Carbohydrates

- Polyhydroxy compounds (poly-alcohols) that contain a carbonyl (C=O) group
- Elemental composition $C_x(H_2O)_y$
- About 80% of human caloric intake
- >90% dry matter of plants
- Functional properties
  - Sweetness
  - Chemical reactivity
  - Polymer functionality

Types of Carbohydrates

- Classifications based on number of sugar units in total chain.

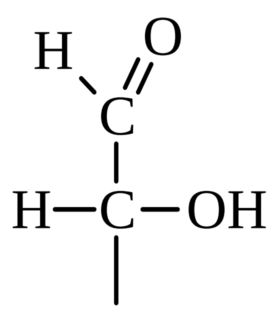
Monosaccharides	- single sugar unit
Disaccharides	- two sugar units
Oligosccharides	- 2 to 10 sugar units
Polysaccharides	- more than 10 units

Chaining relies on 'bridging' of oxygen atoms

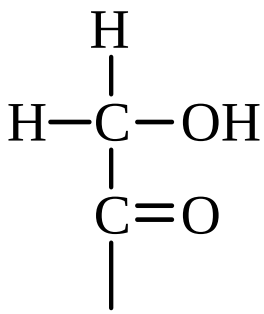
glycoside bonds

Monosaccharides

- Monosaccharides are categorized by the number of carbons (typically 3-8) and whether an aldehyde or ketone
- Most abundant monosaccharides are hexoses (6 carbons)
- Most monosaccharides are aldehydes, i.e. aldoses

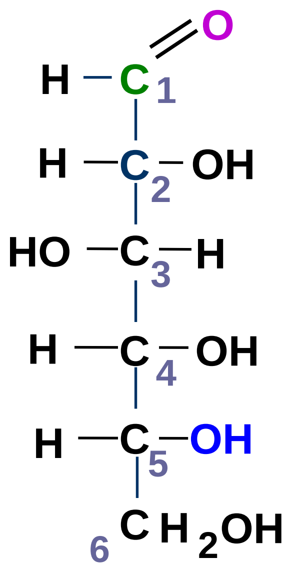


aldehyde

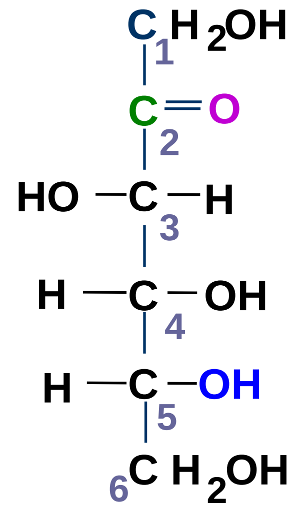


ketone

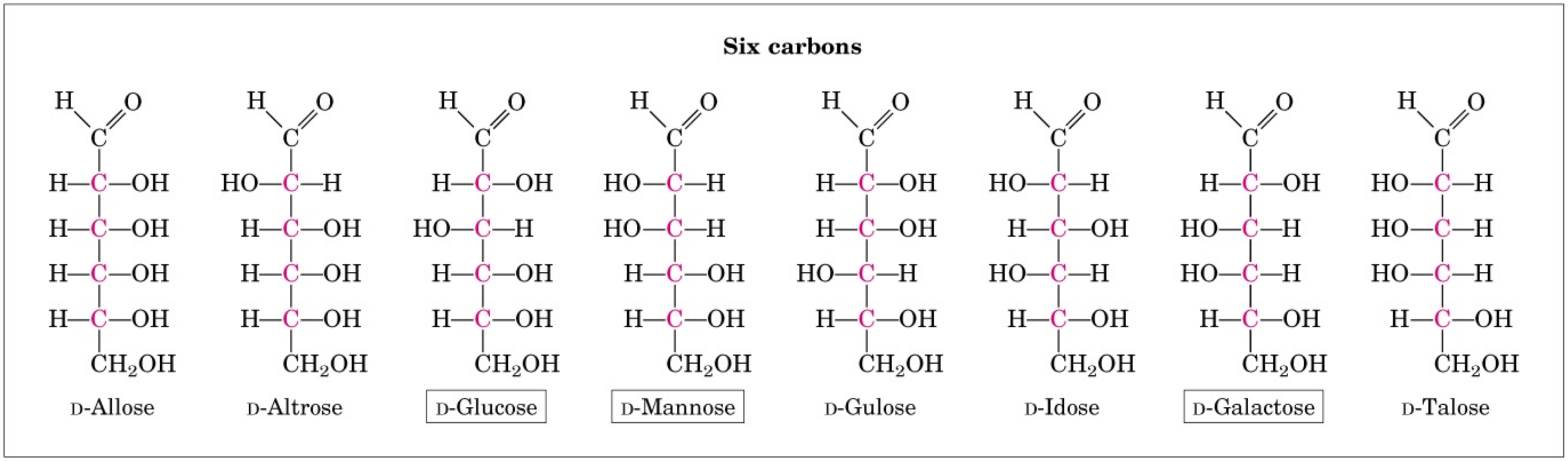
Fisher projections



D-glucose
(an aldohexose)

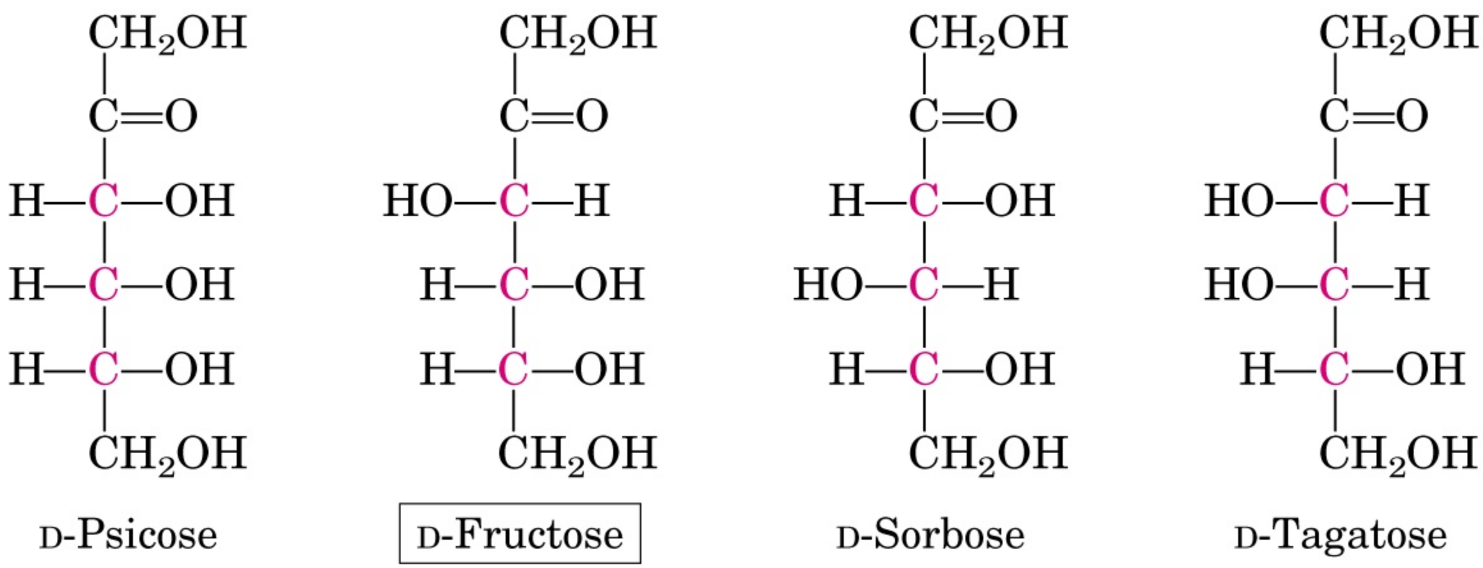


D-fructose
(an ketohexose)


Six carbons
D-Allose
D-Altrose
D-Glucose
D-Mannose
D-Gulose
D-Idose
D-Galactose
D-Talose

D-Aldoses
(a)

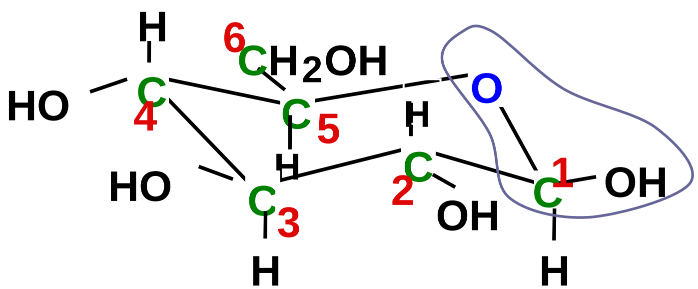
Six carbons



D-Ketoses
(b)

Cyclic Forms

- Lowest energy state



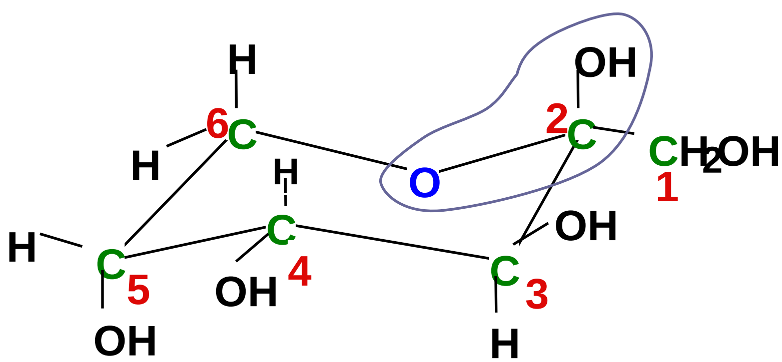
β-D-glucopyranose (glucose)

—an aldose

a hexose

an aldohexose

—C_1 chair conformation



β-D-fructopyranose (fructose)

