

American Chemical Society



USNCO Coaching Session Tutorial Notes: Organic and Biochemistry

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26 February 2021

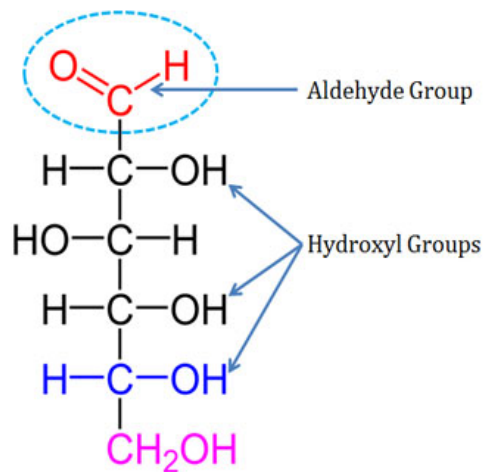
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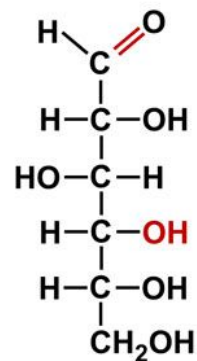
Carbohydrates

- $C_n(H_2O)_n$
- Monosaccharide: Hexose Aldo/Keto

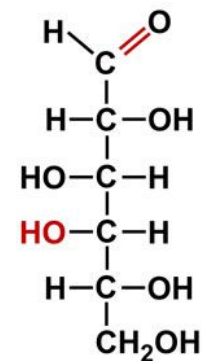


Glucose

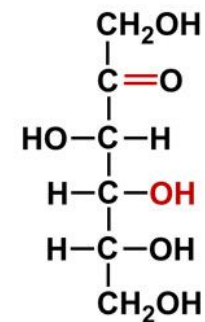
Carbohydrate Isomers



Glucose



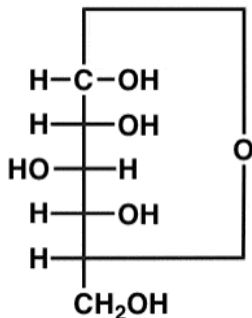
Galactose



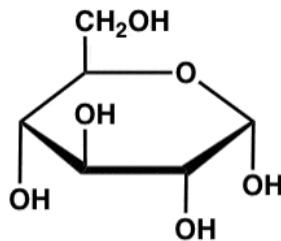
Fructose

Carbohydrates

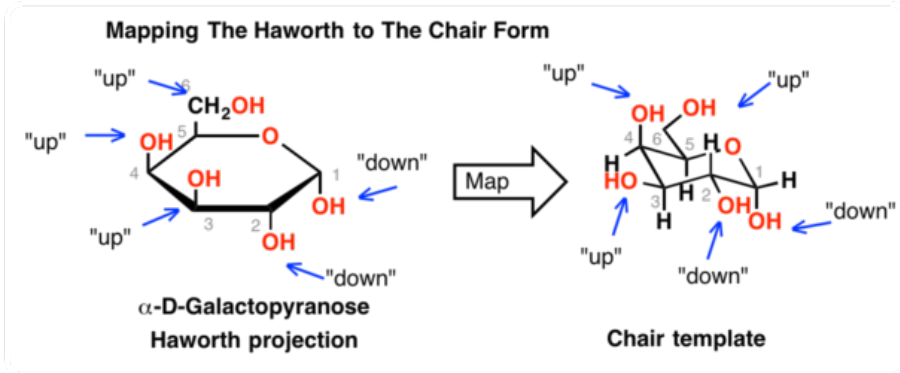
Haworth projection (1929) An improvement over the cyclic Fischer projection



α -D-Glucopyranose
(cyclic Fischer projection)



