optically active forms, which amounts to eight pairs of enantiomers. All of these forms are well-documented and correspond to the D- and L-isomers of glucose, mannose, galactose, allose, idose, and talose. The naturally occurring dextrorotatory glucose, denoted as (+)-glucose, represents just one of the 16 possible stereoisomers.



D (+) Glucose



(+)-Glyceraldehyde

The notations D- and L- to denote configuration were introduced by Rosan off. According to this convention, any compound with its lower asymmetric carbon atom configured similarly to dextrorotatory glyceraldehyde (as illustrated above, with the bottom carbon atom having -OH on the left and H on the right) is assigned the L-configuration. It's important to note that the symbols D- and L- are independent of the specific rotation value, meaning they are not linked to whether a compound is labeled as (+) or (-). For instance, natural (-) fructose falls under the D-series, specifically as D (-)-fructose.

Objections to open-chain structure of glucose:

While the open-chain structure of (+) glucose accounts for many of its reactions, it falls short in explaining several key observations:

- Glucose does not result in the restoration of Schiff's reagent color.
- Glucose does not give rise to a basophile and aldehyde-ammonia compound.
- Glucose yields two isomeric penta-acetates, both of which exhibit no reactivity with carbonyl reagents.
- The existence of two isomeric forms of glucose and the phenomenon of mutarotation cannot be elucidated through an open-chain formula.

- Glucose, in the presence of dry HCl gas and methanol, forms two isomeric glucosides. Due to its reduced solubility in ethanol, it precipitates upon cooling the reaction mixture. Commercially, glucose is produced through the hydrolysis of starch, which is sourced from economical raw materials such as maize, potatoes, and rice.

Constitution of Glucose:

Molecular Formula:

By the usual analytical methods, the molecular formula glucose is found to be $C_6H_{12}O_6$.

Straight Chain of six carbon atoms:

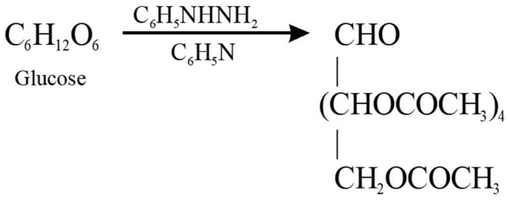
1. The reduction of glucose with concentrated hydroiodic acid (HI) and phosphorus results in the formation of 2-iodohexane and n-hexane. This observation indicates that the six carbon atoms in glucose are arranged in a straight chain.

$$\underset{\textbf{Glucose}}{C_6H_{12}O_6} \underset{\text{Prolonged heating}}{\overset{\text{HIP}}{\longrightarrow}} \underset{\textbf{n-hexane}}{CH_3-(CH_2)_4-CH_3}$$

2. When glucose undergoes oxidation with bromine water, it forms gluconic acid. Subsequent reduction with an excess of HI leads to the formation of n-hexanoic acid, $CH_3.(CH_2)_4.COOH$, thus providing confirmation of the existence of a linear chain containing six carbon atoms in glucose.

Presence of five hydroxyl groups:

Upon treatment with acetic anhydride, glucose produces a penta-acetate, signifying the presence of five -OH groups. Given the stability of glucose, it is evident that these five -OH groups must be connected to five distinct carbon atoms.

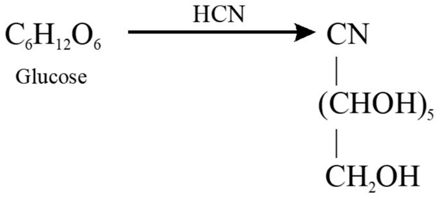


$$\underset{\text{Glucose}}{C_6H_{12}O_6} \xrightarrow[C_6H_5N]{C_6H_5NHNH_2} \begin{array}{l} CHO \\ | \\ (CHOCOCH_3)_4 \\ | \\ CH_2OCOCH_3 \end{array}$$

Glucose pentaacetate

Presence of an aldehydic groups:

1. Glucose yields a cyanohydrin when exposed to hydrogen cyanide and a mono-oxime when in contact with hydroxylamine, indicating the presence of a carbonyl group.



$$\underset{\text{Glucose}}{C_6H_{12}O_6} \xrightarrow{HCN} \begin{array}{l} CN \\ | \\ (CHOH)_5 \\ | \\ CH_2OH \end{array}$$

Glucose cyanohydrin

2. Glucose's ability to reduce Fehling's solution and Tollen's reagent is indicative of an aldehydic carbonyl group in its structure.
3. The presence of this aldehydic group is further substantiated by its oxidation to gluconic acid, which contains the same number of carbon atoms.

$$\underset{\text{Glucose}}{C_5H_{11}.\,CHO} + (O) \xrightarrow{Br_2} \underset{\text{Gluconic acid}}{C_5H_{11}O_5.\,COOH}$$

Now since aldehydic group is monovalent, it must be present on the end of the chain.

Open chain structure:

Considering the aforementioned observations, glucose's partial structure orientation can be described as follows: In the α anomer, the -OH group is positioned trans to the -CH_2OH group, while in the β anomer, the -OH group is situated cis to the -CH_2OH group.

Fructose

Also said to be **fruit sugar**

1. It exists both in a bound form and as a free compound.
2. Fructose is often referred to as "fruit sugar" because it is found freely in honey and many sweet fruits.
3. Being the sweetest monosaccharide, fructose is found in cane sugar and in the combined state within insulin.
4. It is also known as α-Laevulose, denoting that the naturally occurring form is levorotatory.

Preparation By acid hydrolysis of cane sugar:

$$C_{12}H_{22}O_{11} + H_2O\ C \xrightarrow{H^{\oplus}} {}_6H_{12}O_6 + C_6H_{12}O_6$$

Glucose Fructose

1. By enzymatic action of sucrose

$$\text{Sucrose } (C_{12}H_{22}O_{11}) \xrightarrow{\text{Invertase}} \underbrace{\text{Glucose + Fructose}}_{\text{Invert Sugar}}$$

(Disaccharide)

Note: Glucose and fructose, obtained through the acid hydrolysis of sucrose, can be isolated by subjecting them to treatment with Ca $(OH)_2$, resulting in the formation of calcium gluconate and calcium fructose. Notably, calcium fructose is water-insoluble, making it straightforward to separate from the mixture.

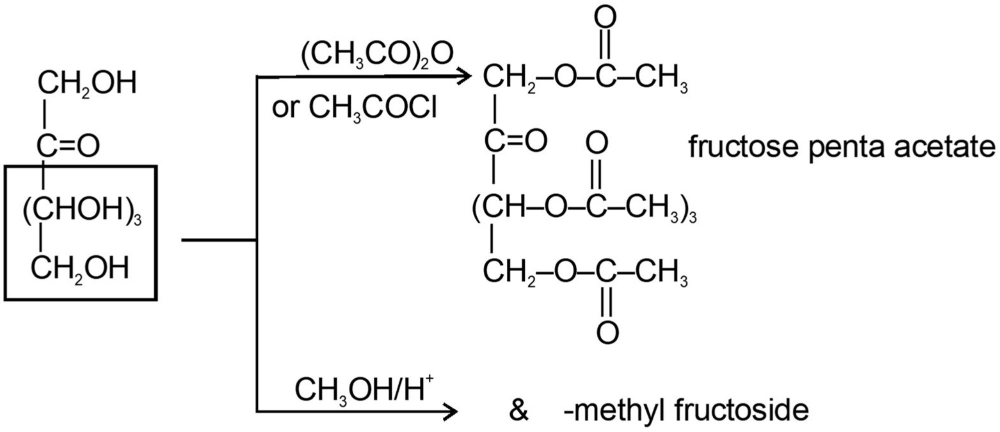
Properties

1. This substance exists as a colorless crystalline solid.
2. It readily dissolves in water but exhibits insolubility in ether, ketone, and benzene.
3. Being a pentahydroxy ketone, it displays mutarotation, similar to glucose.

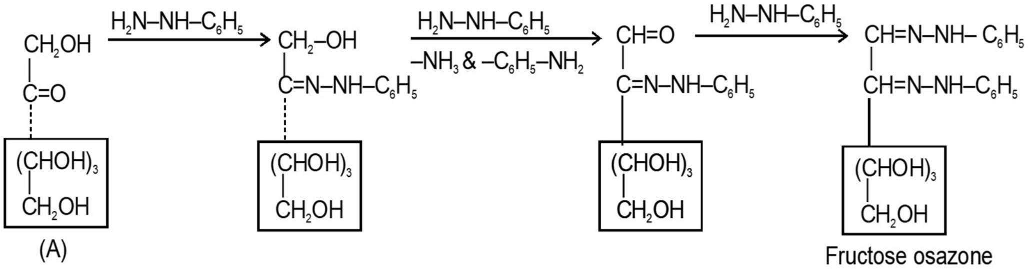
Chemical reaction

Due to OH group at 2nd carbon:

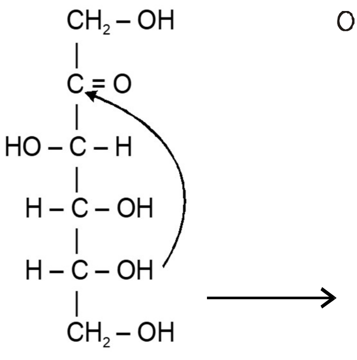
1. It forms fructose pentaacetate with acetyl chloride:

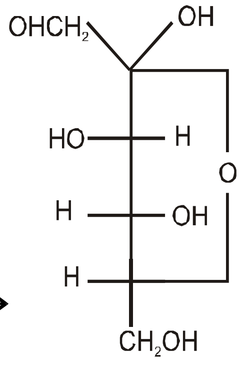


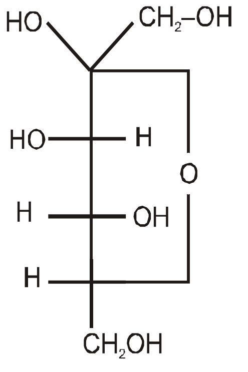
2. **Reaction due to keto group:**
   Additionally, it can produce an oxazine when reacted with an excess of phenyl hydrazine. This allows us to conclude that the formation of an oxazine is a distinctive trait of α-hydroxy carbonyl compounds.