—a ketose

a hexulose

a ketohexose

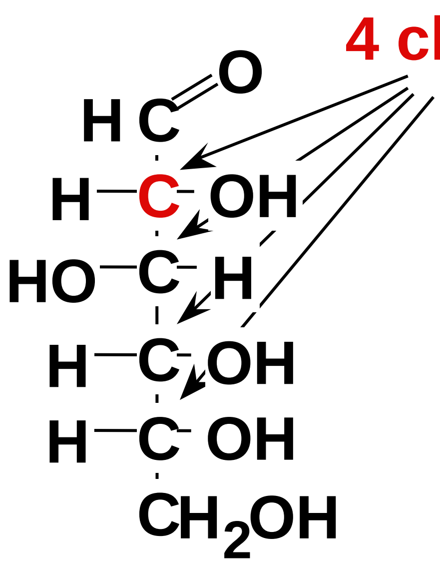
—^1C chair conformation

Ring Nomenclature

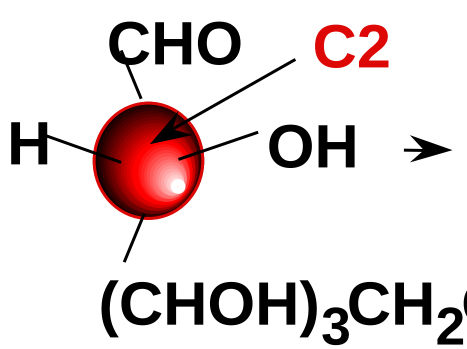
- pyranose is a six-membered ring (a very stable form due to optimal bond angles)
- furanose is a five-membered ring

Chirality

- Geometric property of a rigid object (or spatial arrangement of atoms) of being non-super-imposable on its mirror image



e.g. at C2 carbon: This structure has a non-superimposable mirror image



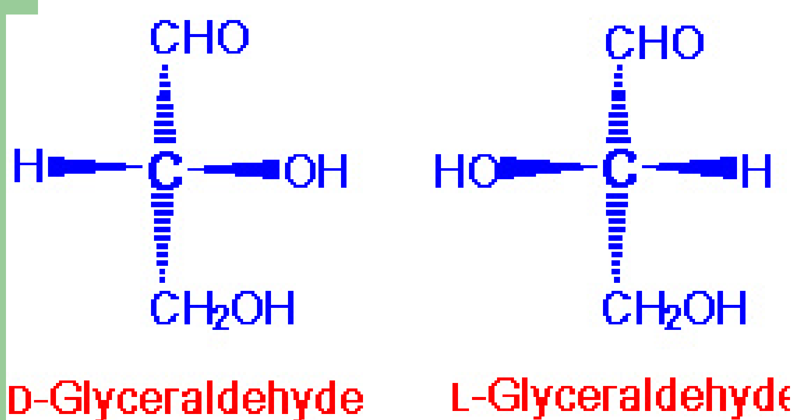
→ its mirror image is an "optical isomer"

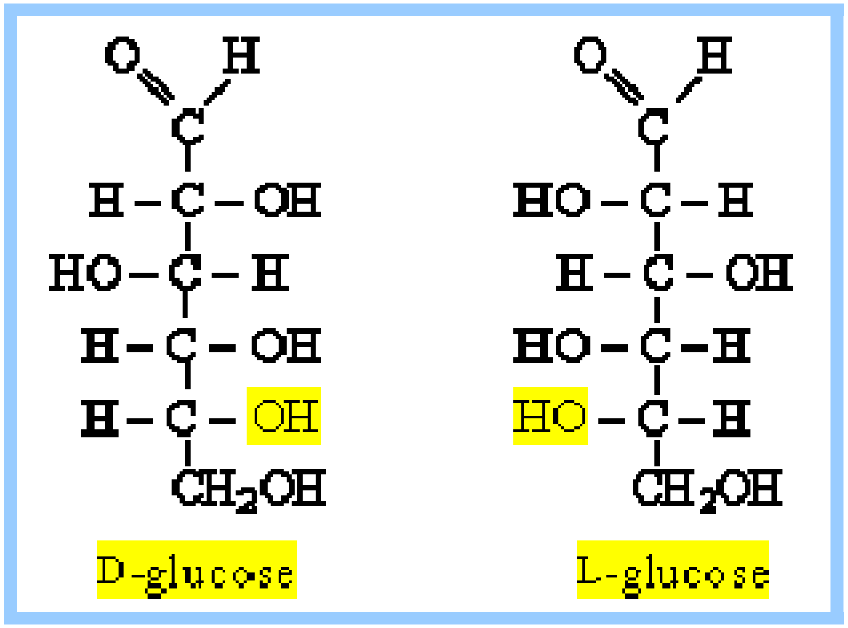
Isomers

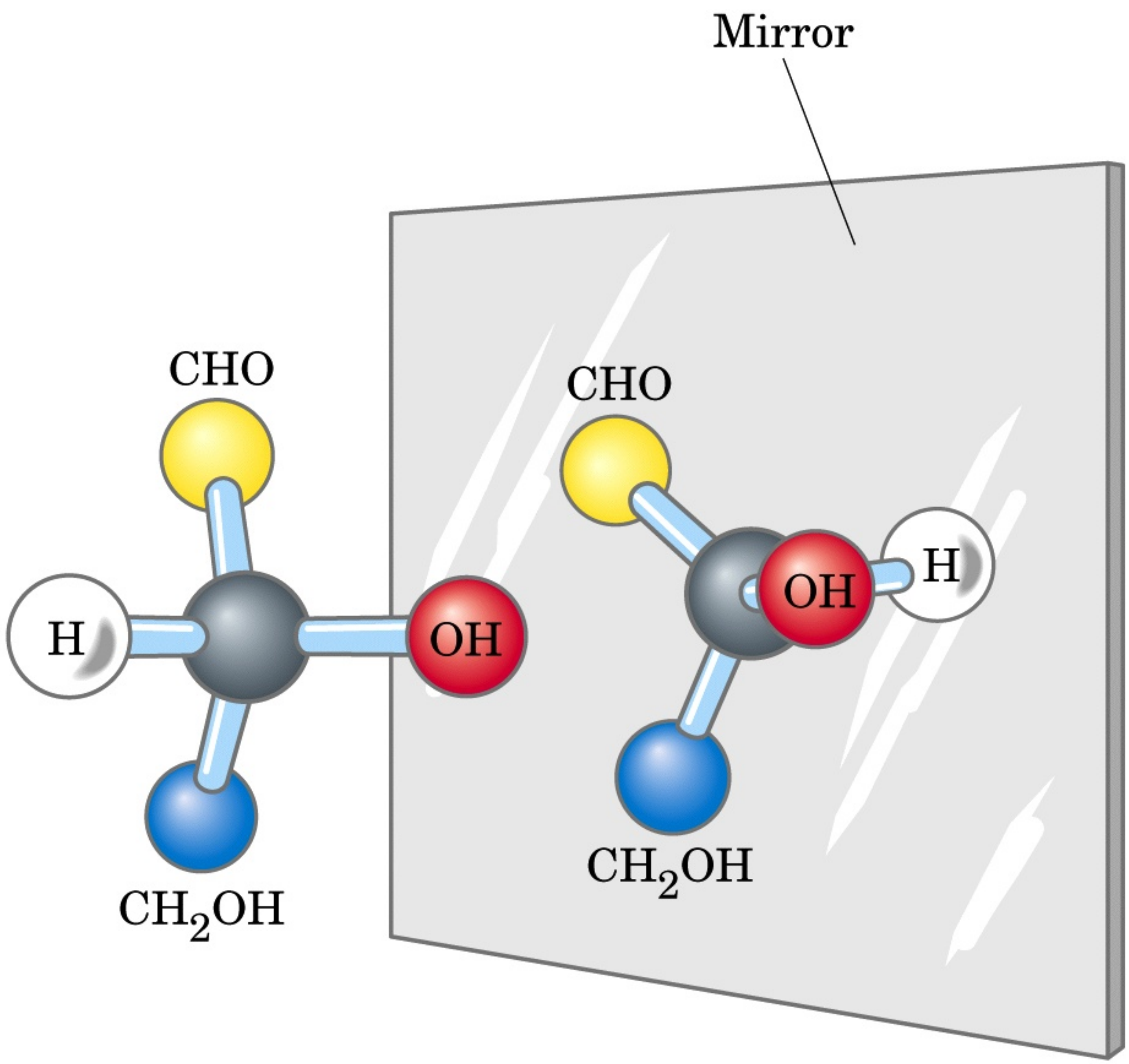
- Isomers are molecules that have the same chemical formula but different structures
- Stereoisomer differs in the 3-D orientation of atoms
- Diastereomers are isomers with > 1 chiral center.
  - Pairs of isomers that have opposite configurations at one or more of the chiral centers but that are not mirror images of each other.
- Epimers are a special type of diastereomer.
  - Stereoisomers with more than one chiral center which differ in chirality at only one chiral center.
  - A chemical reaction which causes a change in chirality at one one of many chiral center is called an epimerisation.