α -D-Glucopyranose
Haworth projection



Fats

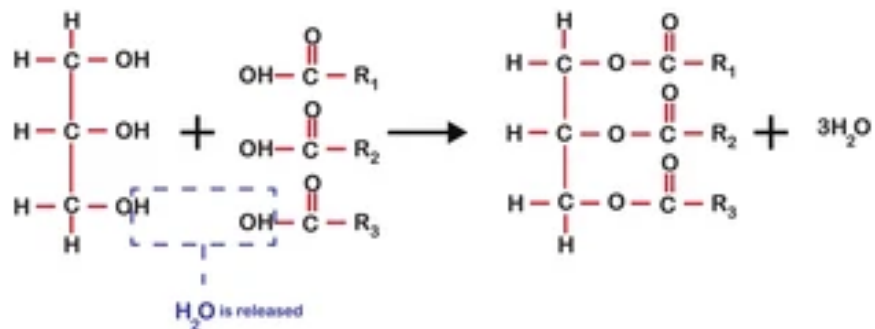
Chemical reaction ●●●

TRIGLYCERIDES

glycerol

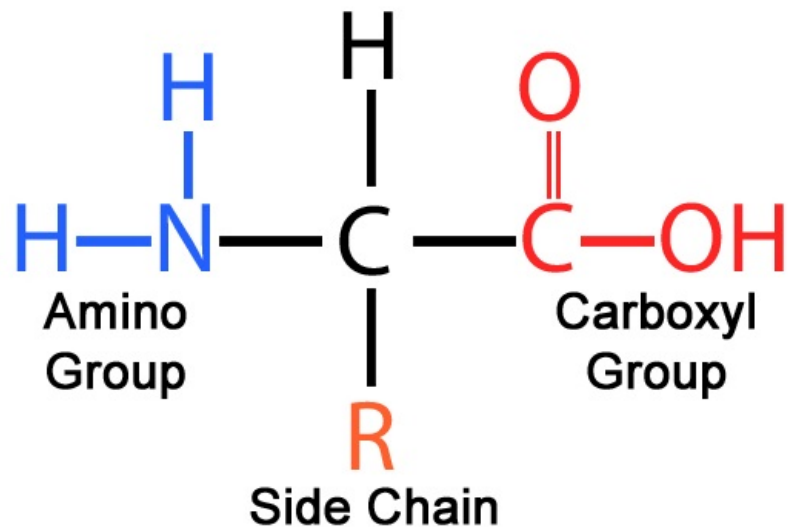
3 fatty acids

triglycerides

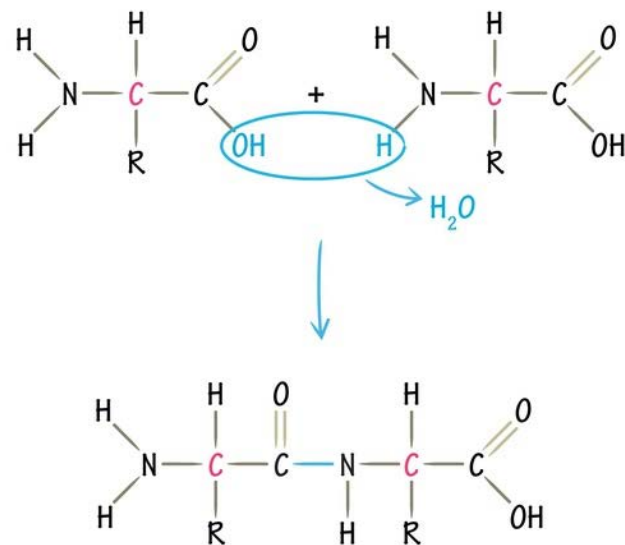


Proteins

- Made of amino acids

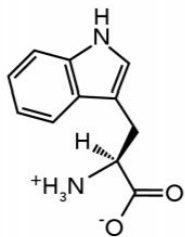


Peptide Bond Formation

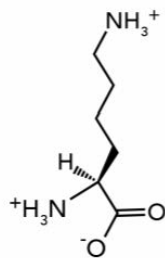


Proteins

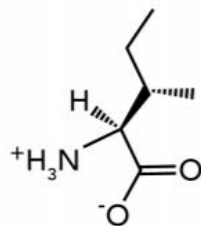
- For each of the following amino acids, label the amino and carboxyl groups, the alpha carbon and the side chain. What are the properties of each of the side chains below? Are they hydrophobic or hydrophilic? Are they charged, polar or neither?



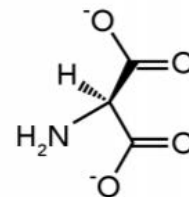
Tryptophan



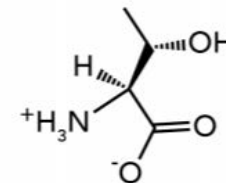
Lysine



Isoleucine



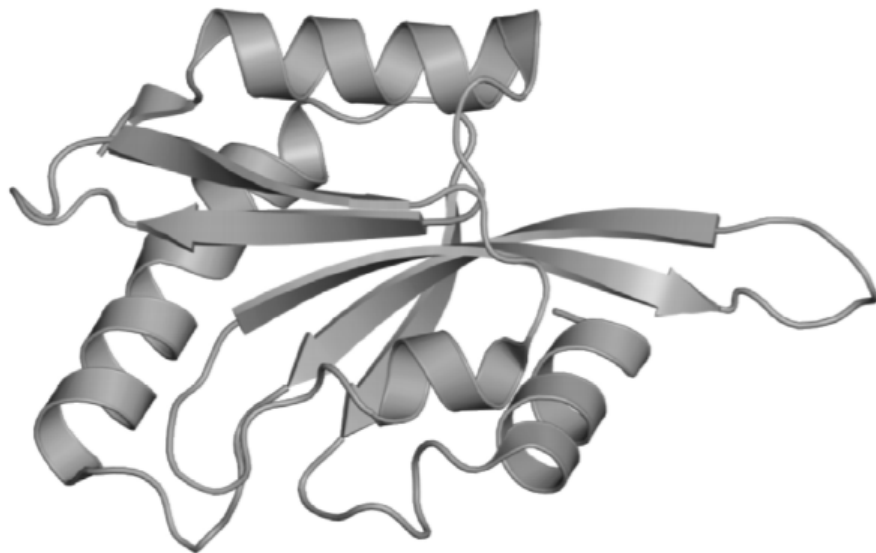
Aspartic acid



Threonine

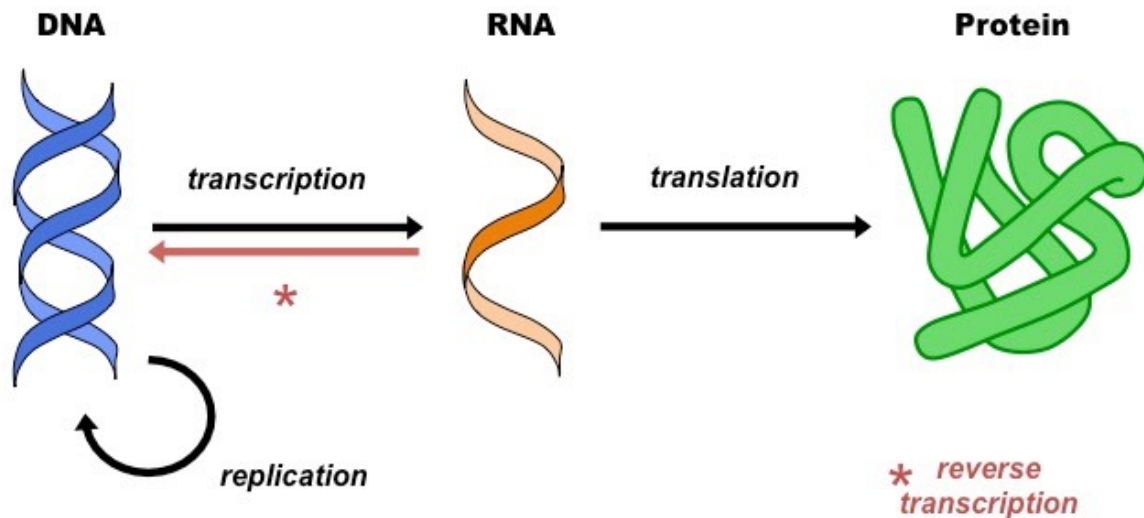
Proteins

- Primary Structure
- Secondary Structure
- Tertiary Structure
- Quaternary Structure
- Enzyme and Enzyme Kinetics