STRUCTURE



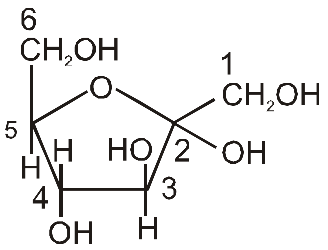




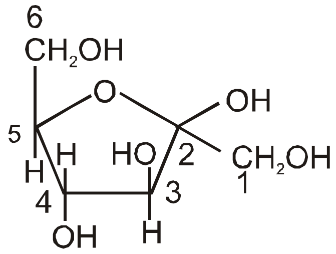
Open chain structure of fructose **α–D- fructose** **β–D- fructose**

Specific Rotation (– 92º) + Specific Rotation (– 21º) Specific Rotation (– 133º)

Haworth projection: Fructofuranans



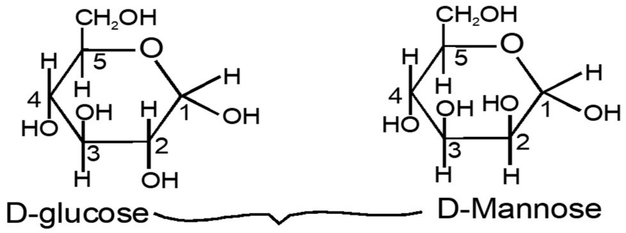
α-fructose



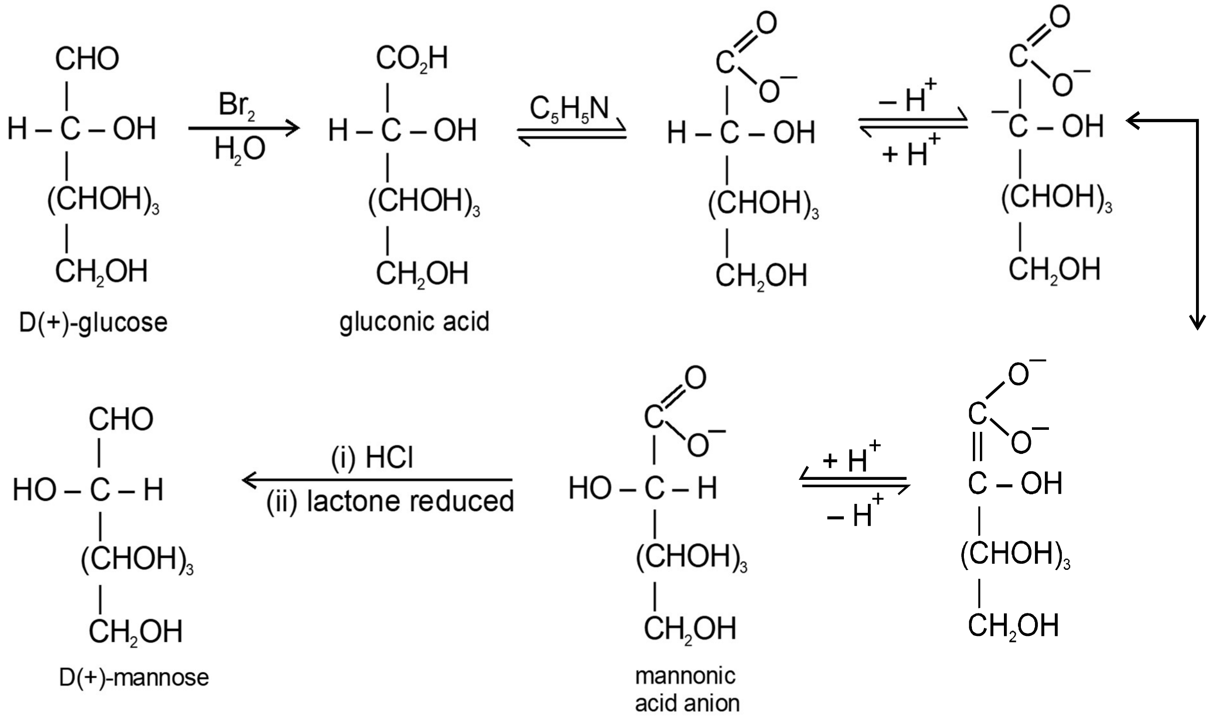
β-fructose

Epimer:

The alteration of configuration in one of the asymmetric carbon atoms within a compound containing two or more such carbon atoms is termed epimerization, and the resulting compounds are referred to as epimers. D-Glucose and D-mannose are examples of epimers, as they exhibit a change in configuration at the second carbon atom.



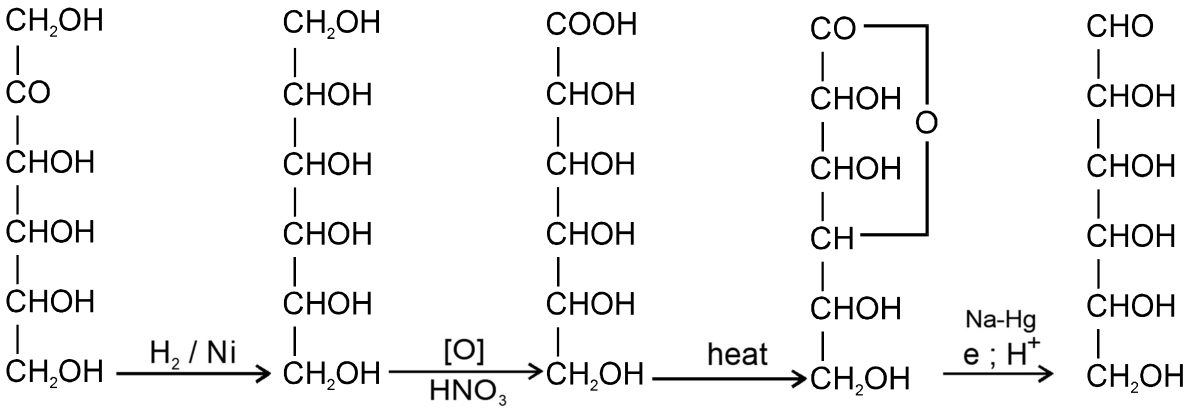
Such sugars are known as epimers e.g., epimerization of glucose into mannose.



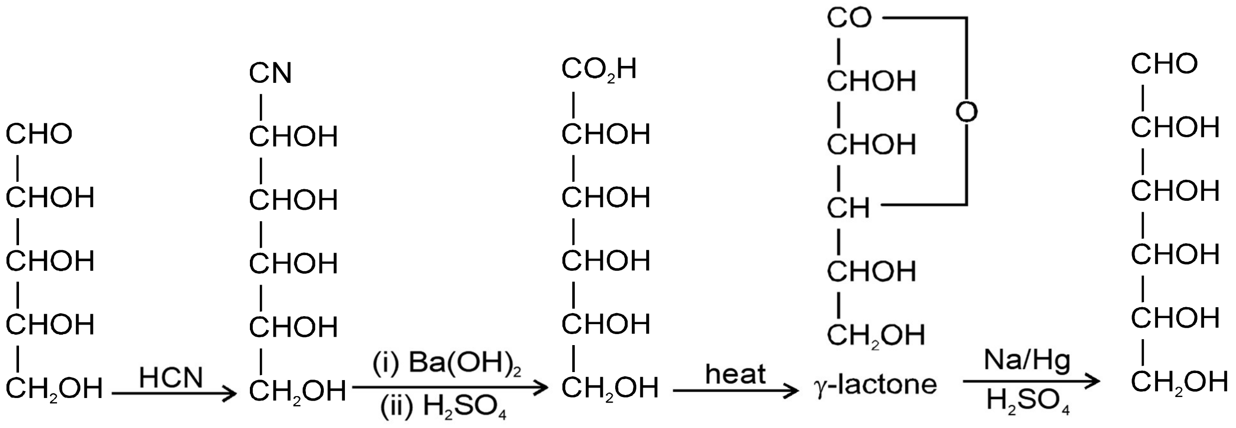
Note:

1. Unlike other ketones, fructose can reduce Fehling sol. and Tollen's reagents it is probably due to formation of an equilibrium between glucose, mannose and fructose.
2. Aldoses which produce the same oxazines must have identical configuration on all their asymmetric carbon atoms except the alpha (since only the aldehyde group and α-carbon atoms are involved in oxazine formation).