Enantiomers

- Isomerism in which two isomers are mirror images of each other. (D *vs* L)



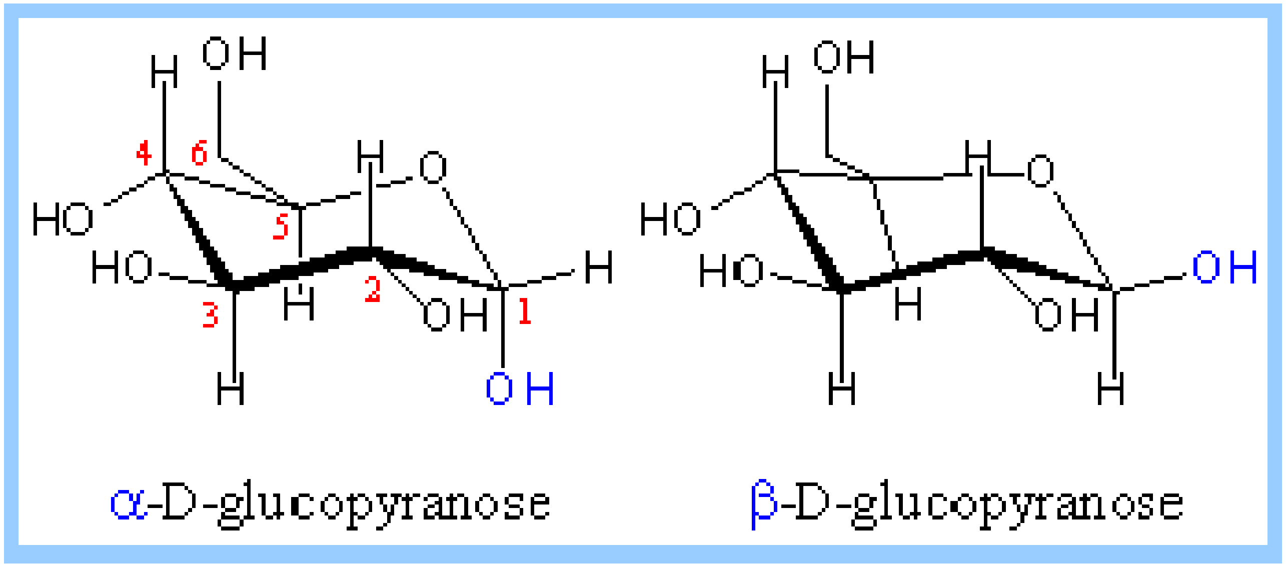




Ball-and-stick models

Anomer

- An anomer is one of a special pair of diastereomeric aldoses or ketoses
  - differ only in configuration about the carbonyl carbon (C1 for aldoses and C2 for ketoses)

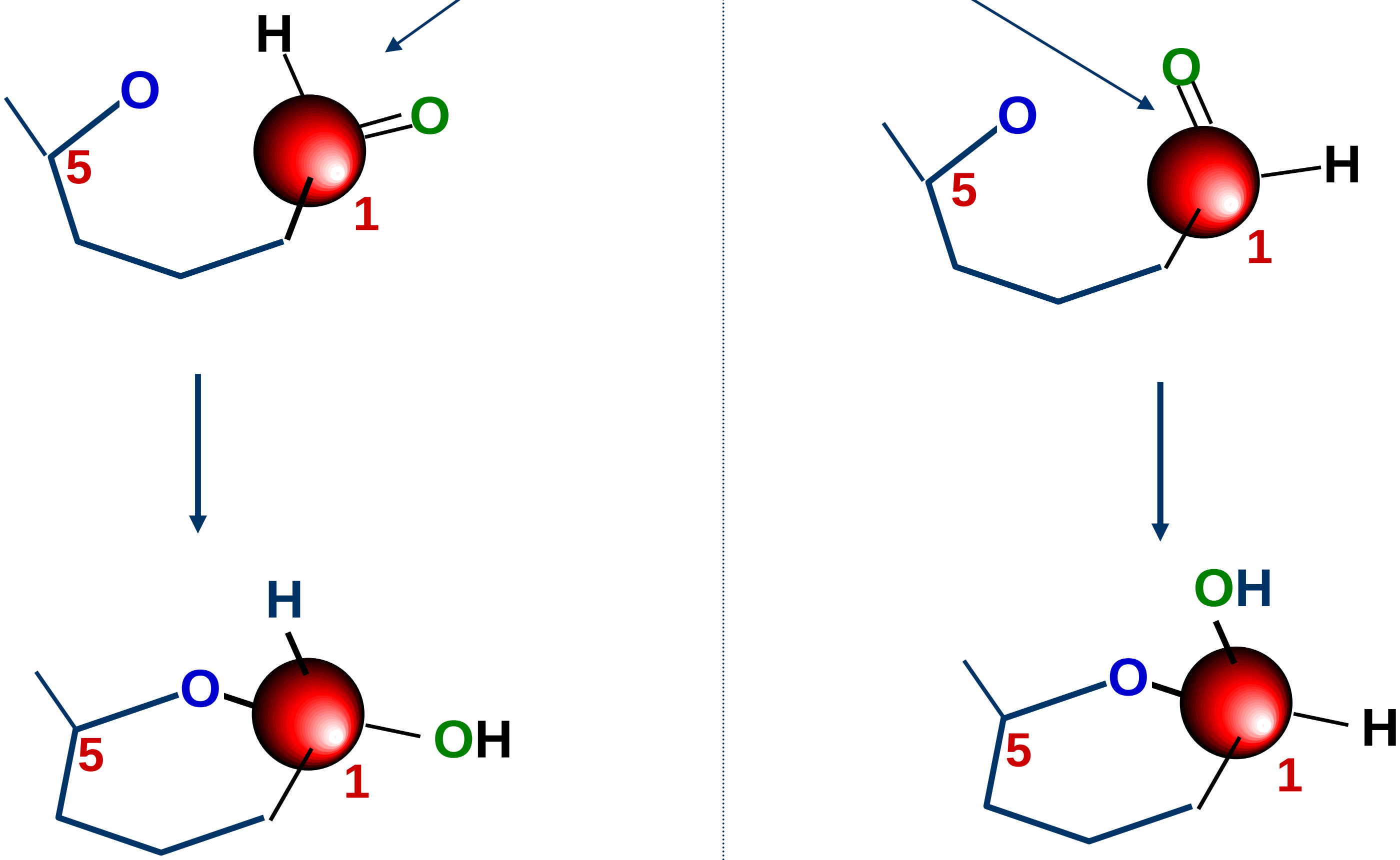


Carbonyl Group

- Carbonyl groups subject to nucleophilic attack, since carbonyl carbon is electron deficient:
  - -OH groups on the same molecule act as nucleophile, add to carbonyl carbon to recreate ring form

Carbonyl carbon freely rotates

→ O can attack either side



α anomer

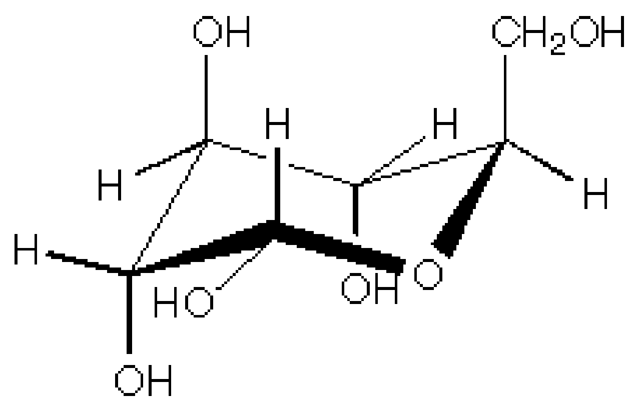
β anomer

Specification of Conformation, chirality and anomeric form of sugars

- Determination of chair conformation
  - Locate the anomeric carbon atom and determine if numbering sequence is clockwise (n= +ve) or counterclockwise (n= -ve).
  - Observe if the puckered ring oxygen atom lies “above” (p= +ve) the plane of the ring or below (p= -ve).
  - Multiply n*p. If the product is +ve then C1, -ve then 1C
- Determination of chiral family
  - Locate the reference carbon atom contained within the ring and determine whether the bulky substituent (OH or CH_2OH) is equatorial (r= +ve) or axial (r= -ve).
  - Multiply n*p*r. If product is +ve the chiral family is D, when it is –ve the chiral family is L

Specification of Conformation, chirality and anomeric form of sugars

- Determination of Anomeric form:
  - Determine if the hydroxyl substituent on the anomeric carbon atom is equatorial (a= +ve) or axial (a= -ve).
  - Multi[ly (n*p) by (n*p*r) by a. When the product is positive, the anomer is β; when the product is negative the anomer is α

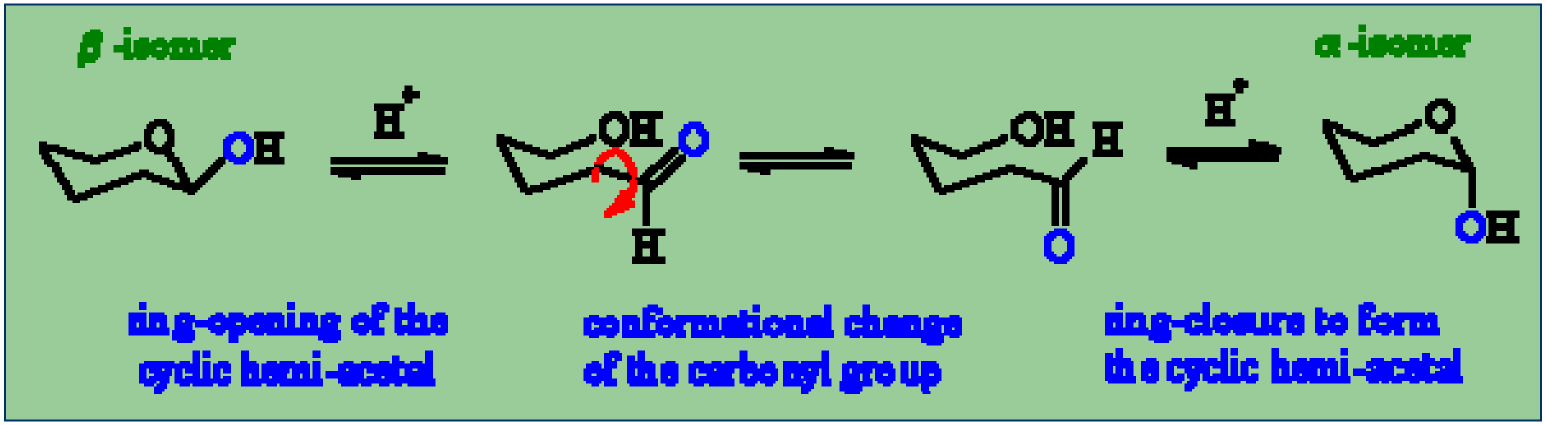


Mutarotation

- The α- and β- anomers of carbohydrates are typically stable solids.
- In solution, a single molecule can interchange between
  - straight and ring form
  - different ring sizes
  - α and β anomeric isomers
- Process is
  - dynamic equilibrium
  - due to reversibility of reaction
- All isomers can potentially exist in solution
  - energy/stability of different forms vary