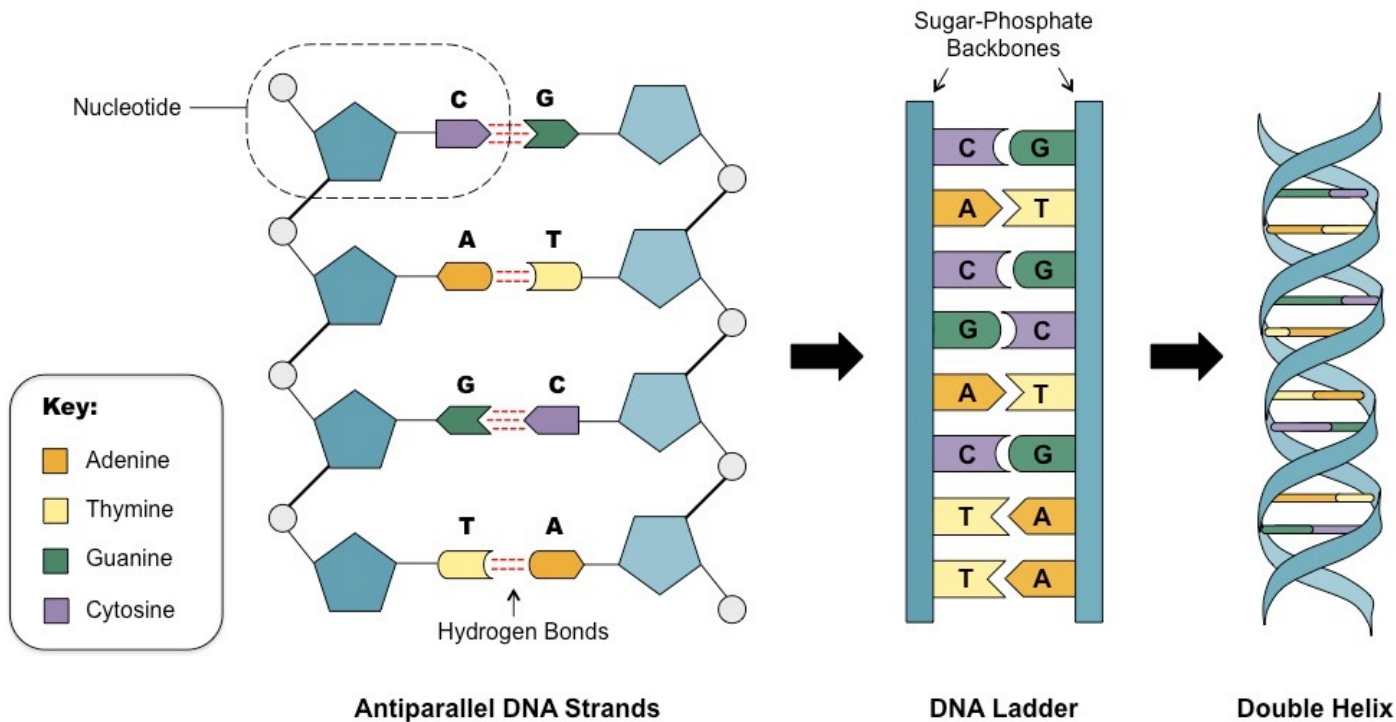


Nucleic Acids

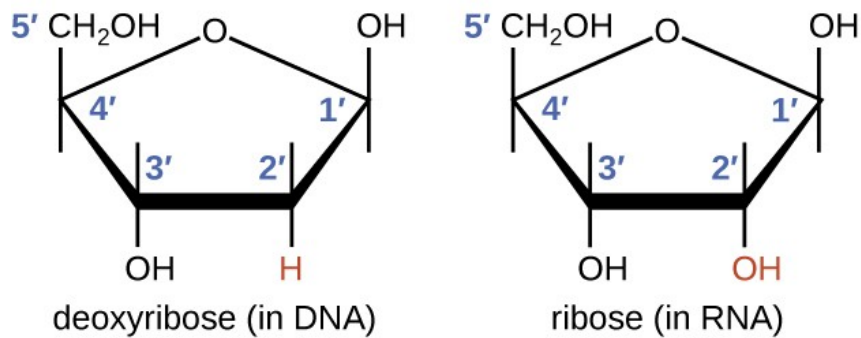
- DNA and RNA
- Central Dogma:



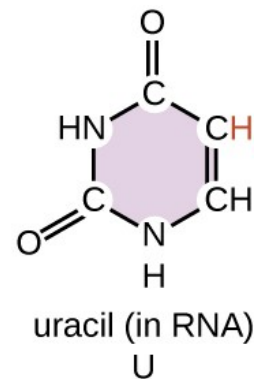
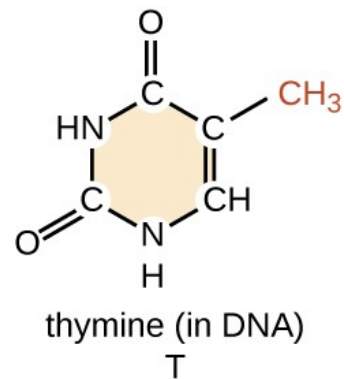
DNA



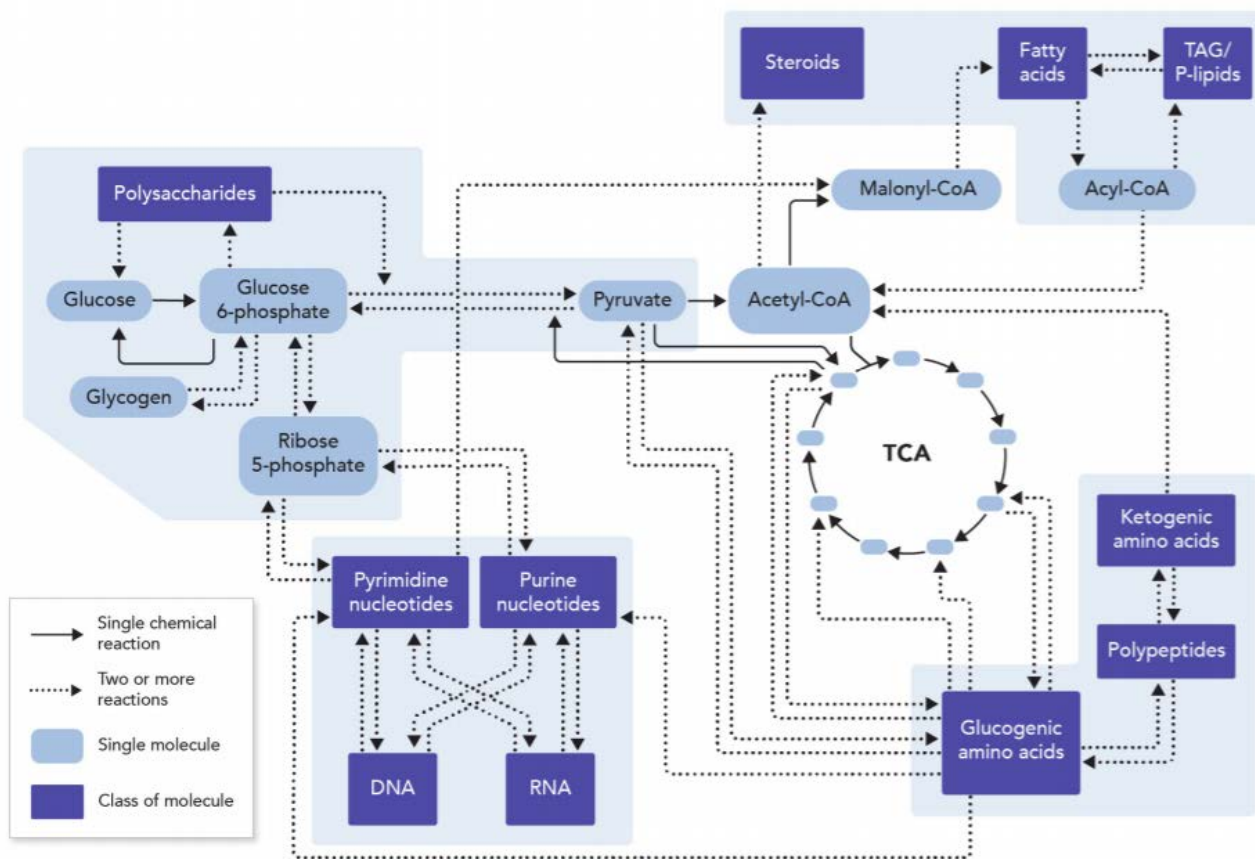
RNA



(a)