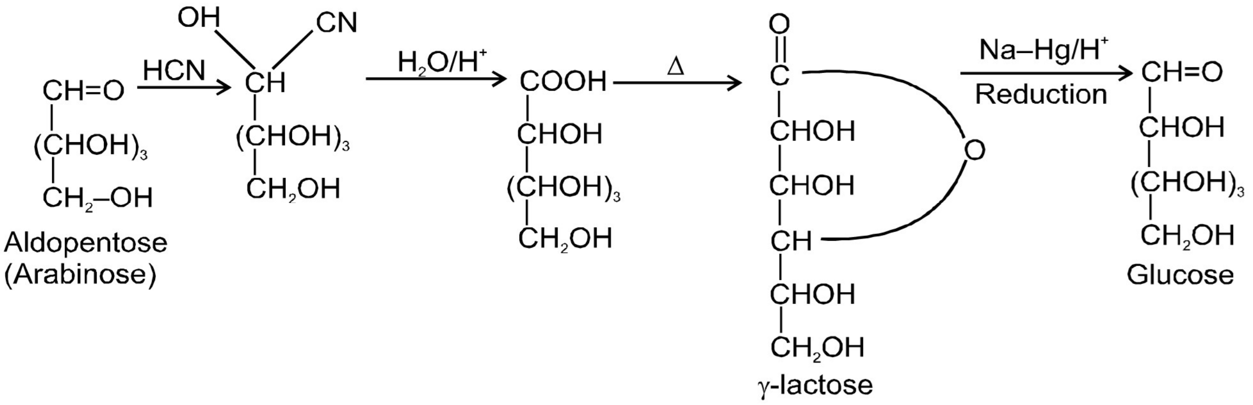
Conversion of Ketose into Aldose:



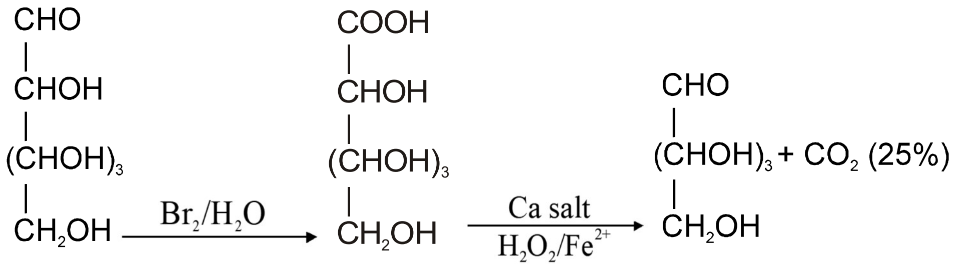
Conversion of Aldose into Ketose:



Chain lengthening:



Chain shortening:



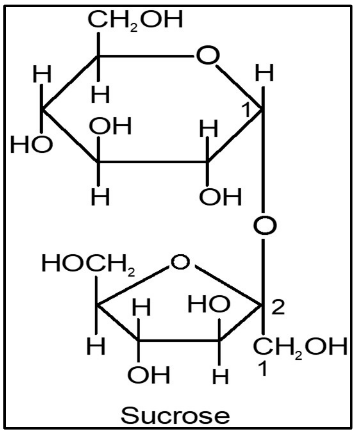
SUCROSE

1. (Sucrose, commonly known as cane sugar, with the chemical formula $C_{12}H_{22}O_{11}$)
2. Sucrose is a white crystalline solid that readily dissolves in water.
3. When subjected to temperatures exceeding its melting point, it undergoes a transformation into a brown substance recognized as caramel.
4. The application of concentrated sulphuric acid results in the charring of sucrose, yielding a product that is nearly pure carbon.
5. Sucrose exhibits dextrorotatory behavior, with a specific rotation value of +66.5°.
6. On hydrolysis with dilute acids sucrose yields an equimolecular mixture of D (+)-glucose and D (−)-fructose:

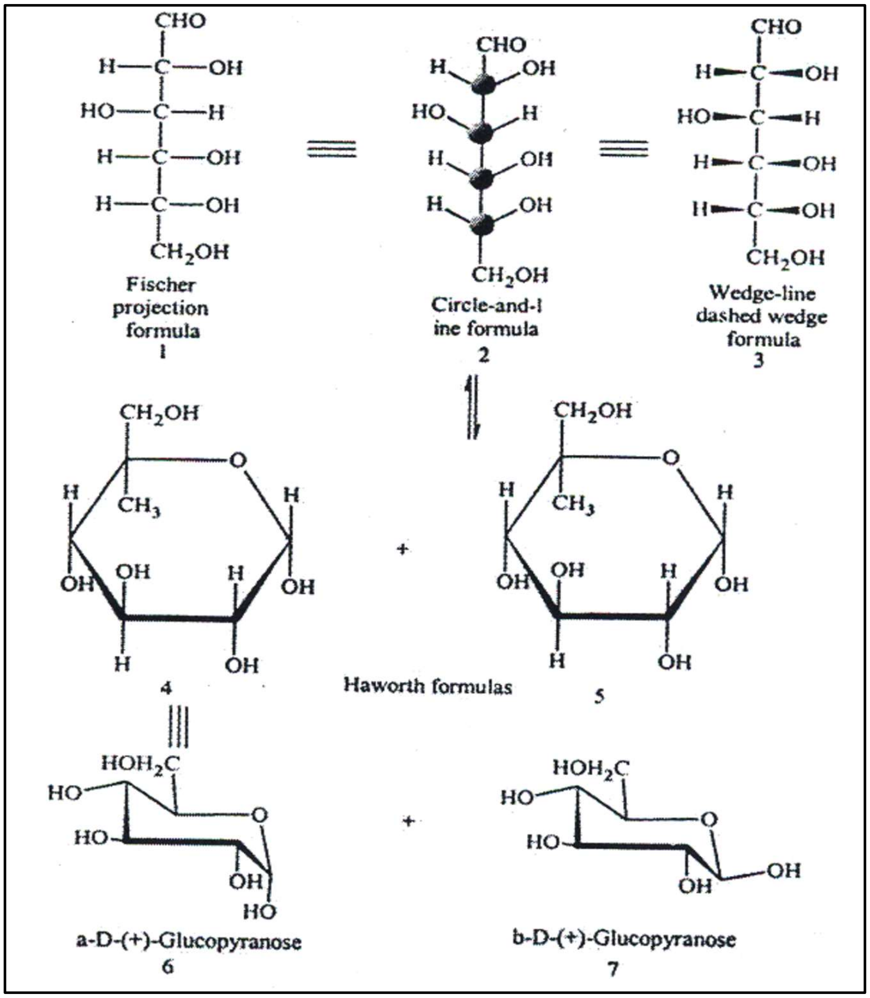
$$C_{12}H_{22}O_{11} + H_2O \overset{\text{HCl}}{\longrightarrow} \underset{\text{Glucose}}{C_6H_{12}O_6} + \underset{\text{Fructose}}{C_6H_{12}O_6}$$

   As D (−)-fructose displays a higher specific rotation compared to D (+)-glucose, the resulting mixture exhibits levorotatory properties. Consequently, the hydrolysis of cane sugar is termed the inversion of cane sugar, a distinct concept from the Walden inversion. This resulting mixture is referred to as invert sugar. The inversion, or hydrolysis, of cane sugar can also be catalyzed by the enzyme invertase, which is naturally found in yeast.

7. Sucrose is categorized as a non-reducing sugar, as evidenced by its inability to reduce Fehling's solution, failure to form an oxime or an oxazine, and lack of participation in mutarotation. These characteristics suggest that neither the aldehyde group of glucose nor the ketonic group of fructose is accessible in sucrose.



Sucrose

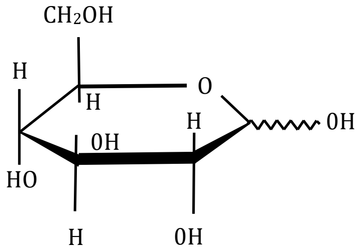


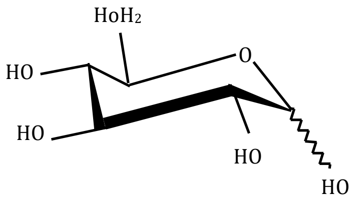
Structures 4 and 5, illustrating the glucose anomers, are commonly referred to as Haworth formulas. Although they do not provide a precise depiction of the six-membered ring's shape, they are highly practical and find numerous applications. These formulas showcase how the representation of each stereo genic center in the open-chain form aligns with its portrayal in the Haworth formula.

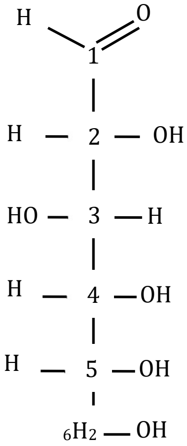
Each glucose anomer is identified as either an α anomer or a β anomer based on the positioning of the –OH group at C_1. When we sketch the cyclic configurations of a D sugar...

Structure formulas for monosaccharides:

Although many of the properties of D (+)-glucose can be explained in terms of an open-chain structure (1, 2, or 3), a considerable body of evidence indicates that the open-chain structure exists, primarily, in equilibrium with two cyclic forms. These can be represented by structures 4 and 5 or 6 and 7. The cyclic forms of D(+)-glucose are hemiacetals formed by an intramolecular reaction of the –OH, group at C_5 with the aldehyde group. Cyclisation creates a new stereo genic centre at C_1, and this stereo genic centre explains how two cyclic forms are possible. These two cyclic forms are diastereomers that different only in the configuration of C_1. In carbohydrate chemistry diastereomers of this type of called anomers, and the hemiacetal carbon atom is called the anomeric carbon atom.