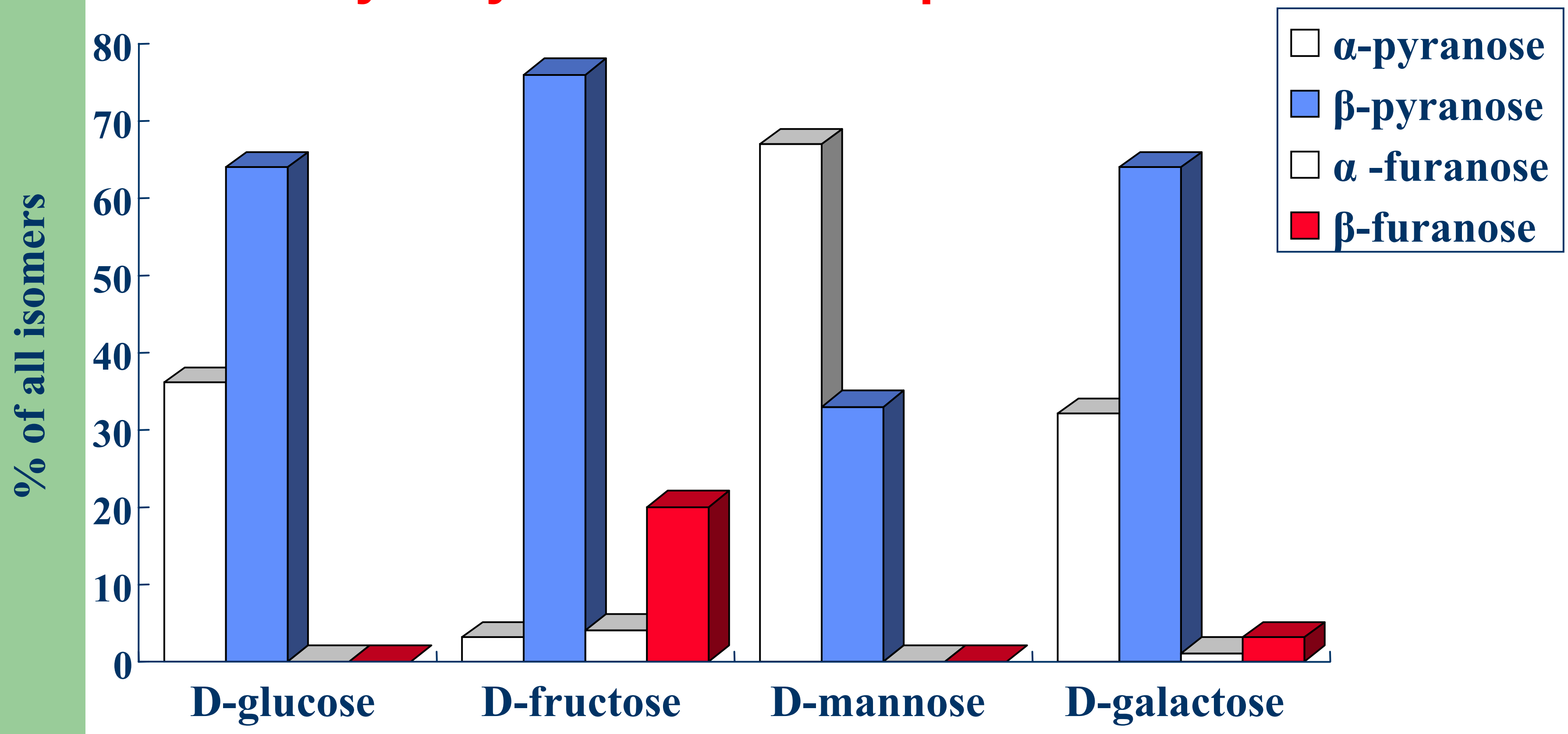
Mutarotation : interconversion of α- and β- anomers

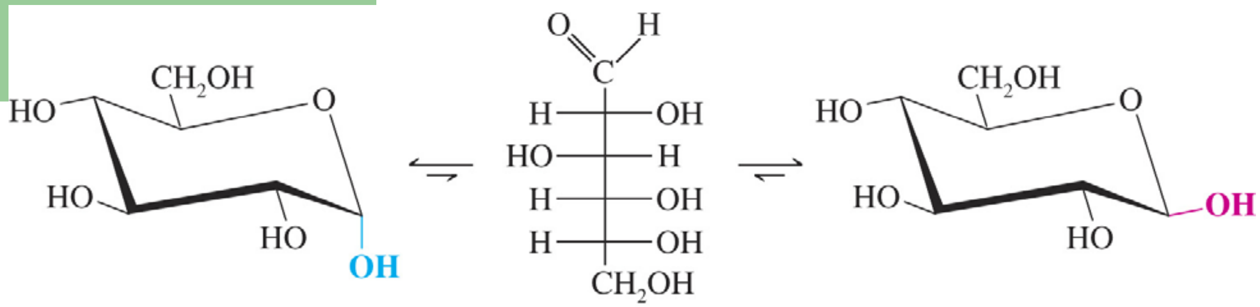
- For example, in aqueous solution, glucose exists as a mixture of 36% α - and 64% β - (>99% of the pyranose forms exist in solution).



Anomer Interconverision

Generally only a few isomers predominate

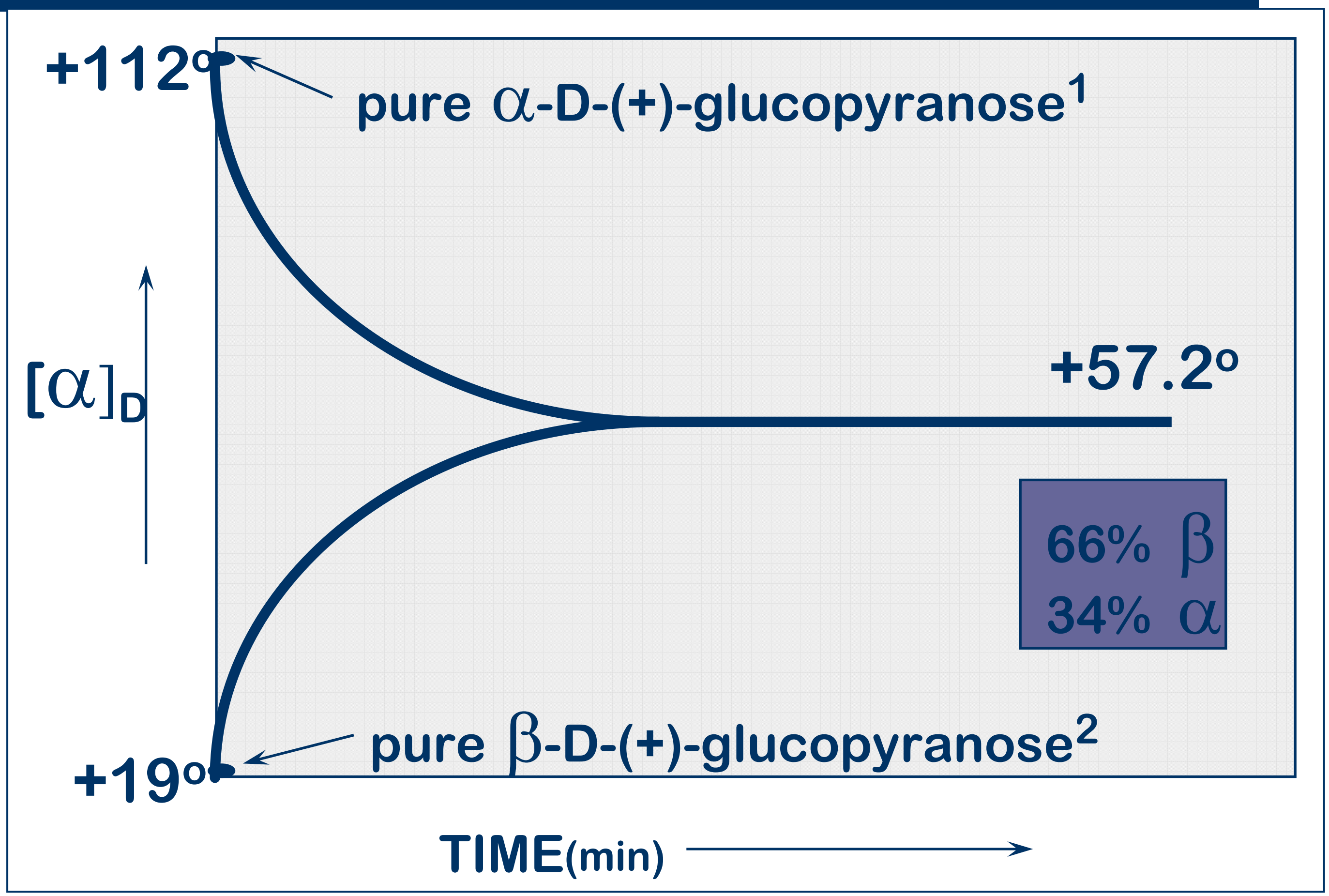


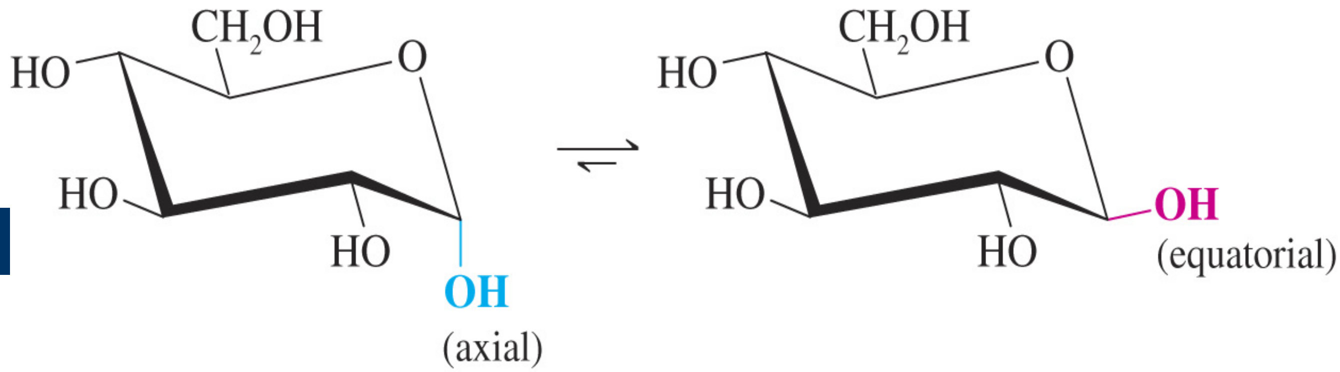


α-D-(+)-Glucopyranose (mp 146°C; $[\alpha]_D^{25} = +112°$)