(b)



Lecture Note 3 – Fundamental Organic Chemistry

Feb 13th, 2020

[Pre-Reading]: Organic Chemistry with a Biological Emphasis Volume I (*open textbook*) by Tim Soderberg, University of Minnesota, Morris

[Learning Objectives]

1. Hydrocarbons and Isomer Counting

1.1 Types of hydrocarbons

	<i>saturated</i>	<i>unsaturated</i>		
	Alkane	Alkene	Alkyne	Benzene
Structure				
Formula	C_nH_{2n+2}			
Hybrid of carbon				
Bond angle	$\sim 109.5^\circ$			
DBE*	0			

Double bond equivalent (DBE; UN; degree of unsaturation): The number of molecules of H_2 that would have to be added to a molecule to convert all pi bonds to single bonds, and all rings to acyclic structures.

One DBE = one _____ or one _____ bond. How to calculate DBE based on the molecular formula?

1.2 Isomer counting

Isomers are molecules with the same _____ but different _____.

Types of isomers

Fill the black with the type of isomers and summarize the character of each type of isomer.

STRUCTURAL ISOMERISM			STEREISOMERISM	
CHAIN				
BUTANE	BUT-2-ENE	BUT-2-ENE	(E)-1,2-DICHLOROETHENE E = opposite side	L: (S)-1-CHLOROETHANOL R: (R)-1-CHLOROETHANOL
METHYL PROPANE	BUT-1-ENE	CYCLOBUTANE	(Z)-1,2-DICHLOROETHENE Z = same side	

Source: <https://www.compoundchem.com/2014/05/22/typesofisomerism/>

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Isomer counting**[Introductory Example]** Draw all distinct isomers of C_4H_8 .

0. DBE =			
1. Functional isomers			
Alkene		Cycloalkane	
2. Chain isomers			
Straight chain	Branched chain	Three-membered ring	Four-membered ring
3. Positional isomers			
4. Stereoisomers			

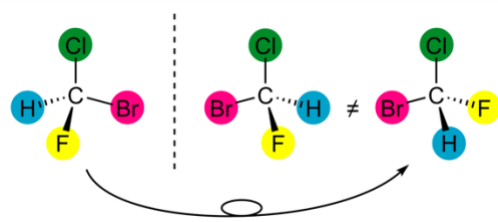
[USNCO Examples]

<i>N2018P1-Q57</i>	<i>L2018-Q56</i>
How many distinct acyclic compounds have the formula C_5H_{10} ?	How many isomers have the formula $C_2H_2Br_2$?
(A) 3 (B) 4 (C) 5 (D) 6	(A) 1 (B) 2 (C) 3 (D) 4

1.3 Chirality and optical isomers**Chirality**

A chiral molecule is **non-superimposable** on its mirror image. Most chiral compound has a **chiral carbon**, which connects to **four different groups**. *The chiral molecule and its mirror images are called *enantiomers*.

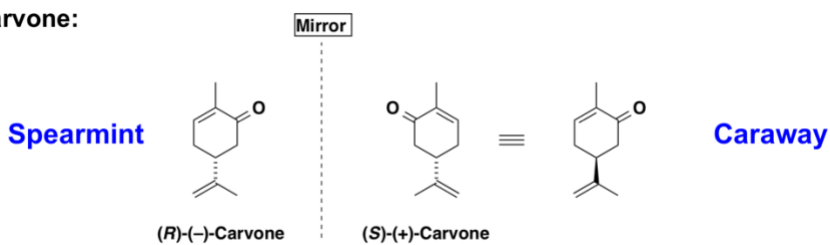
Is CX_2YZ chiral? Why or why not?



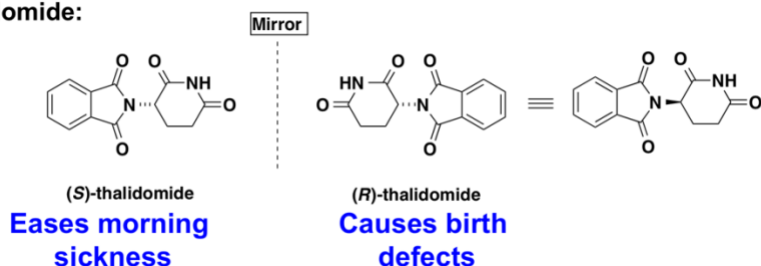
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Chirality is important because it imparts different physical, chemical or biological properties. Enantiomers are mirror images of one another but they do not necessarily have the same properties.

Carvone:

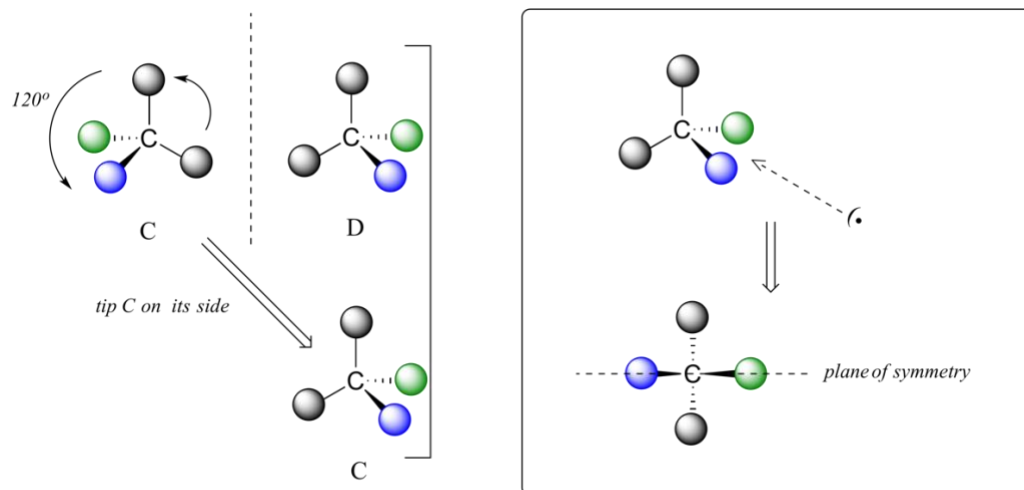


Thalidomide:



source: Cambridge lecture note

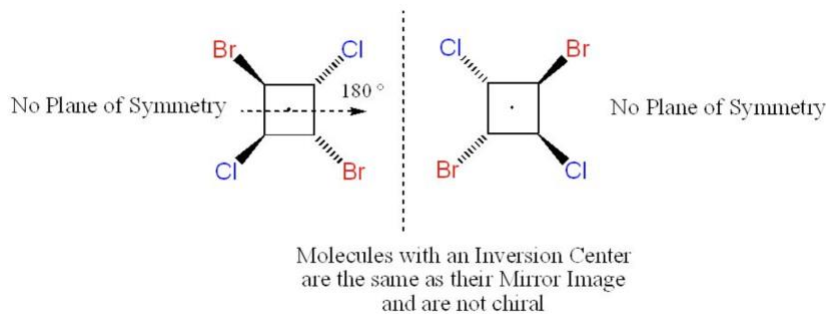
Specifically, a chiral compound can contain NO **planes of symmetry** AND **inversion center**.