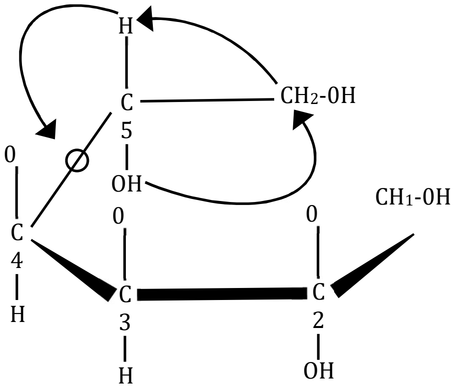




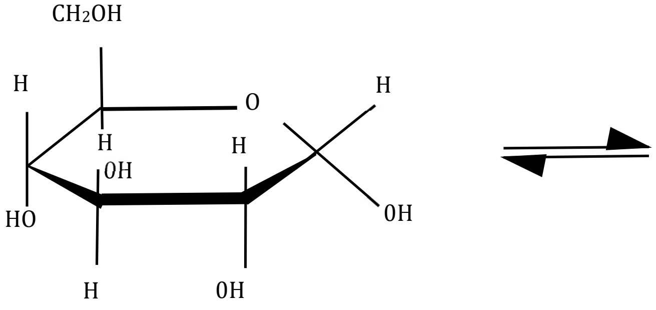
Glucose

(Plane projection formula)

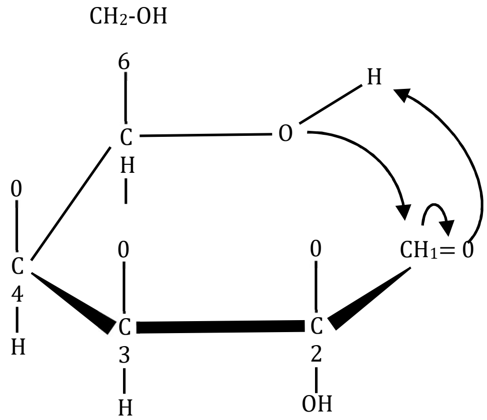
When a model of this is made it will coil as follows:



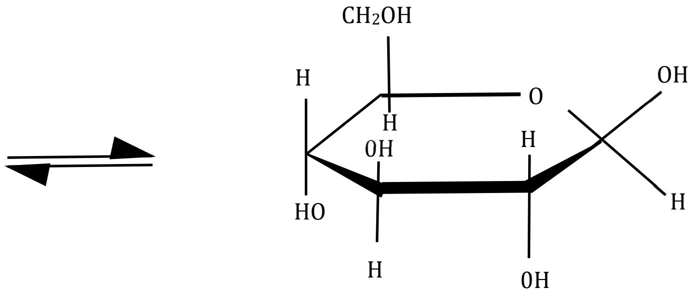
if the group attached to c4 is pivoted as the arrows indicate, we have the structure below.



a-D-(+)-Glucopyranose (Starred -OH)–OH) is the Hemiacetal OH, which in a-glucose is on the opposite side of the ring from the -CH, OH group at CS.



Open-chain form of D-glucose (The proton transfer step occurs between separate molecules. It is not intramolecular or concerted.)



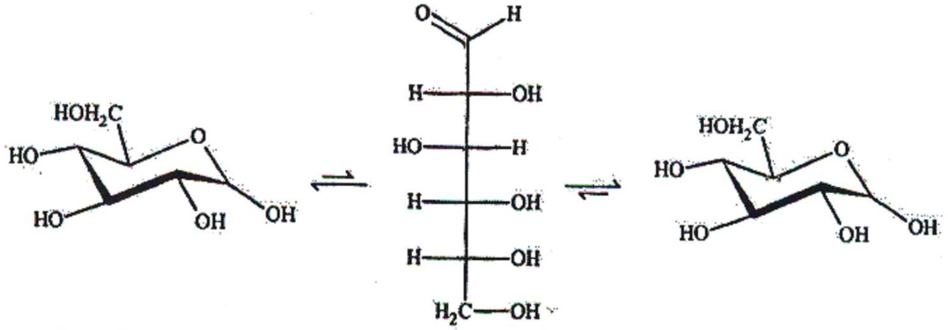
B-D-(+)-Glucopyranose (Starred -OH) is the hemiacetal-OH, which in B-glucose is on the same side of the ring as the--CH, OH group at C_5)

Mutarotation:

Ordinary D(+)-glucose has a melting point of 146°C. However, when D(+)-glucose is crystallized by evaporating an aqueous solution kept above 98°C, a second form of D(+)-glucose with a melting point of 150°C can be obtained. When the optical rotations of these two forms are measured, they are found to be significantly different, but when an aqueous solution of either form is allowed to stand, its rotation changes. The specific rotation of one form decreases and the rotation of the other increases, until both solutions.

Show the same value. A solution of original D-(+) glucose (mp 146°C) has an initial specific rotation of +112°, but, ultimately, the specific rotation of this solution falls to +52.7°. A solution of second form of D(+) glucose (mp 150°C) has an initial specific rotation of +18.7°, but slowly, the specific rotation of this solution rises to +52.7°. This change in rotation towards an equilibrium value is called mutarotation.

Ordinary D (+)-glucose exhibits a melting point of 146°C. However, if D (+)-glucose is crystallized by evaporating an aqueous solution maintained above 98°C, a second variant of D (+)-glucose with a melting point of 150°C can be obtained. When the optical rotations of these two variants are gauged, they are notably distinct. Nonetheless, when an aqueous solution of either variant is left to stand, its optical rotation undergoes modifications. The specific rotation of one variant diminishes while the rotation of the other increases, until both solutions converge to the same value.
Initially, a solution of the original D-(+) glucose (melting point 146°C) possesses a specific rotation of +112°. Over time, the specific rotation of this solution eventually decreases to +52.7°. Conversely, a solution of the second form of D(+) glucose (melting point 150°C) has an initial specific rotation of +18.7°. Gradually, the specific rotation of this solution ascends to +52.7°. This alteration in rotation towards an equilibrium value is known as mutarotation.
The reason behind this mutarotation phenomenon can be attributed to the equilibrium between the linear structure of D(+) glucose and the α and β forms of the cyclic hemiacetals.



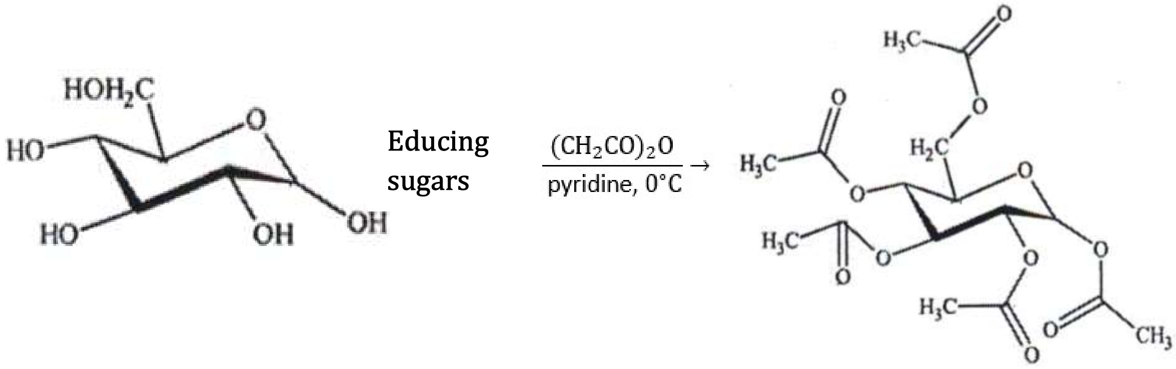
α-D-(+)-Glucopyranose (mp 146°C; $[\alpha]_D^{25} = +112°$)

Open-chain form of D-(+)-glucose

β-D-(+)-Glucopyranose (mp 150°C; $[\alpha]_D^{25} = +18.7°$)

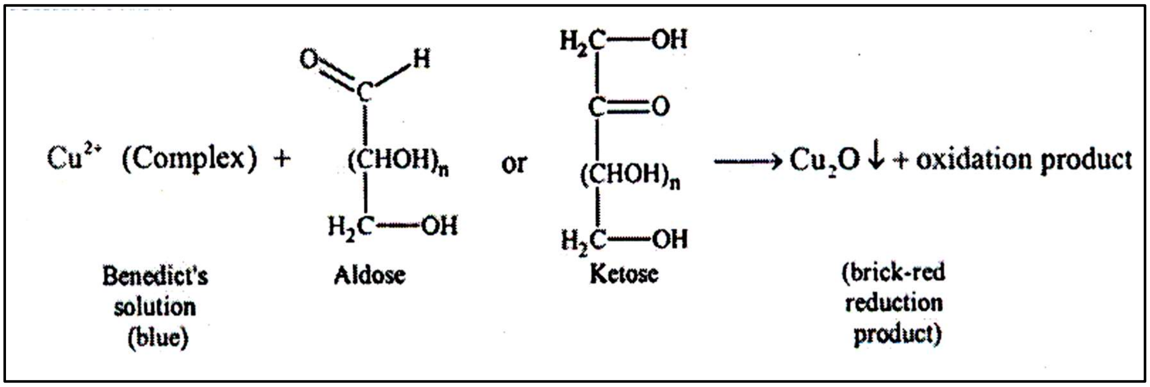
Conversion to Esters:

When a monosaccharide is exposed to an excess of acetic anhydride and a mild base like pyridine or sodium acetate, all of its hydroxyl groups, including the anomeric one, are transformed into ester groups. If this reaction takes place at a low temperature (e.g., 0°C), it proceeds with stereo-specificity, meaning the α anomer yields the α-acetate, and the β anomer yields the β-acetate. Acetate esters are frequently used as protective groups for hydroxyls in carbohydrates.



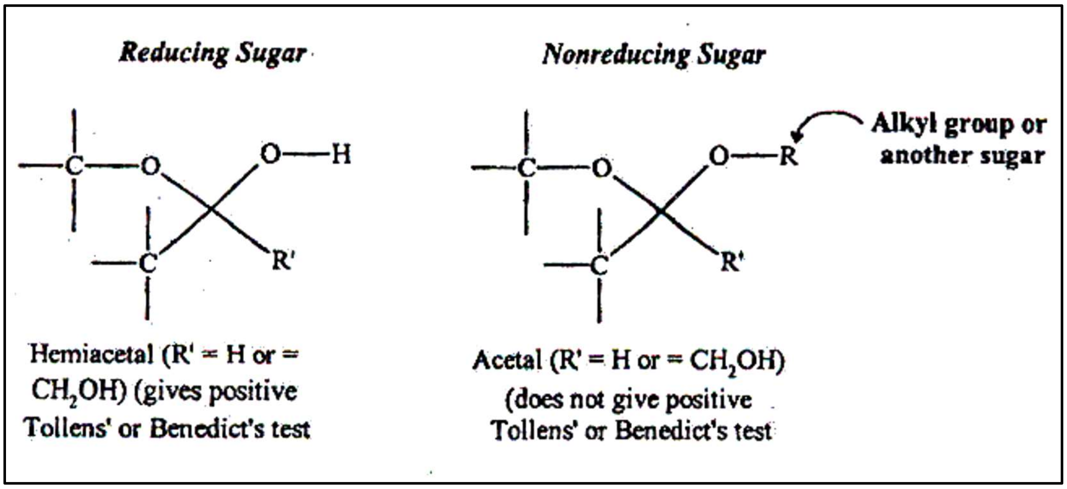
Benedict's or tollens' reagents: r

Benedict's reagent (A alkaline solution containing a cupric citrate complex ion) and Tollen's solution $[Ag^{+}(NH_3)_2OH]^{-}$ oxidize and thus give positive tests with aldoses and ketoses. The tests are positive even though aldoses and ketoses exist primarily as cyclic hemiacetals.