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

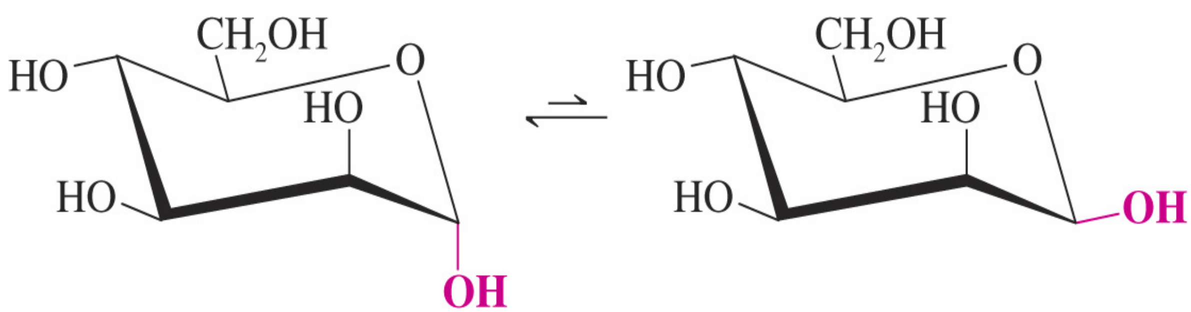
β-D-(+)-Glucopyranose (mp 150°C; $[\alpha]_D^{25} = +18.7°$)





α-D-(+)-Glucopyranose
(36% at equilibrium)

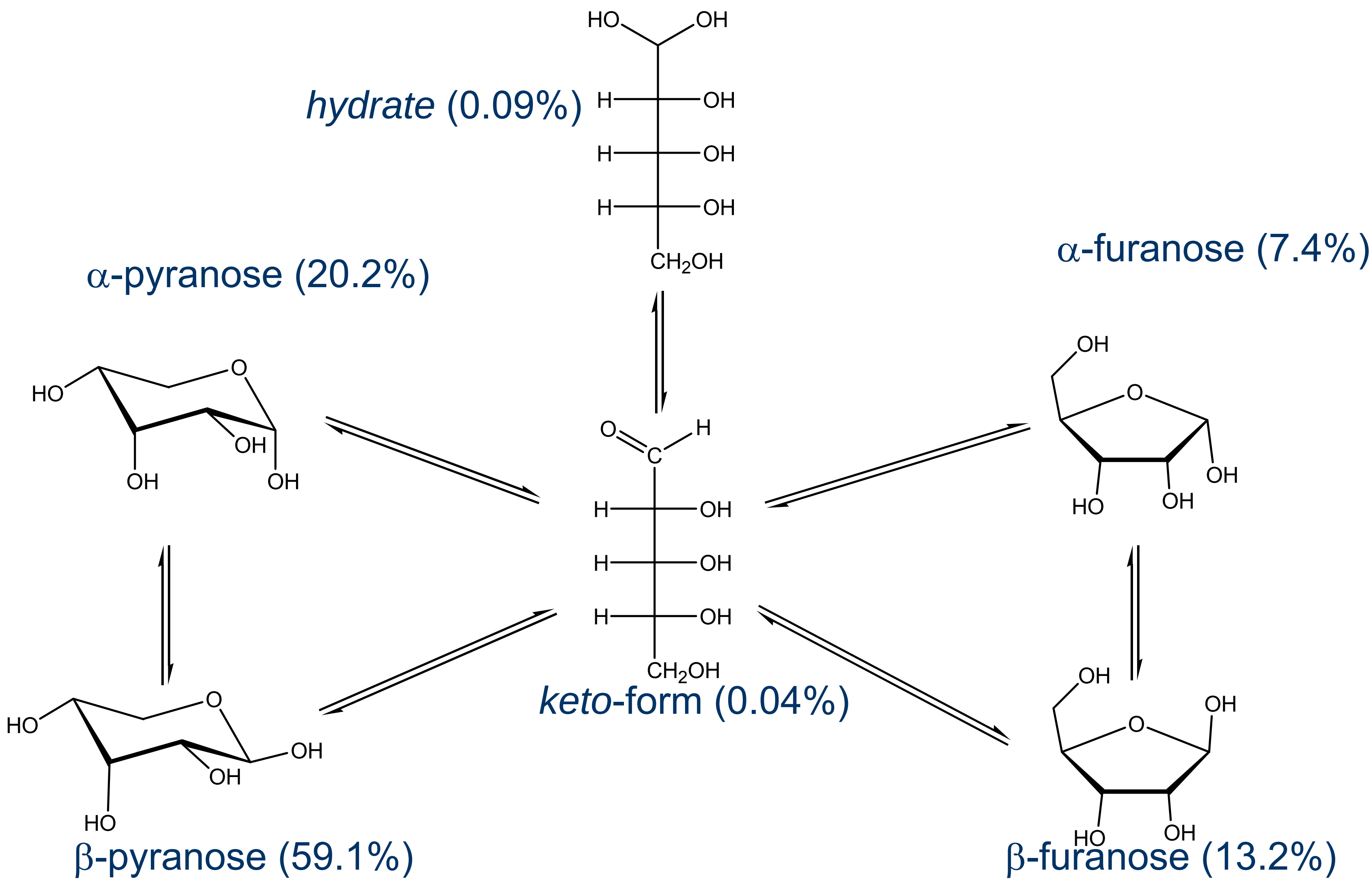
β-D-(+)-Glucopyranose
(64% at equilibrium)



α-D-Mannopyranose
(69% at equilibrium)

β-D-Mannopyranose
(31% at equilibrium)

Mutarotation of ribose



Stability of Hemiacetals/Hemiketals

- As general rule the most stable ring conformation is that in which all or most of the bulky groups are equatorial to the axis of the ring

