Chapter 25: Carbohydrates
hydrates of carbon: general formula $C_n(H_2O)_n$

Plants: photosynthesis
$$6 \text{ CO}_2 + 6 \text{ H}_2\text{O} \xrightarrow{hv} \text{ C}_6\text{H}_{12}\text{O}_6 + 6 \text{ O}_2$$

Polymers: large molecules made up of repeating smaller units (monomer)

Biopolymers:
- carbohydrates (Chapter 25)
- peptides and proteins (Chapter 27)
- nucleic acids (Chapter 28)

Monomer units:
- monosaccharides
- amino acids
- nucleotides

25.1: Classification of Carbohydrates.
I. Number of carbohydrate units
   - monosaccharides: one carbohydrate unit (simple carbohydrates)
   - disaccharides: two carbohydrate units (complex carbohydrates)
   - trisaccharides: three carbohydrate units
   - polysaccharides: many carbohydrate units
II. **Position of carbonyl group**
   at C1, carbonyl is an aldehyde: aldose
   at any other carbon, carbonyl is a ketone: ketose

III. **Number of carbons**
   - three carbons: triose
     - glyceraldehyde (triose)
   - six carbons: hexose
     - fructose (hexose)
   - four carbons: tetrose
     - threose (tetrose)
   - seven carbons: heptose
     - ribose (pentose)
   - five carbons: pentose
     - glucose (hexose) (aldohexose)
   - etc.

IV. **Cyclic form** (chapter 25.6 and 25.7)

![Cyclic forms of carbohydrates](image)

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**25.2: Fischer Projections and the D-L Notation.** Representation of a three-dimensional molecule as a flat structure. Tetrahedral carbon represented by two crossed lines:

- Horizontal line is coming out of the plane of the page (toward you)
- Vertical line is going back behind the plane of the paper (away from you)

(R)-(+) glyceraldehyde

(S)-(−) glyceraldehyde
before the R/S convention, stereochemistry was related to (+)-glyceraldehyde

\[
\begin{align*}
\text{CHO} & \quad \text{CHO} \\
\text{H-} & \quad \text{H-} \\
\text{O} & \quad \text{O} \\
\text{CH}_2\text{OH} & \quad \text{CH}_2\text{OH}
\end{align*}
\]

D-glyceraldehyde  
R-(+)-glyceraldehyde  
(+)-rotation = dextrorotatory = D

L-glyceraldehyde  
S-(−)-glyceraldehyde  
(−)-rotation = levorotatory = L

D-carbohydrates have the -OH group of the highest numbered chiral carbon pointing to the right in the Fisher projection as in R-(+)-glyceraldehyde

For carbohydrates, the convention is to arrange the Fischer projection with the carbonyl group at the top for aldoses and closest to the top for ketoses. The carbons are numbered from top to bottom.

Carbohydrates are designated as D- or L- according to the stereochemistry of the highest numbered chiral carbon of the Fischer projection. If the hydroxyl group of the highest numbered chiral carbon is pointing to the right, the sugar is designated as D (Dextro: Latin for on the right side). If the hydroxyl group is pointing to the left, the sugar is designated as L (Levo: Latin for on the left side). Most naturally occurring carbohydrates are of the D-configuration.
25.3: The Aldotetroses. Glyceraldehyde is the simplest carbohydrate (C₃, aldotriose, 2,3-dihydroxypropanal). The next carbohydrate are aldotetroses (C₄, 2,3,4-trihydroxybutanal).

aldotrioise

aldotetroses

highest numbered “chiral” carbon

25.4: Aldopentoses and Aldohexoses.

Aldopentoses: C₅, three chiral carbons, eight stereoisomers

Aldohexoses: C₆, four chiral carbons, sixteen stereoisomers
Manipulation of Fischer Projections

1. Fischer projections can be rotated by 180° (in the plane of the page) only!

[Diagrams showing 180° rotation of Fischer projections]

- A 90° rotation inverts the stereochemistry and is illegal!

[Diagrams showing 90° rotation of Fischer projections]

This is not the correct convention for Fischer projections and is the enantiomer.
2. If one group of a Fischer projection is held steady, the other three groups can be rotated clockwise or counterclockwise.

![Fischer projections with groups being rotated](image)

**Assigning R and S Configuration to Fischer Projections**

1. Assign priorities to the four substituents according to the Cahn-Ingold-Prelog rules.
2. Perform the two allowed manipulations of the Fischer projection to place the lowest priority group at the top or bottom.
3. If the priority of the other groups \(1 \rightarrow 2 \rightarrow 3\) is clockwise then assign the carbon as \(R\), if priority of the other groups \(1 \rightarrow 2 \rightarrow 3\) is counterclockwise then assign the center as \(S\).