C and D can be superposed: they are the same molecule!

Source:

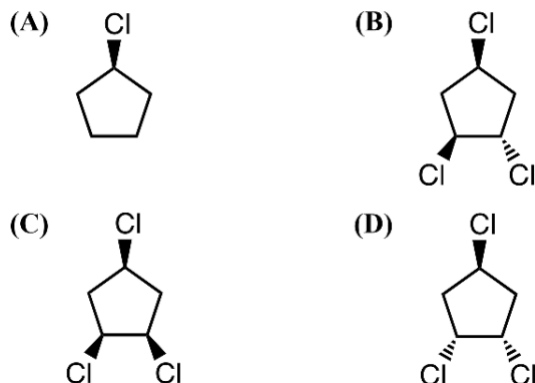
[LibreTexts](#)



*There are chiral compounds without chiral carbon(s).

[USNCO Examples – N2017P1-Q55]

Which of the following molecules is chiral?



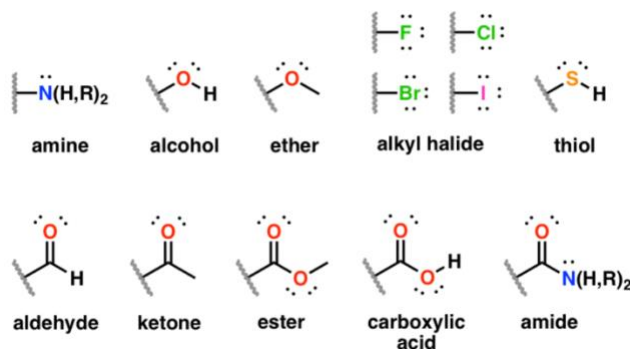
[USNCO Examples – N2019P1-Q56]

How many distinct compounds of the formula $C_5H_{11}Cl$ can be formed by free radical chlorination of 2-methylbutane?

- (A) 2 (B) 4 (C) 6 (D) 8

2. Introduction to Organic Reactions

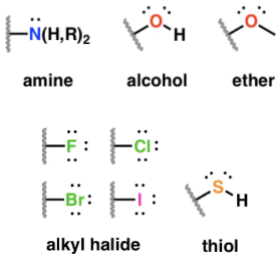
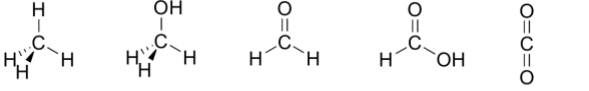
2.1 Common functional groups and oxidation level

Functional groups can be further categorized based on their *oxidation level*, the number of **heteroatoms** (N, O, etc.) the connected to the carbon.

Source:

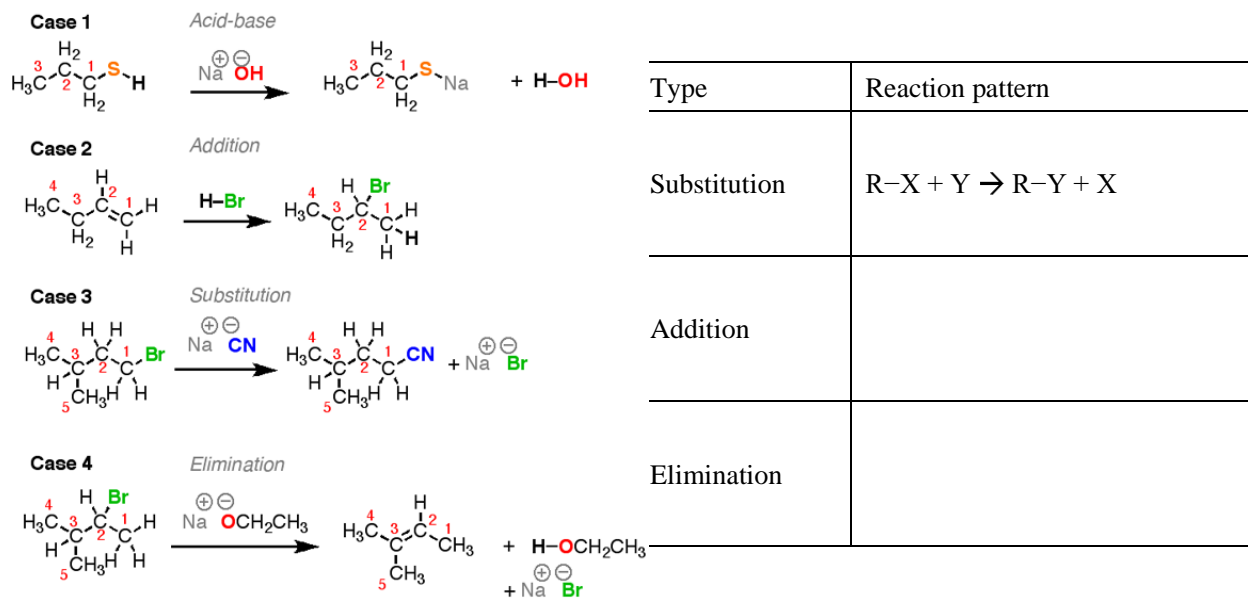
<https://www.masterorganicchemistry.com/2010/10/06/functional-groups-organic-chemistry/>

Put the functional groups listed above into the table below based on their oxidation levels

Level 0	Level 1	Level 2	Level 3
alkanes	 <p>amine alcohol ether</p> <p>alkyl halide thiol</p>		
	 <p>most reduced $\xrightarrow{\hspace{10em}}$ most oxidized</p>		

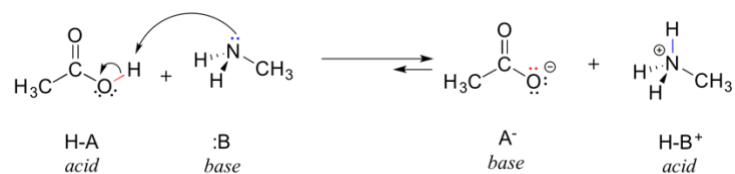
*What is the type of reactions for the conversion of functional groups with the same oxidation number?