Reactions

- Isomerization

  glucose $\rightleftharpoons$ fructose $\rightleftharpoons$ mannose

- Oxidation

  R-CHO $\longrightarrow$ R-COOH

  R-CH_2OH $\longrightarrow$ R-COOH

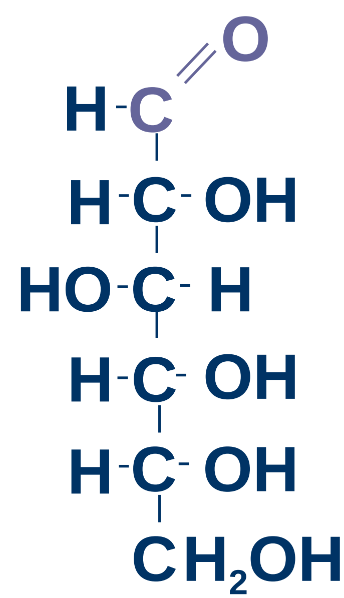
- Reduction

  sugar $\longrightarrow$ sugar alcohols

- Acetal formation

  sugar $\longrightarrow$ glycoside

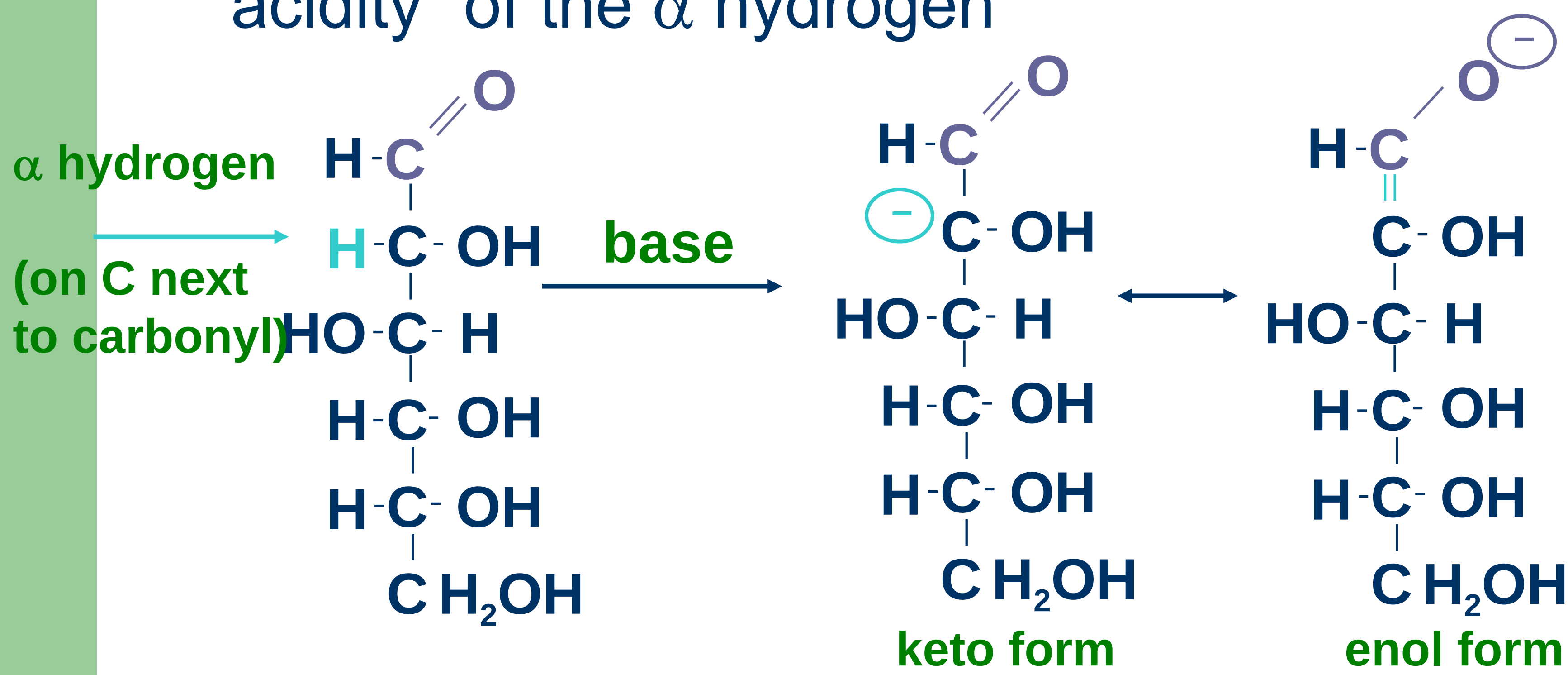
- Browning reactions



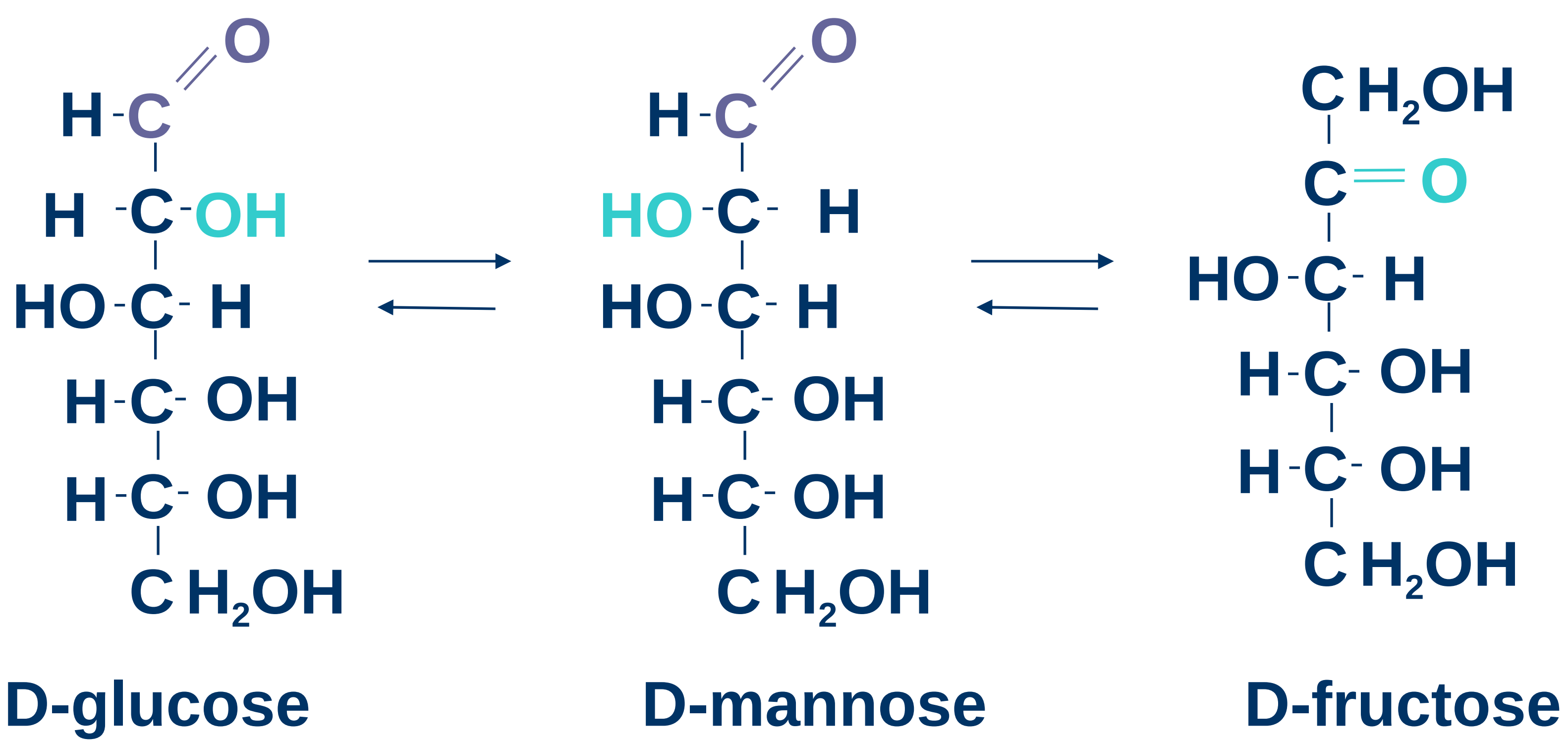
carbonyl group is key

Isomerization

- Isomerization is possible because of the "acidity" of the α hydrogen



Isomerization



Oxidation/Reduction

Oxidation

Increase oxygen or decrease hydrogen

Increase oxidation state

Remove electrons

Reduction

Decrease oxygen or increase hydrogen

Decrease oxidation state

Add electrons

Oxidation

- Carbonyl group can be oxidized to form carboxylic acid
- Forms "-onic acid" (e.g. gluconic acid)
- Can not form hemiacetal
- Very hydrophillic
  - Ca gluconate
- Can react to form intramolecular esters:
  - lactones

Oxidation

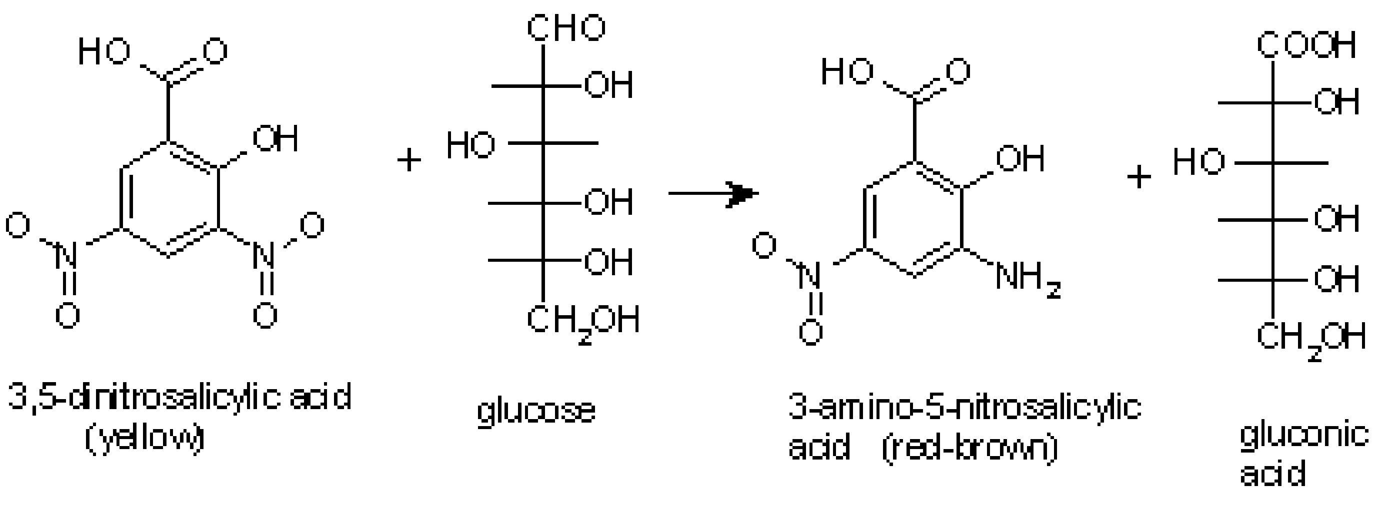
- Also possible to oxidize alcohols to carboxylic acids
  - "-uronic acids"
    - Galacturonic acids
    - Pectin
- Reactivity
  - Aldehydes are more reactive than ketones
    - In presence of base ketones will isomerize
    - Allows ketones to oxidize

Reducing sugars

- Reducing sugars are carbohydrates that can reduce oxidizing agents
- Sugars which form open chain structures with free carbonyl group
- Reduction of metal ions
  - Fehling test: $CuSO_4$ in alkaline solution

DNSA assay

- Colorimetric analysis: the sugars present reduce 3,5-dinitrosalicylic acid, DNSA, to 3-amino-5-nitrosalicylic acid

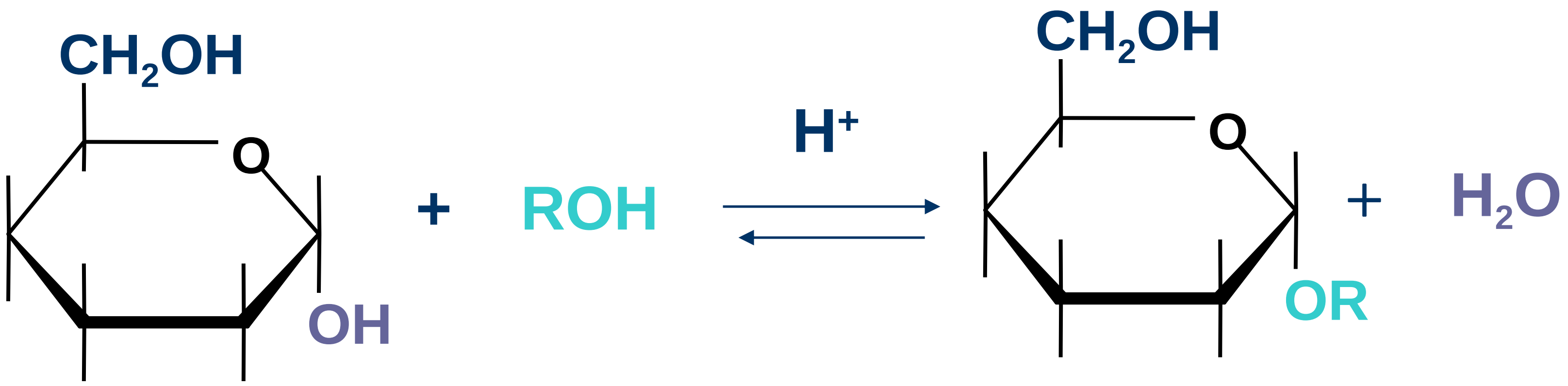


Reduction

- Carbonyl group can be reduced to form alcohol
  - hydrogenation reaction
- Forms sugar alcohol ("-itol")
  - glucose → glucitol (aka sorbitol)
  - mannose → mannitol
  - xylose → xylitol
- Sweet, same calories as sugar, non-cariogenic
- Very hydrophillic
- Good humectants