![Assigning R and S configuration](image)
25.5: A Mnemonic for Carbohydrate Configuration.
(please read)

25.6: Cyclic Forms of Carbohydrates: Furanose Forms.

(Ch. 17.8)

(Ch. 25.13)

Fischer projections with more than one chiral center:

(2S, 3R)
In the case of carbohydrates, cyclization to the hemiacetal creates a new chiral center.

Converting Fischer Projections to Haworth formulas

25.7: Cyclic Forms of Carbohydrates: Pyranose Forms.
25.8: Mutarotation and the Anomeric Effect. The hemiacetal or hemiketal carbon of the cyclic form of carbohydrates is the anomeric carbon. Carbohydrate isomers that differ only in the stereochemistry of the anomeric carbon are called anomers.

*Mutarotation:* The α- and β-anomers are in equilibrium, and interconvert through the open form. The pure anomers can be isolated by crystallization. When the pure anomers are dissolved in water they undergo mutarotation, the process by which they return to an equilibrium mixture of the anomer.

25.9: Ketoses. Ketoses are less common than aldoses

Fructofuranose and Fructopyranose
25.10: Deoxy Sugars. Carbohydrates that are missing a hydroxy group.

25.11: Amino Sugars. Carbohydrates in which a hydroxyl group is replaced with an -NH$_2$ or -NHAc group

25.12: Branched-Chain Sugars. (Please read)

Note that only the anomeric hydroxyl group is replaced by ROH

25.14: Disaccharides. A glycoside in which ROH is another carbohydrate unit (complex carbohydrate).

25.15: Polysaccharides. Cellulose: glucose polymer made up of 1,4'-β-glycoside linkages

Amylose: glucose polymer made up of 1,4'-α-glycoside linkages
25.16: Reactions of Carbohydrates. Glycoside formation is related to acetal formation.

25.17: Reduction of Monosaccharides. C1 of aldoses are reduced with sodium borohydride to the 1° alcohol (alditols)

Reduction of ketoses

25.17: Oxidation of Monosaccharides. C1 of aldoses can be selectively oxidized to the carboxylic acid (aldonic acids) with Br₂ or Ag(I) (Tollen’s test).

Reducing sugars: carbohydrates that can be oxidized to aldonic acids.
Oxidation of aldoses to *aldaric acids* with HNO₃.

![Diagram of aldose oxidation](image)

*Uronic Acid:* Carbohydrate in which only the terminal -CH₂OH is oxidized to a carboxylic acid.

![Diagram of uronic acid formation](image)

*Reducing sugars:* carbohydrates that can be oxidized to aldonic acids.

![Diagram of reducing sugar reactions](image)

- **Cellulose and maltose** are reducing sugars.
- **Lactose** (1,4'-glycoside) is a reducing sugar.
- **Sucrose** (1,2'-glycoside) is not a reducing sugar.
25.19: Cyanohydrin Formation and Chain Extension.

*Kiliani-Fischer Synthesis* - chain lengthening of monosaccharides

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**Determination of carbohydrate stereochemistry**

- **D(-)-glyceraldehyde**
  - Kiliani-Fischer synthesis
  - 1) HCN
  - 2) H₂, Pd/BaSO₄
  - 3) H₂O

- **D(-)-erythrose**
  - 1) HCN
  - 2) H₂, Pd/BaSO₄
  - 3) H₂O

- **D(-)-threose**
  - 1) HCN
  - 2) H₂, Pd/BaSO₄
  - 3) H₂O

- **Tartaric acid**
  - HNO₃, heat

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Killiani-Fischer synthesis

D-(-)-xylose
D-(-)-lyxose
CHO
OHH
OHH
CH2OH

D-(-)-arabinose
D-(-)-erythrose
CHO
OHH
OHH
OHH
CH2OH
CHO
HHO
OHH
CO2H

1) HCN
2) H2, Pd/BaSO4
3) H2O

Killiani-Fischer synthesis

D-(-)-ribose
D-(-)-arabinose
CHO
OHH
OHH
CH2OH

D-(-)-threose
D-(-)-lyxose
CHO
OHH
OHH
OHH
CH2OH
CHO
HHO
OHH
CO2H

1) HCN
2) H2, Pd/BaSO4
3) H2O

riboinic acid

arabonic acid

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25.20: Epimerization, Isomerization and Retro-Aldol Cleavage.

Fructose is a reducing sugar (gives a positive Tollen's test)
25.21: Acylation and Alkylation of Hydroxyl Groups

Acylation (ester formation):

$$\beta-D-glucopyranose + H_2C\cdot CO\cdot CH_3 \xrightarrow{pyridine}$$

Alkylation (ether formation):

$$\beta-D-glucopyranose + AgO\cdot CH_3 \xrightarrow{}$$

25.22: Periodic Acid Oxidation. The vicinal diols of carbohydrate can be oxidative cleaved with HIO₄.