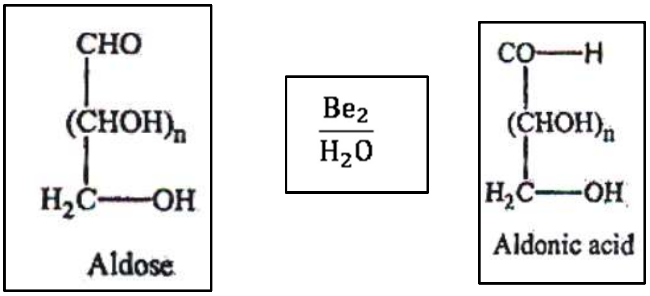
Sugars that produce positive reactions with Tollen's or Benedict's solutions are referred to as reducing sugars, and this category includes all carbohydrates possessing a hemiacetal group. In an aqueous solution, these hemiacetals maintain an equilibrium with a relatively small, though not negligible, concentration of noncyclic aldehydes or α-hydroxy ketones. It is these aldehydes and α-hydroxy ketones that undergo oxidation until one of the reactants is depleted.

Conversely, carbohydrates containing only acetal groups do not yield positive results when subjected to Benedict's or Tollen's solutions, and they are categorized as non-reducing sugars. Acetals do not participate in an equilibrium with aldehydes or α-hydroxy ketones in the alkaline aqueous environment of these test reagents.

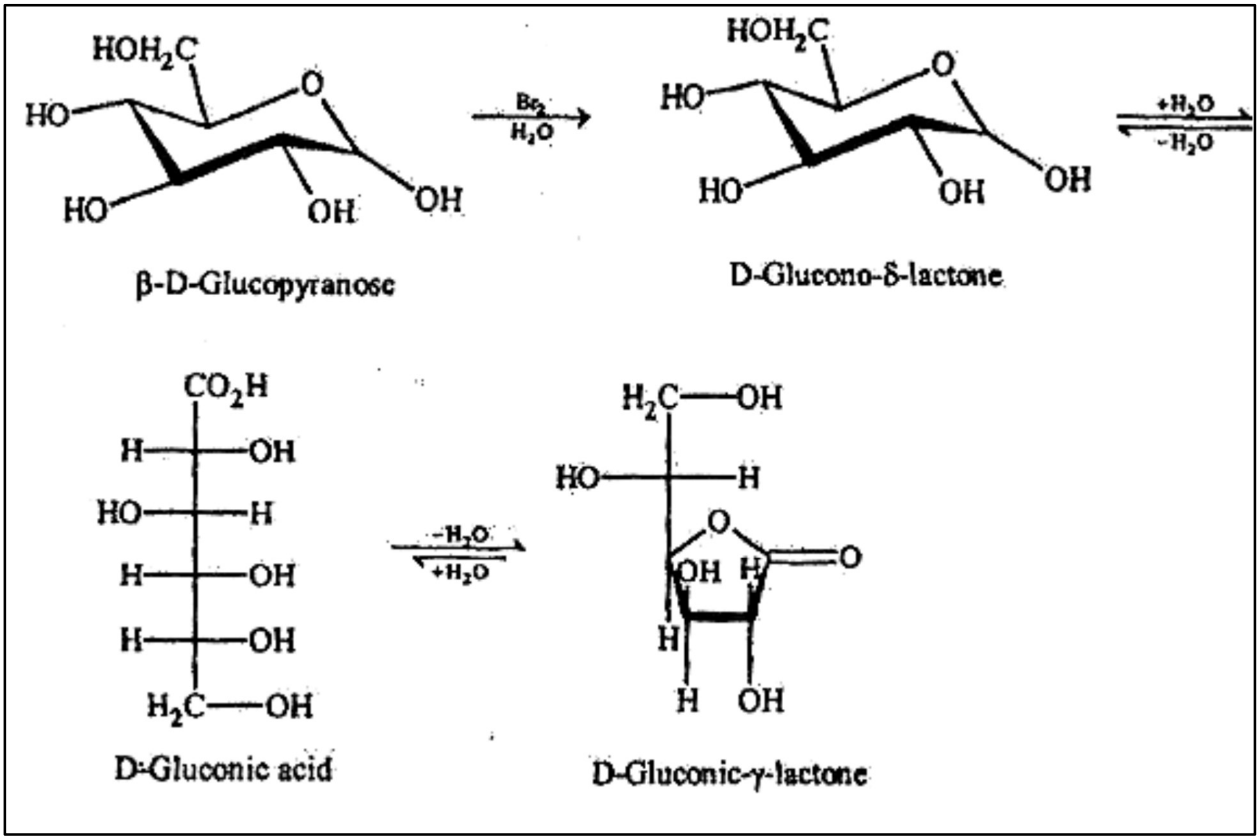


Bromine Water: The synthesis of Adonic Acid

In mildly acidic solutions, monosaccharides remain unaffected by isomerization and fragmentation reactions. Consequently, a valuable oxidizing agent for preparative objectives is bromine in water with a pH of 6.0. Bromine water serves as a versatile reagent with the specific capability to oxidize the -CHO group into a $-CO_2H$ group. It effectively transforms an aldose into an adonic acid.

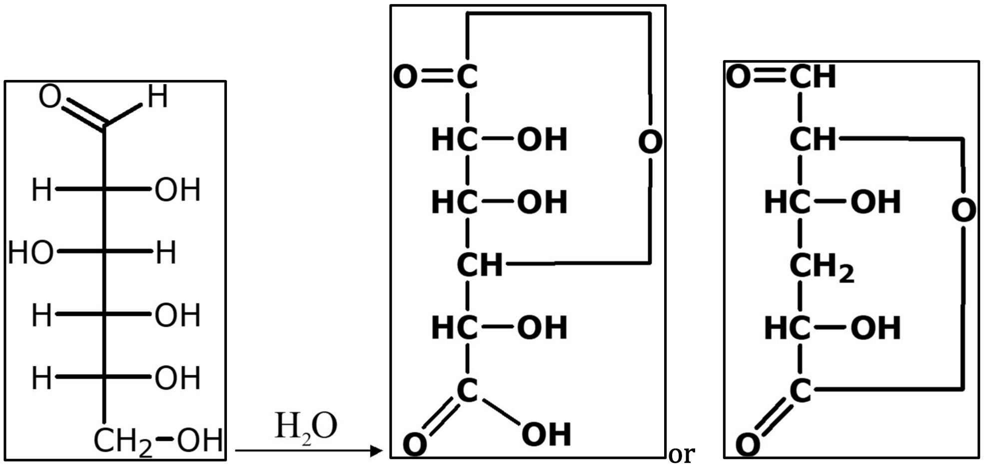


Studies involving Aldo pyranoses have revealed that the reaction's actual progression is somewhat more intricate than outlined previously. Bromine water specifically targets the β anomer, and the initial product that materializes is a δ-Aldon lactone. This compound might subsequently undergo hydrolysis to become an adonic acid, with the adonic acid potentially participating in a subsequent ring closure to generate a γ-Aldon lactone.



Nitric acid oxidation: allaric acid

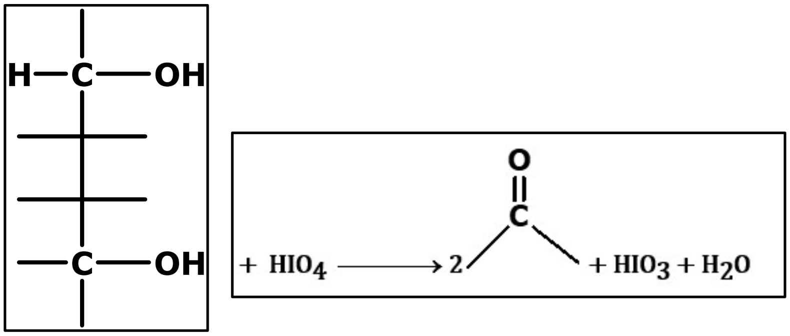
Mild nitric acid, a more potent oxidizing agent compared to bromine water, oxidizes both the -CHO group and the terminal -CH_2OH group of an aldose to form dicarboxylic acids referred to as allaric acids.



This allaric acid obtained from D-glucose is called D-glucaric acid.

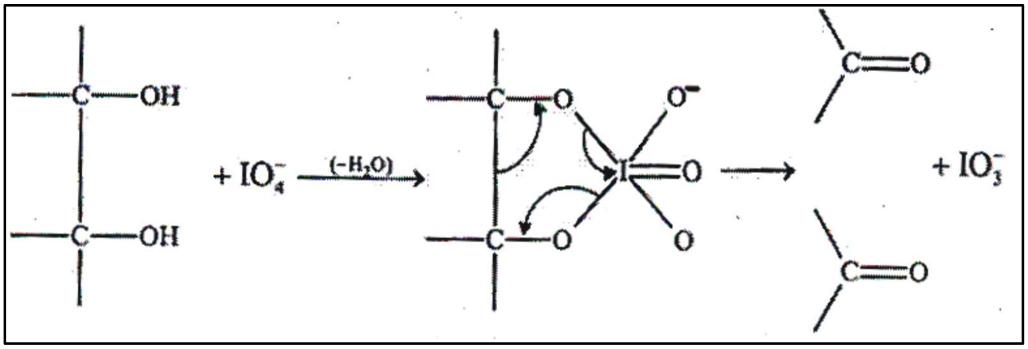
Periodate oxidation: oxidative cleavage of polyhydroxy compounds

Substances containing hydroxyl groups on neighboring atoms experience oxidative cleavage when subjected to an aqueous solution of periodic acid (HIO_4). This process results in the cleavage of carbon-carbon bonds and the production of carbonyl compounds, such as aldehydes, ketones, or acids.