Acetal Formation

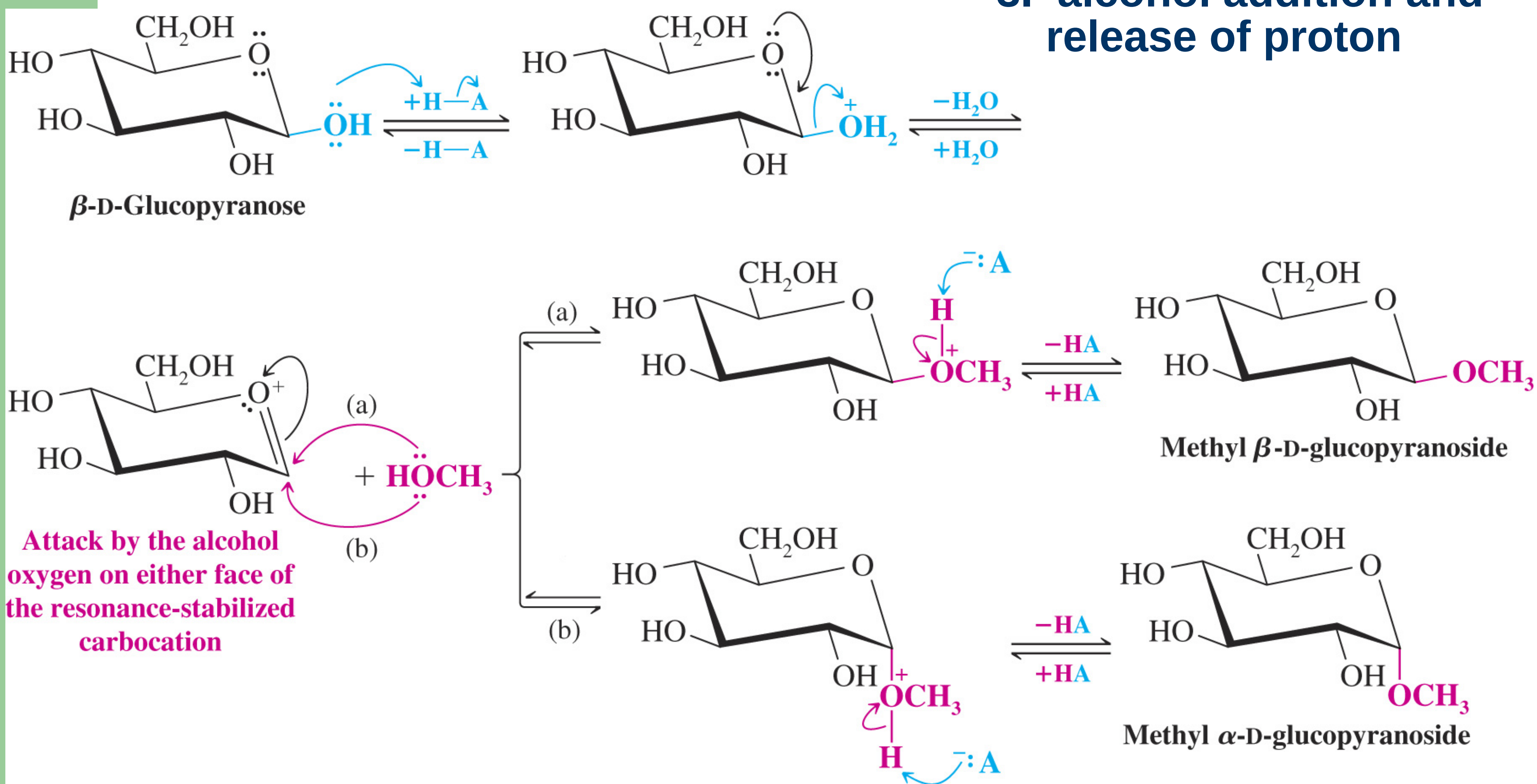
- In acid solution, sugars can react with alcohols to form acetals known as glycosides

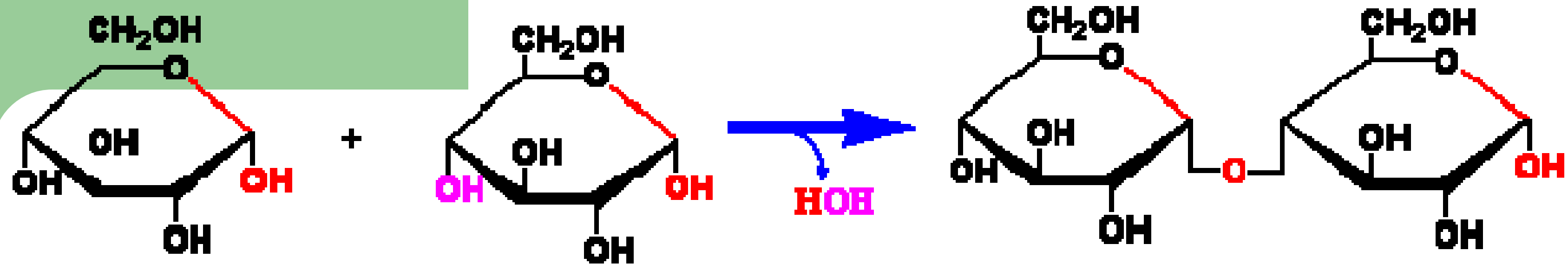


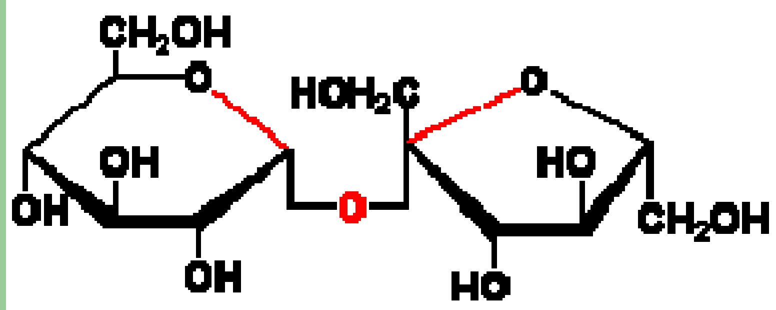
- Reaction is a nucleophilic addition of two alcohols to aldehydes

Acetal Formation

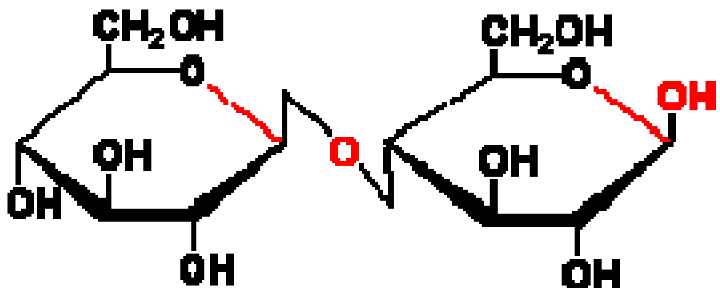
1. Protonation of OH group
2. water removal to form carbocation
3. alcohol addition and release of proton