2.2 Types of organic reactions



Source: <https://shorturl.at/ap269> (Libretexts: General Chemistry, 27.1: Organic Reactions: An Introduction)

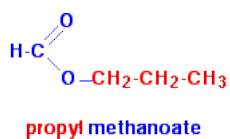
2.3 Acid-base reactions



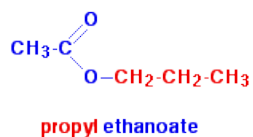
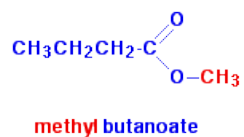
List the acidic and basic functional groups in 2.1 in aqueous solution, respectively.

2.4 Esterification and saponification

Structure and nomenclature of esters



Summarize the structure character of esters and how to name esters



Naming: (alcohol) (acid-anoate)

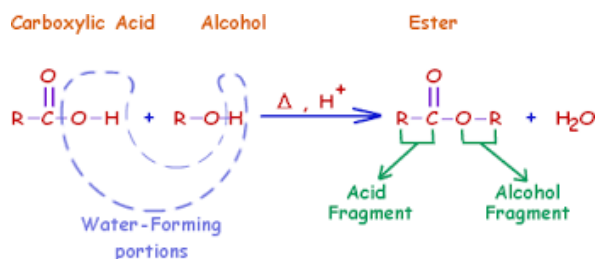
drop -anol change from “-oic acid”

replace with “-yl” to “-oate”

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Basic model of esterification

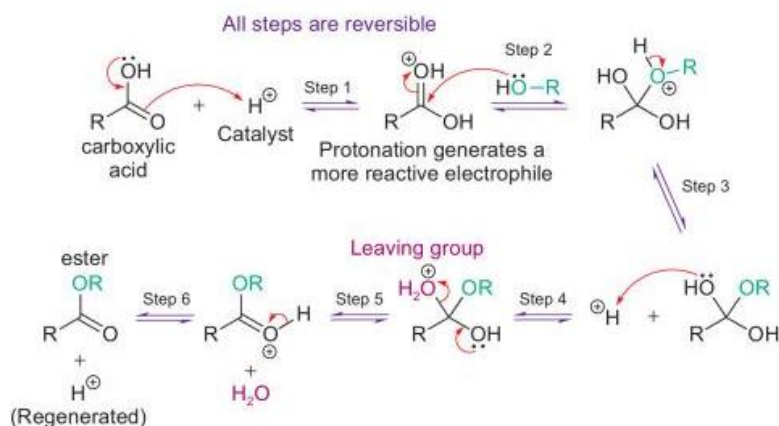
The reversible formation of an ester by reaction of an *alcohol* (ROH) with a *carboxylic acid* (RCOOH) using *strong acid as catalyst*. *The hydroxyl H of the alcohol combines with the OH of the carboxylic acid to form water. The hydroxyl oxygen of the alcohol bonds to the carboxyl carbon to form the ester.



Esterification is a **dehydration** process, which is a _____ reaction (substitution, elimination, or addition).

How to experimentally confirm the way of dehydration process (The hydroxyl H of the alcohol combines with the OH of the carboxylic acid to form water)?

*Mechanism of acid-catalyzed esterification



What's the function of the strong acid?

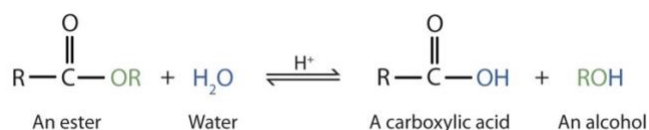
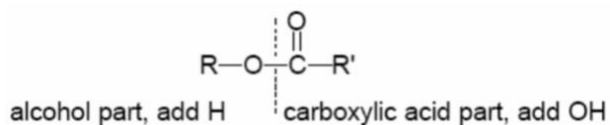
If the alcohol O is labeled as ^{18}O , which product will have the ^{18}O ?

How to increase the yield of ester?

Ester hydrolysis

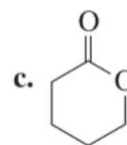
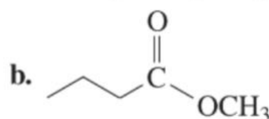
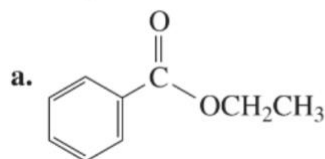
- Acid-catalyzed hydrolysis

Decomposition of an ester. This is the *reverse* of esterification reaction. The ester breaks apart at the bond between the carboxyl carbon and the singly-bonded oxygen. H and OH from a water molecule are inserted to form the original alcohol and carboxylic acid.



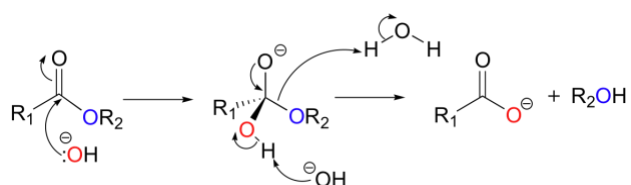
[Practice Example]

What products are formed from the acid-catalyzed hydrolysis of the following esters?

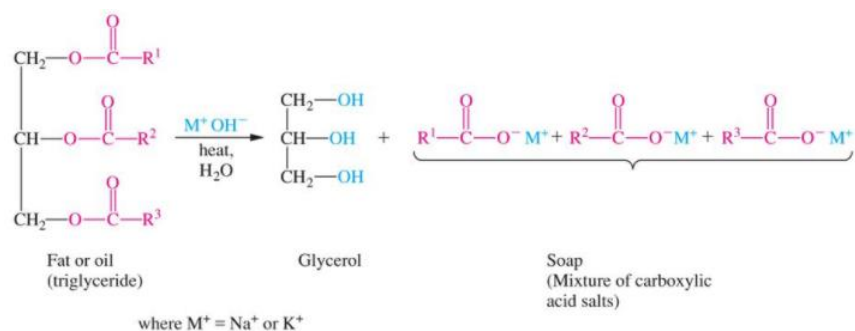


o Basic hydrolysis (saponification)

Excess strong base is used to decompose the ester. The original alcohol and the salt containing the conjugate base of the carboxylic acid are formed. The free carboxylic acid can be generated by making the solution acidic. Different from the acid-catalyzed hydrolysis of esters, saponification is *irreversible*. Why?