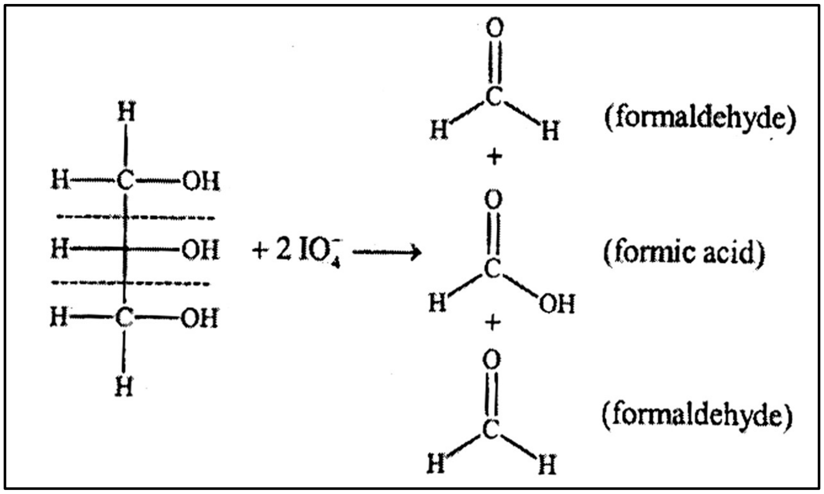
Because the reaction typically proceeds with high efficiency, valuable insights can frequently be obtained by quantifying the amount of periodic acid consumed during the reaction and identifying the resulting carbonyl products.

Periodate oxidations are though to take place through a cyclic intermediate:

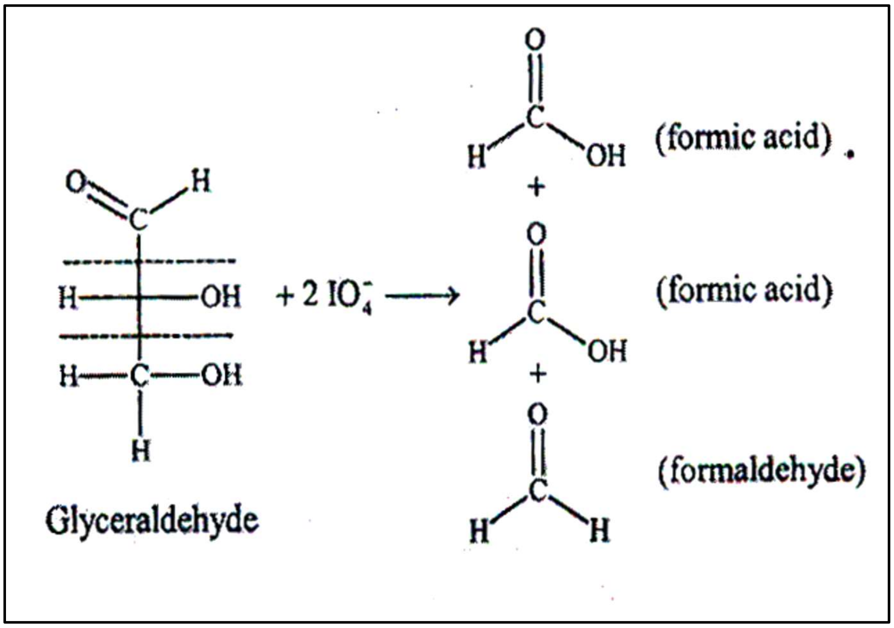


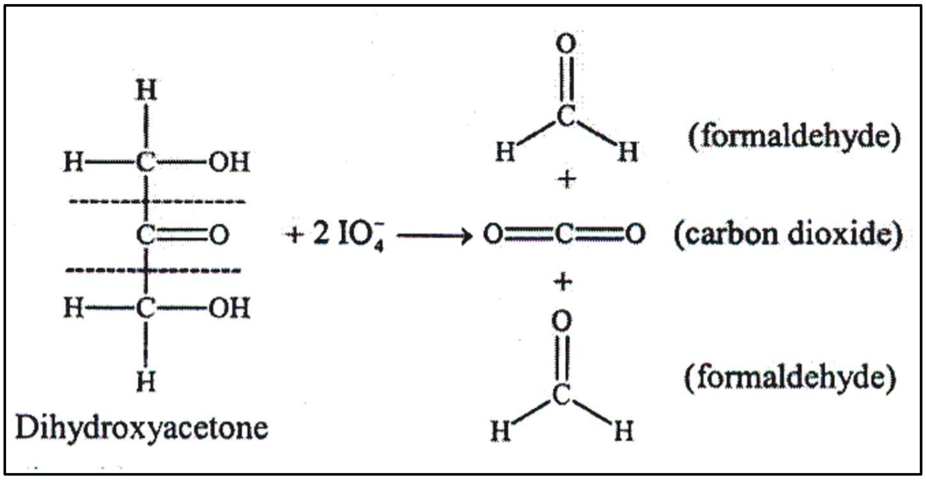
Before delving into the application of periodic acid in carbohydrate chemistry, let's elucidate the progression of the reaction with a few straightforward examples. It's essential to observe in these periodate oxidations that for every C–C bond that is severed, a new C–O bond is established at each carbon atom.

1. In situations where three or more consecutive -CHOH groups are present; the inner ones are transformed into formic acid.
   For instance, the periodate oxidation of glycerol yields two molar equivalents of formaldehyde and one molar equivalent of formic acid.

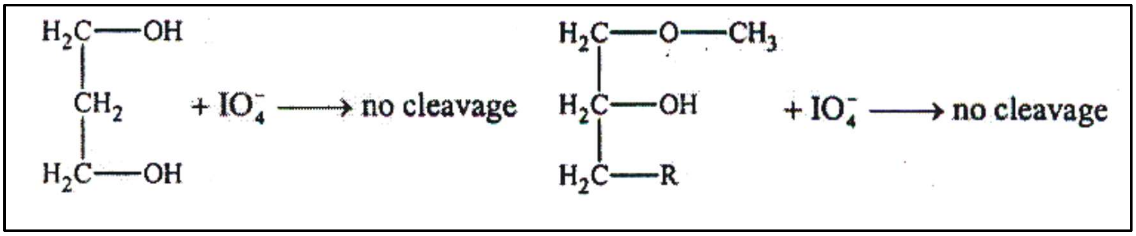


2. Oxidative cleavage also occurs when a -OH group is positioned next to the carbonyl group of an aldehyde or ketone (but not in the case of an acid or an ester). In this context, glyceraldehyde produces two molar equivalents of formic acid and one molar equivalent of formaldehyde. Similarly, dihydroxyacetone generates two molar equivalents of formaldehyde and one molar equivalent of carbon dioxide.



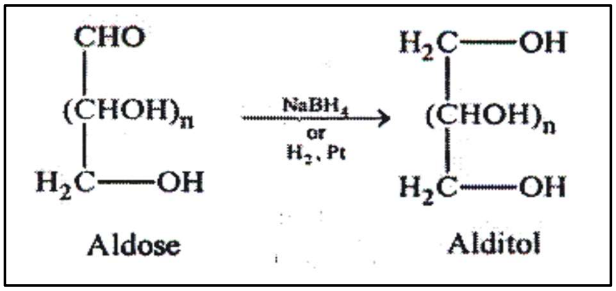


Periodic acid does not cleave compound in which the hydroxyl groups are separated by an intervening $-CH_2$ group, nor those in which a hydroxyl group is adjacent to an ether or acetal.



Reduction of monosaccharides: alditols

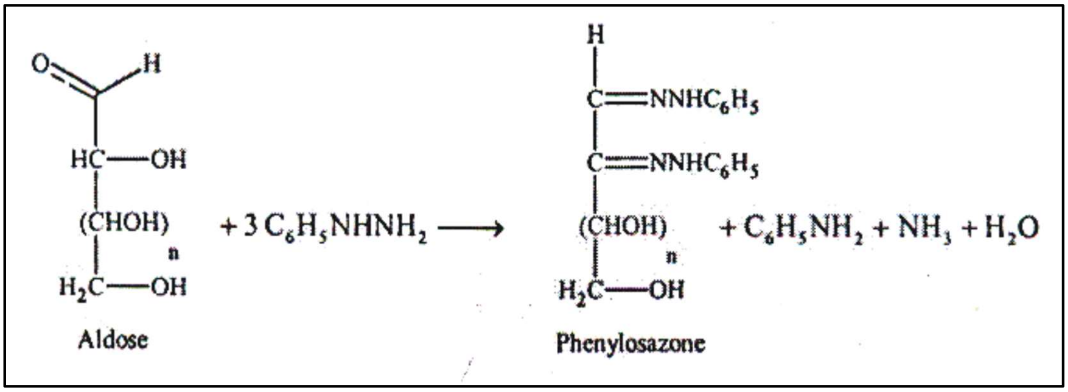
Aldoses (and ketoses) can be reduced with sodium borohydride to compounds called alditols:



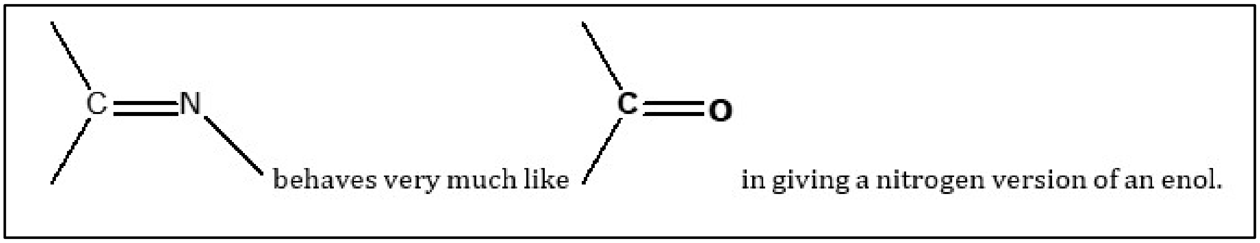
Reduction of D-glucose, for example, yields D-glucitol.