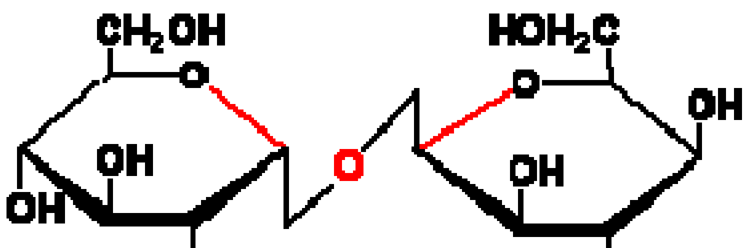




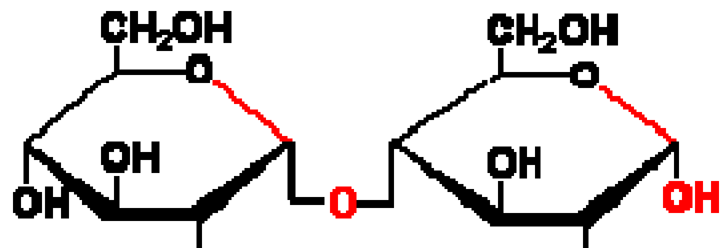
Sucrose



Maltose



Trehalose



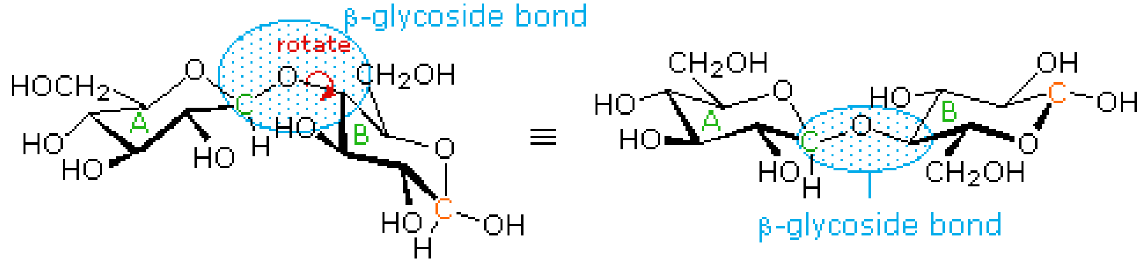
Cellobiose

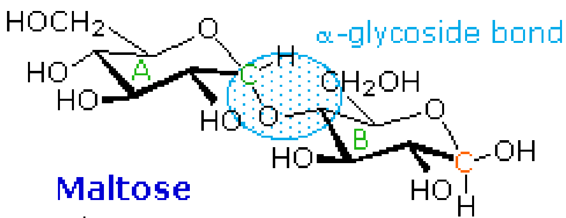
Disaccharides Composed of Glucose

C = hemiacetal
a reducing sugar

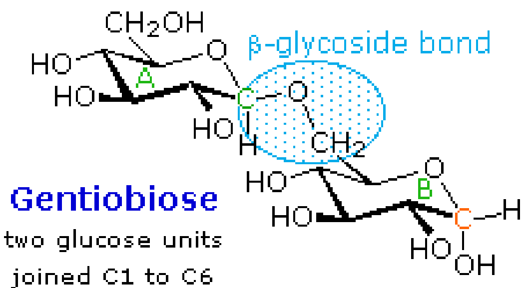
C = acetal
non- reducing sugar

Cellobiose
two glucose units
joined C1 to C4
as a β-glycoside

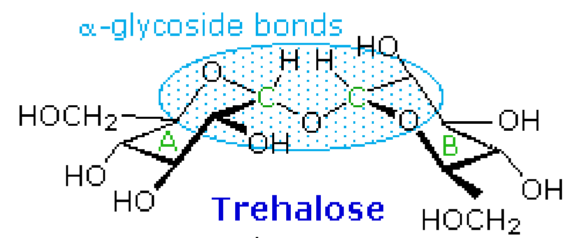




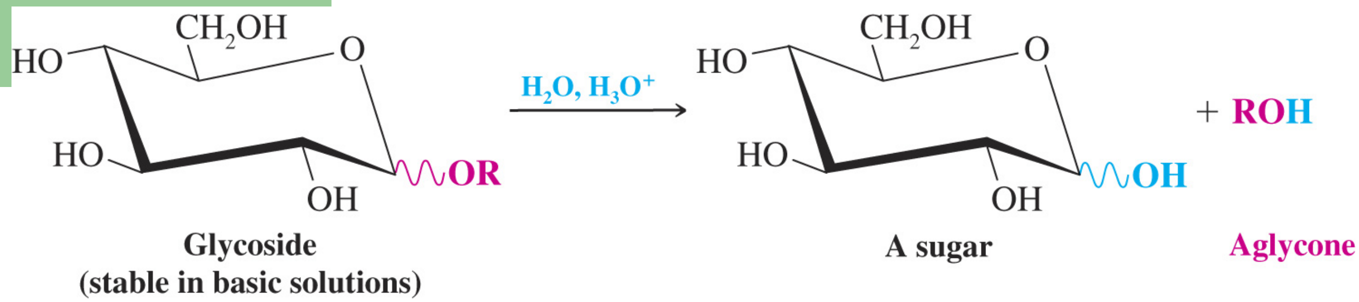
Maltose
two glucose units
joined C1 to C4
as an α-glycoside

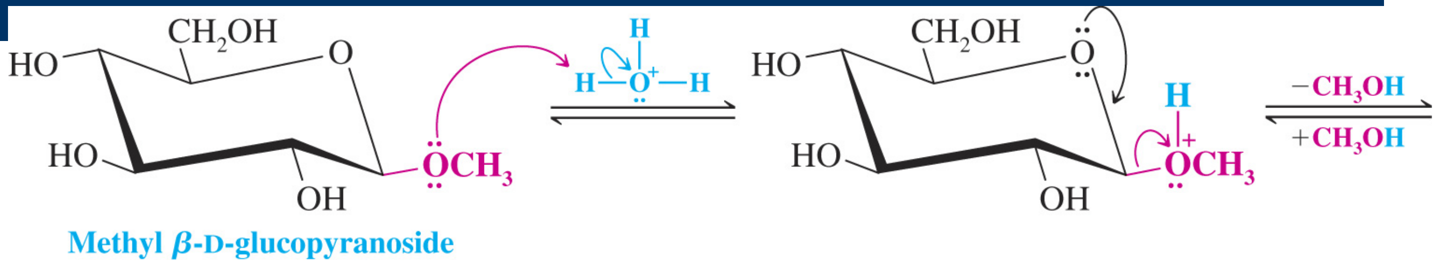


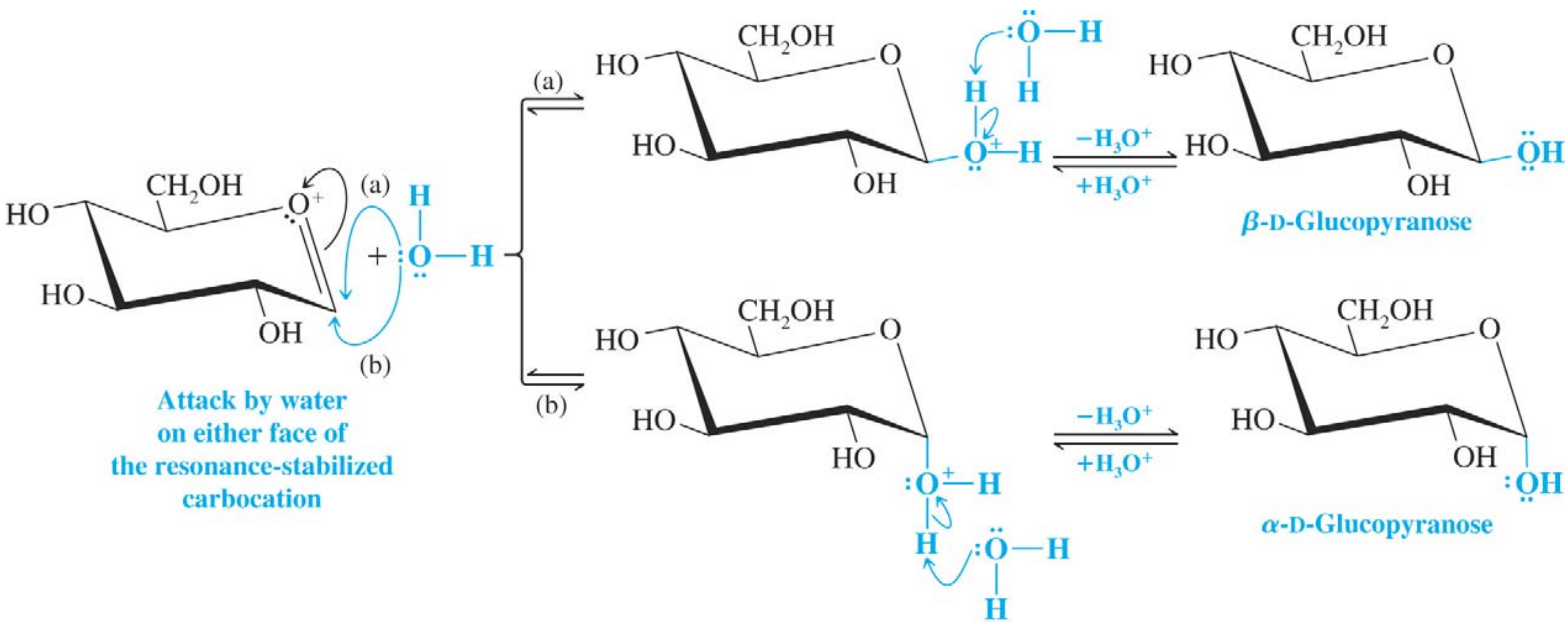
Gentiobiose
two glucose units
joined C1 to C6
as a β-glycoside



Trehalose
two glucose units
joined C1 to C1
as two α-glycosides


CH2OH
HO
O
HO
OH
OR
H2O, H3O+
OH
+ ROH
Glycoside
(stable in basic solutions)
A sugar
Aglycone


CH2OH
HO
O
HO
OH
OCH3
H
H—O+—H
−CH3OH
+CH3OH
Methyl β-D-glucopyranoside

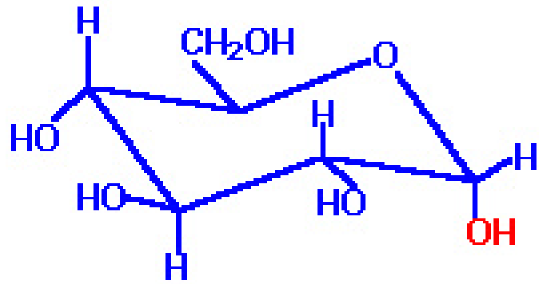

(a)
(b)
O+
H
O—H
−H3O+
+H3O+
β-D-Glucopyranose
α-D-Glucopyranose
Attack by water
on either face of
the resonance-stabilized
carbocation

Stability of acetals

- Pyranose >>>> Furanose
- β -glycosidic > α-glycosidic
- 1,6>1,4>1,3>1,2

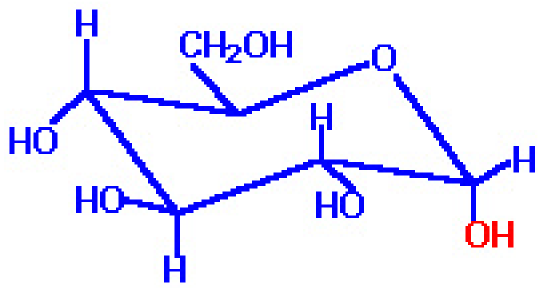
- Allow to predict stability of glycosidic linkages in terms of their resistance to hydrolysis
  - Gentiobiose

Acid catalyzed Rxns



- Acid hydrolysis of hemiactals and hemiketals (mutarotation)
- Anhydro sugars
  - 1C conformation
- Reversion sugars
  - Formation of oligosaccharides under conditions of high sugar concentration, dilute acid……. Maple syrup, fruit juice concentrates
  - Detection of invert sugar in juices/honey
- Enolization and Dehydration
  - Formation of 3-deoxyosones and HMF/furfural

Base catalyzed Rxns



- Hydrolysis of hemiactals and hemiketals (mutarotation)
  - Base catalyzed loss of H from anomeric –OH
- Acetals and Ketals are stable
  - Sugar esters will be hydrolyzed in alkali
- Enolization
  - Favored by alkali
- Reduction of metal ions
  - Alkali prevents hydrolysis of non-reducing sugar