Soap synthesis: Fats are esters of glycerol (a trialcohol) and long chain (C14-C22) carboxylic acids called fatty acids. Heating fat with strong base was once used to make soap (salt of fatty acids)

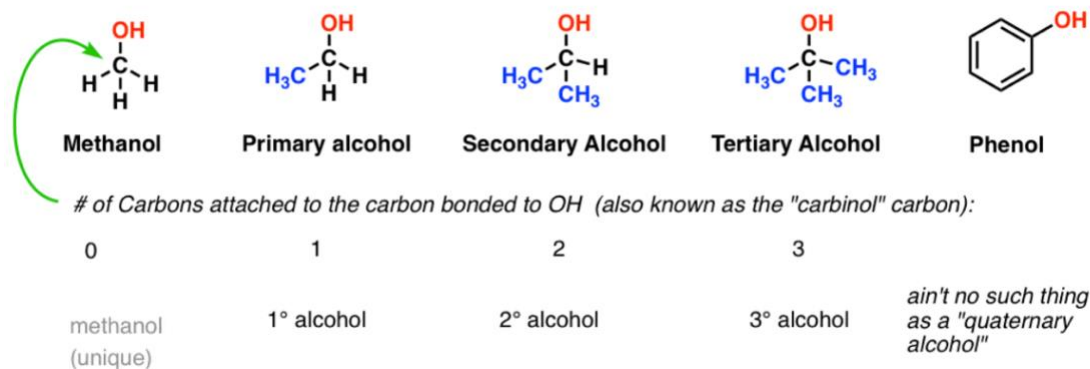


*Soap is a common household *amphiphilic* compound, possessing both *hydrophilic* (water-loving, polar) and *lipophilic* (fat-loving) properties.

*How does soap work?

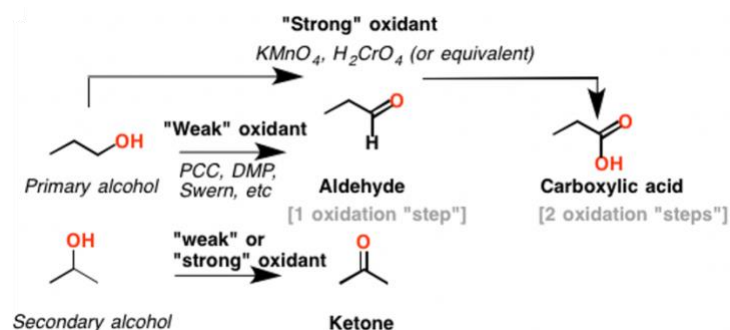
2.5 Oxidation of alcohols and aldehydes

Primary, secondary, tertiary alcohols

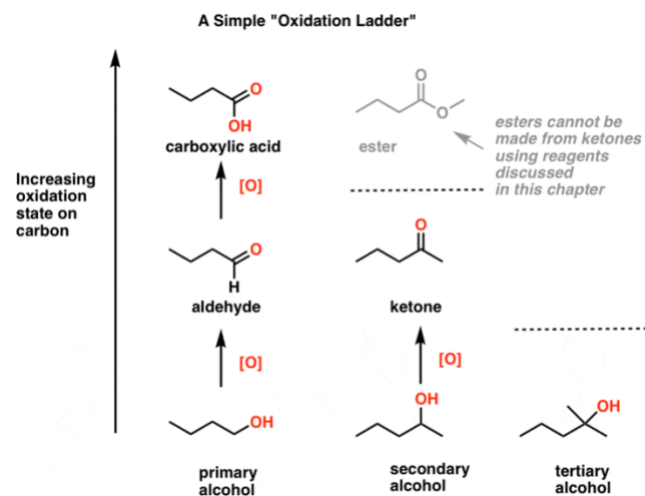


Source: <https://www.masterorganicchemistry.com/2014/09/17/alcohols-1-nomenclature-and-properties/>

Oxidation of alcohols – break C–H, form C–O on the same carbon

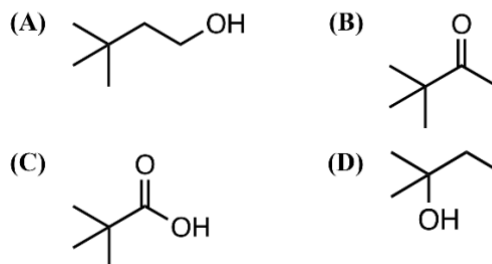


Summary



[USNCO Example – L2017-Q57]

Which compound reacts readily with Cr(VI) reagents?



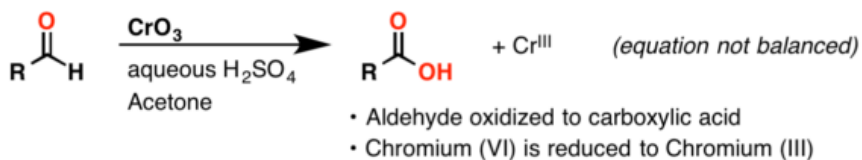
*Why can't tertiary alcohols be oxidized?

Source: [MasterOrganicChemistry](https://www.masterorganicchemistry.com/)

Oxidation of aldehydes and tests for aldehydes

- **Strong oxidants** – KMnO_4 and $\text{K}_2\text{Cr}_2\text{O}_7$

Example: Jones Oxidation



Source: MasterOrganicChemistry

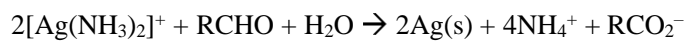
What is the color change?

How about ketone? Does it have the similar reaction, why or why not?

- **Weak oxidant - Tollens' test** (silver mirror)

Tollens' reagent is a chemical reagent used to determine the presence of an **aldehyde**, aromatic aldehyde and alpha-hydroxy ketone functional groups. The reagent consists of a solution of silver nitrate and ammonia to form a complex $[\text{Ag}(\text{NH}_3)_2]^+$. [*What's the color of the complex?]

Tollens' reagent is indicated by the precipitation of elemental silver, often producing a characteristic "silver mirror" on the inner surface of the reaction vessel.



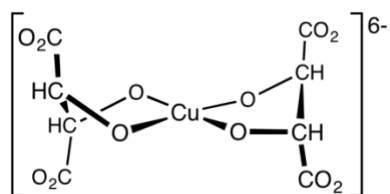
*Which of the following will give a negative Tollens' test?

- A. acetaldehyde B. formic acid C. ethyl formate D. acetone E. *glucose $[\text{CH}_2\text{OH}(\text{CHOH})_4\text{CHO}]$

- **Fehling's Test**

Fehling's solution is a chemical reagent used to differentiate between water-soluble carbohydrate and ketone functional groups, and as a test for *reducing sugars* and *non-reducing sugars*, supplementary to the Tollens' reagent test.

The *deep blue* active ingredient in Fehling's solution is the bis(tartrate) complex of Cu^{2+} . The tartrate tetraanions serve as bidentate alkoxide ligands.



How to tell a sugar is reducing or non-reducing based on the observation?