Reactions of monosaccharides with phenylhydrazone: oxazines

The aldehyde group found in an aldose is reactive towards specific carbonyl reagents such as hydroxylamine and phenylhydrazone. When it reacts with hydroxylamine, it forms the expected oxime product. However, when subjected to an excess of phenylhydrazone, three moles of phenylhydrazone are consumed, and a second phenylhydrazone group is introduced at C_2. The resulting product is known as a phenylalanine. Remarkably, phenylacetones readily crystallize (in contrast to sugars) and are useful derivatives for identifying sugars.

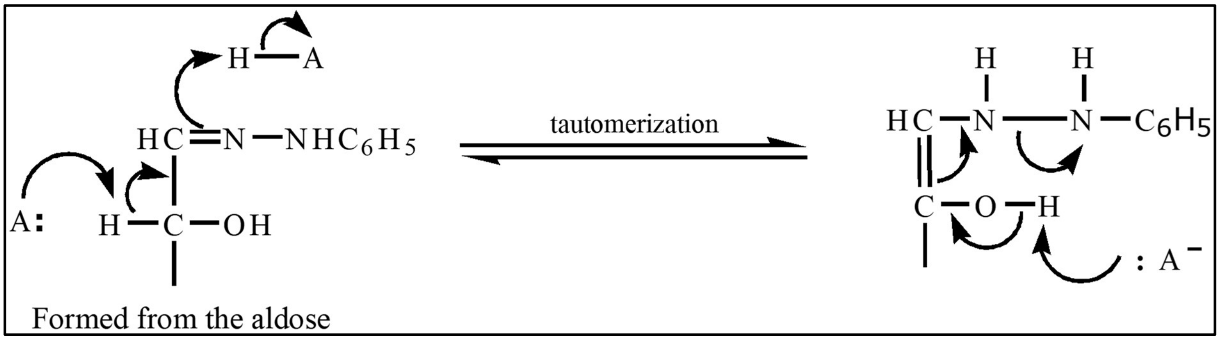


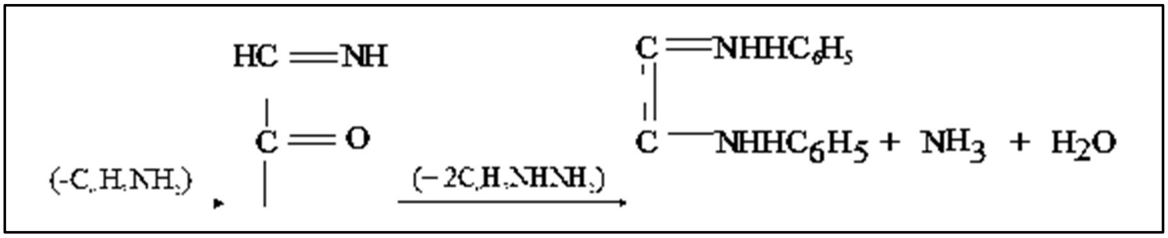
The mechanism for oxazine formation probably depends on a series of reaction in which


behaves very much like in giving a nitrogen version of an enol.

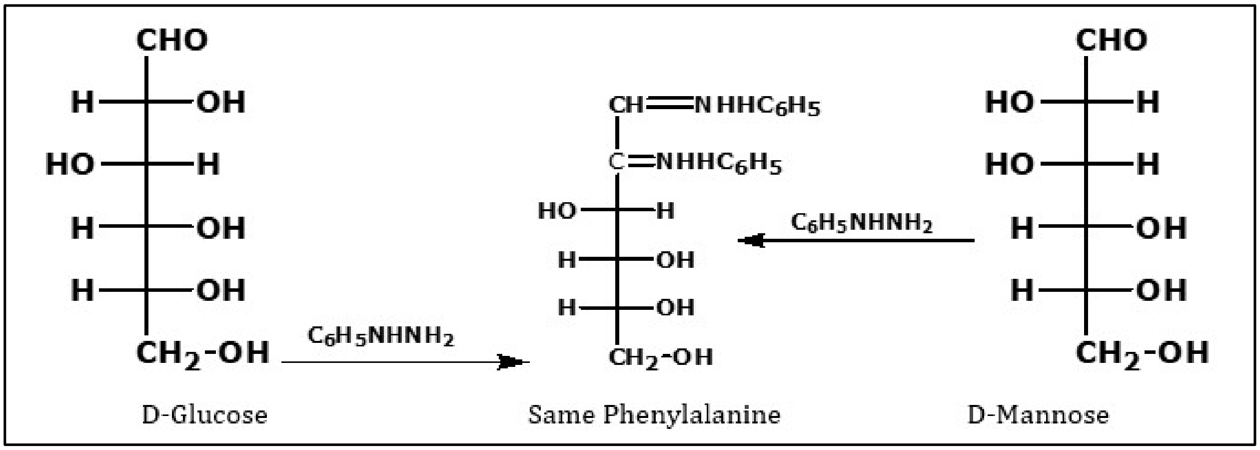
A mechanism for the reaction

Phenylacetone Formation





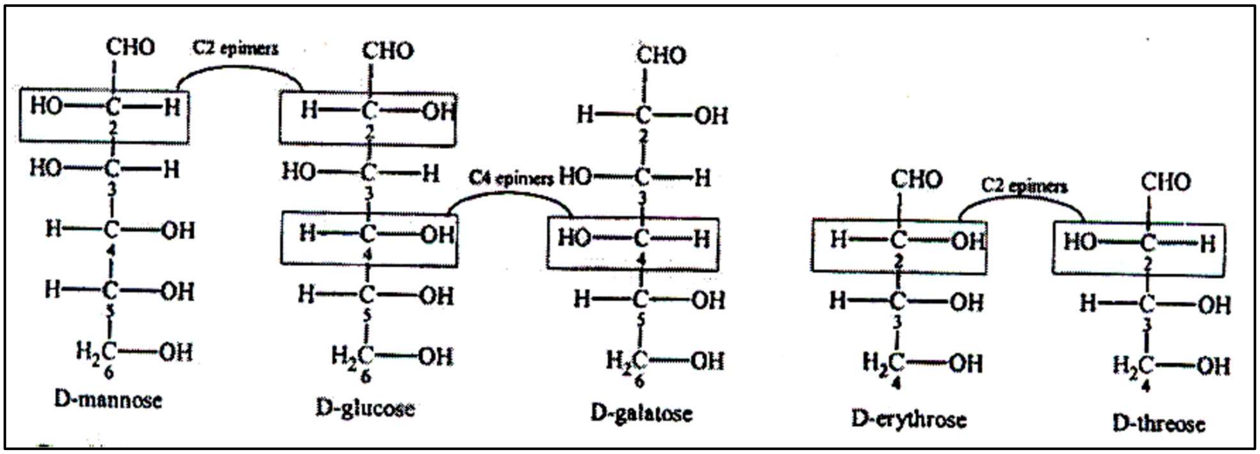
Orasone formation result in a loss of the stereo genic center at C_2 but does not affect other stereo genic carbons; D-glucose and D-mannose, for example, yield the same phenylalanine:



This experiment, originally conducted by Emil Fischer, confirmed that D-glucose and D-mannose share the same configuration concerning C_3, C_4, and C_5. Diastereomeric aldoses that exhibit distinct configurations at only one carbon (as seen in the case of D-glucose and D-mannose) are termed epimers. Broadly speaking, any pair of diastereomers that vary in configuration at just one tetrahedral stereo genic carbon can be referred to as epimers.

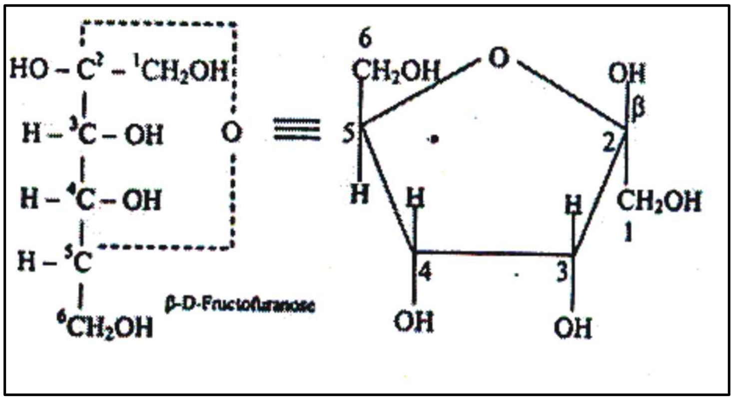
Epimers:

Many common sugars share a close relationship, with the primary distinction being the stereochemistry at a solitary carbon atom. For instance, glucose and mannose exhibit variance solely at C_2, which is the first asymmetric carbon atom. Sugars that vary only in stereochemistry at a single carbon atom are referred to as epimers, and the specific carbon atom where this difference occurs is typically indicated. In cases where the carbon atom is not explicitly mentioned, it is understood to be C_2. Consequently, glucose and mannose are known as "C_2 epimers" or simply "epimers." Another example includes galactose, which is the C_4 epimer of glucose, and threose, which is the C_2 epimer of erythrose.



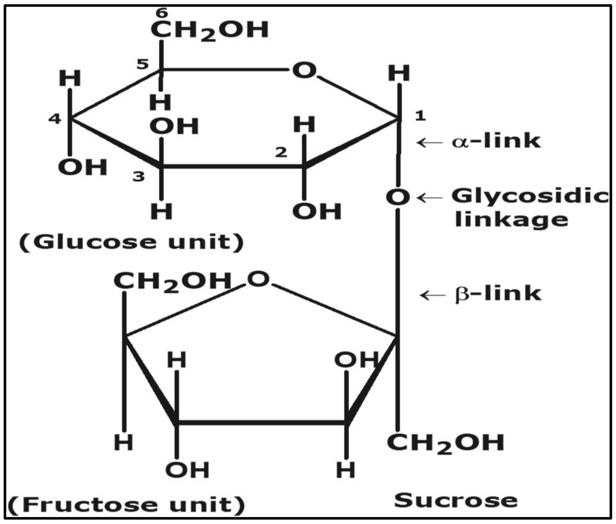
Cyclic structure of Fructose:

Similar to glucose, fructose also adopts a cyclic structure. Due to the presence of a keto group, fructose undergoes the formation of an intramolecular hemiketal. In this process, the C_5–OH group in fructose interacts with the C_2-keto group. Consequently, C_2 acquires chirality, resulting in two potential configurations with respect to the arrangement of the CH_2OH and OH groups around it.



D-fructose is found in two stereoisomeric forms, namely, α-fructopyranose and β-D-fructopyranose. However, in its combined state, such as in sucrose, fructose adopts the furanose form as depicted below:

Hydrolysis of Sucrose:



(Invert Sugar or Invertase). Hydrolysis of sucrose with hot dilute acid yields D-glucose and D fructose.

$$C_{12}H_{22}O_{11} \quad + \quad H_2O \xrightarrow{H^+} C_6H_{12}O_6 \quad + \quad C_6H_{12}O_6$$

Sucrose	D(+)-glucose	D(−)-Fructose
$[\alpha]_D = +66.5°$	$[\alpha]_D = +53°$	$[\alpha]_D = -92°$
$[\alpha]_D = (+53°)$ –	$(-92°) = 39°$	Invert Sugar

Sucrose exhibits dextrorotatory behavior with a specific rotation of +66.5%, while D-glucose also demonstrates dextrorotation with $[\alpha]D = +53°$. On the other hand, D-fructose has a notably negative rotation with $[\alpha]D = -92°$. As D-fructose possesses a more substantial specific rotation compared to D-glucose, the resulting mixture becomes levorotatory. This is why the hydrolysis of sucrose is referred to as the inversion of sucrose, and the equimolecular combination of glucose and fructose is termed invert sugar or invertase.

Polysaccharides

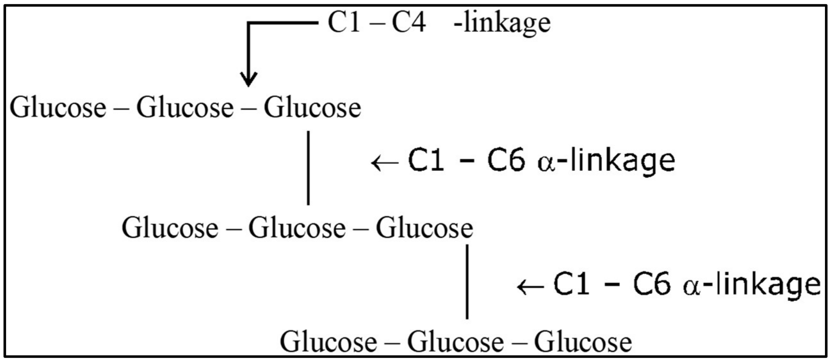
Polysaccharides are composed of monosaccharide polymers, and typical natural polysaccharides usually consist of approximately 100 to 3000 monosaccharide units. Interestingly, the three most prevalent natural polysaccharides—cellulose, starch, and glycogen—originate from the same monomer, namely glucose.

Starch: It

Starch is a polymer composed of glucose, with its molecular formula represented as $(C_6H_{10}O_5)$ n. The value of n can vary between 200 and 1000, depending on the source. It is the primary food reserve material or storage polysaccharide found in plants, predominantly in seeds, roots, and tubers. Rich sources of starch include wheat, rice, potatoes, corn, bananas, and more.

Starch is not a single compound but is rather a combination of two components: a water-soluble part known as amylose (comprising 20%) and a water-insoluble component referred to as amylopectin (constituting 80%). Both amylose and amylopectin are comprised of α-D glucose monomers.

Amylose represents a linear polymer of α-D glucose. It consists of approximately 200 glucose units linked to each other through α-linkages, involving C_1 of one glucose unit and C_4 of the adjacent unit. In contrast, amylopectin is a highly branched polymer.

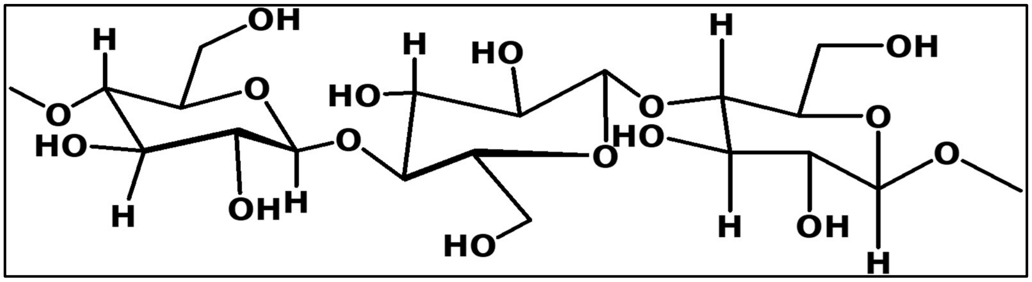


It is composed of numerous short chains, each containing 20-25 glucose units, which are interconnected through α-linkages, specifically C_1 of one glucose unit with C_4 of another. Additionally, the C_1 of the terminal glucose unit in each chain is further linked to C_6 of the adjacent glucose unit in the next chain, forming α-linkages between C_1 and C_6. This branching structure imparts amylopectin with its highly branched nature.

Hydrolysis: The breakdown of starch can be achieved through the hydrolysis of starch using hot dilute acids or enzymes, resulting in the formation of dextrin's of different levels of complexity, maltose, and ultimately D-glucose. Notably, starch does not exhibit the ability to reduce Tollen's reagent and Fehling's solution.

Uses: Starch finds application as a food ingredient and is a common part of our daily diet, present in foods like potatoes, bread, cakes, and rice. It serves a purpose in coating and sizing paper to enhance its writing properties. Additionally, starch is employed in the treatment of textile fibers before they are woven into fabric, ensuring they can be woven without rupturing. Starch plays a role in the production of various products including dextrin's, glucose, and ethyl alcohol. Notably, starch is also utilized in the manufacturing of starch nitrate, which serves as an explosive material.

Cellulose: Cellulose serves as the primary constituent of wood and plant fibers. For example, cotton consists almost entirely of cellulose. It exhibits insolubility in water, has a neutral taste, and qualifies as a non-reducing carbohydrate. These characteristics are, at least in part, attributed to its exceptionally high molecular weight.



Cellulose

Cellulose possesses the chemical formula $(C_6H_{10}O_5)$ n. When subjected to complete acid hydrolysis, it yields D (+)-glucose as the resulting monosaccharide. Full methylation of cellulose leads to the production of a substantial amount of 2, 3, 6-tri-O-methyl-D-glucose. Hence, like starch, cellulose is comprised of chains composed of D-glucose units. These units are interconnected through glycoside linkages at C-4 of the subsequent glucose unit.

However, cellulose distinguishes itself from starch through the configuration of its glycoside linkage. When treated with acetic anhydride and sulfuric acid, cellulose forms octa-O-acetyl cellobiose, which suggests that all the glycoside linkages in cellulose, similar to the one in (+) cellobiose, are beta linkages.

Physically determined molecular weights for cellulose range from 250,000 to over 1,000,000, with an estimated minimum of approximately 1,500 glucose units per molecule. End group analysis through both methylation and periodic acid oxidation indicates a chain length of 1,000 glucose units or more. X-ray analysis and electron microscopy reveal that these lengthy chains lie closely together in bundles, firmly bound by hydrogen bonds formed between the numerous neighboring -OH groups. These bundles are twisted together to create a rope-like structure, and these structures, in turn, combine to form the fibers visible to the naked eye. In wood, these cellulose "ropes" are embedded in lignin, creating a structure akin to reinforced concrete.

Properties of Cellulose: We have observed that the glycoside linkages within cellulose can be cleaved through the action of acids, yielding numerous molecules of D (+)-glucose from each cellulose molecule. Now, let's briefly examine reactions of cellulose in which the polymer chain remains predominantly intact. In cellulose, each glucose unit contains three available -OH groups, which serve as sites for various reactions.

These cellulose reactions, conducted to modify the characteristics of an easily accessible and cost-effective polymer, hold immense industrial significance.

Similar to other alcohols, cellulose can form esters. When treated with a combination of nitric and sulfuric acid, cellulose is transformed into cellulose nitrate. The properties and applications of the resulting product are contingent on the degree of nitration. Guncotton, which finds use in the production of smokeless powder, is nearly completely nitrated cellulose and is sometimes referred to as cellulose trinitrate, signifying the presence of three nitrate groups per glucose unit. Pyroxylin is a less heavily nitrated material, containing between two and three nitrate groups per glucose unit. It is utilized in the manufacturing of items such as celluloid, collodion, photographic film, and lacquers. It should be noted that pyroxylin is flammable and emits highly toxic nitrogen oxides when burned.

In industrial applications, cellulose is alkylated to form ethers by employing alkyl chlorides (which are more cost-effective than sulfates) in the presence of alkali. It is important to acknowledge that these reactions unavoidably result in some degree of chain degradation. Methyl, ethyl, and benzyl ethers of cellulose play a crucial role in the production of textiles, films, and a variety of plastic items.