The brick red precipitate produced in the test is copper(I) oxide, Cu_2O , write down the equation of the reaction.

Source: [Wikipedia](https://en.wikipedia.org/wiki/Fehling's_solution)

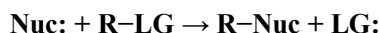
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2.6 Nucleophilic substitutions

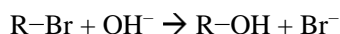
Nucleophile and Nucleophilic substitution

A *nucleophile* is a chemical species that _____ an electron pair to form a chemical bond in relation to a reaction. All molecules or ions with a *free pair of electrons* or at least *one pi bond* can act as nucleophiles. Because nucleophiles donate electrons, they are by definition Lewis bases.

The most general form of the reaction may be given as the following:



The electron pair (:) from the nucleophile (Nuc) attacks the substrate (R-LG) forming a new bond, while the leaving group (LG) departs with an electron pair. The principal product in this case is R-Nuc. The nucleophile may be electrically neutral or negatively charged, whereas the substrate is typically neutral or positively charged. An example of nucleophilic substitution is the hydrolysis of an alkyl bromide, R-Br, under basic conditions, where the attacking nucleophile is the OH⁻ and the leaving group is Br⁻.



*Summary and Comparison (Source: [Wikipedia](#) and [MasterOrganicChemistry](#))

	S _N 1 (unimolecular)	S _N 2 (bimolecular)
mechanism		
analogue		
*energy profile		
rate law		
substrate	<p>Tertiary > secondary >> primary > methyl</p> <p> Tertiary carbocation: most stable </p> <p> Secondary carbocation </p> <p> Primary carbocation: least stable (methyl carbocations are even more unstable) </p>	<p> Primary alkyl halide: Fast </p> <p> Secondary alkyl halide: Intermediate </p> <p> Tertiary alkyl halide: So slow it doesn't happen </p> <p>Why?</p>

big barrier	Carbocation stability	Steric hindrance
*stereochemistry		

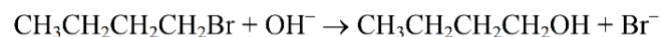
[USNCO Example – N2016P1-Q55]

Which alkyl halide reacts most rapidly with aqueous sodium hydroxide solution?

- (A) CH_3Cl (B) CH_3I
 (C) $(\text{CH}_3)_3\text{CCH}_2\text{Cl}$ (D) $(\text{CH}_3)_3\text{CCH}_2\text{I}$

[USNCO Example – L2017-Q56]

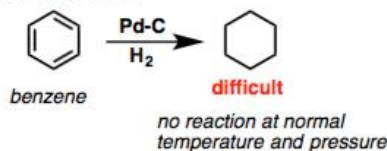
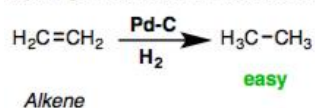
What is the role of hydroxide ion in the reaction below?



- (A) Oxidizing agent (B) Lewis acid
 (C) Catalyst (D) Nucleophile

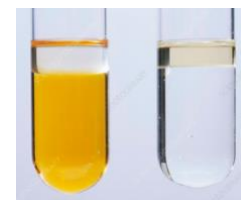
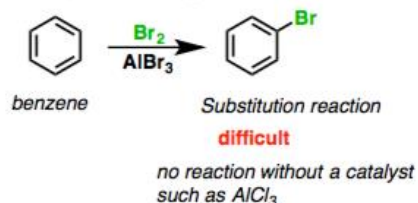
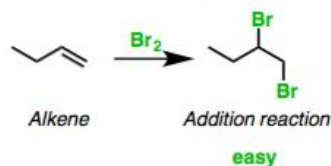
2.7 *Aromatic substitutions**Aromaticity – benzene vs alkene**

Hydrogenation: more difficult with aromatic compounds



Source: MasterOrganicChemistry

Reaction with electrophiles (such as bromine): aromatics give substitution, not addition

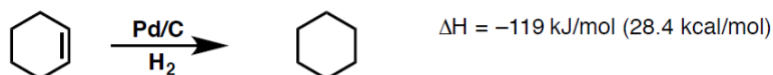


alkene + bromine water

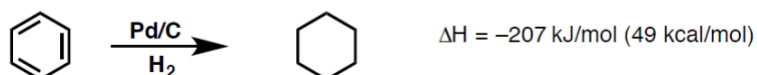
*What is the observation if benzene(l) is added to bromine water?

An introduction to resonance energy and aromaticity

Hydrogenation of alkenes liberates 119 kJ/mol of energy



We would expect hydrogenation of benzene to liberate $3 \times 119 = 357$ kJ/mol.



We would expect hydrogenation of benzene to liberate _____ kJ/mol if all of the C=C bonds are independent.

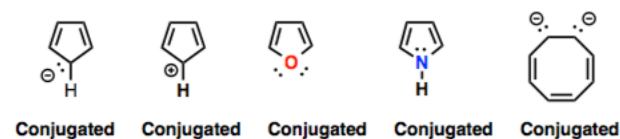
The extra stability of benzene is called the "resonance energy".

Benzene has a particularly large resonance energy, which leads us to classify it as "aromatic".

4n + 2 rule

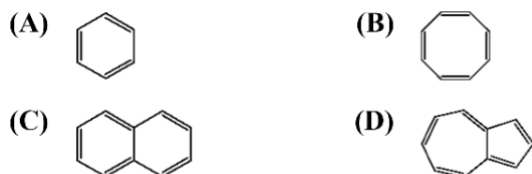
A cyclic ring molecule that follows Hückel's rule when the number of its π -electrons equals $4n + 2$ where n is a non-negative integer, is aromatic, and more stable than theoretically predicted using hydrogenation data of simple alkenes.

A few examples of aromatic systems



[USNCO Examples – L2019-Q59]

Which compound is NOT considered aromatic?

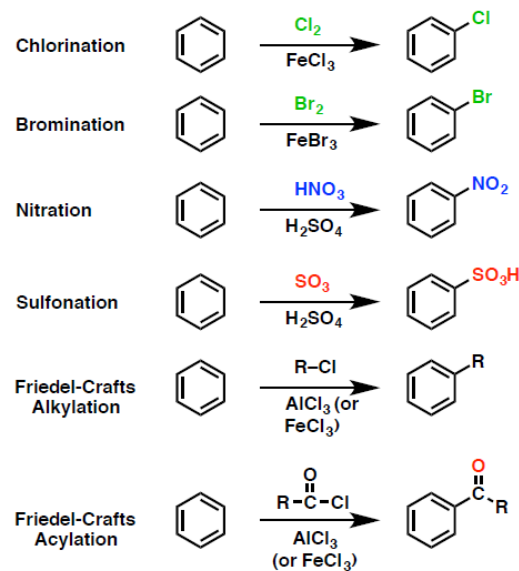
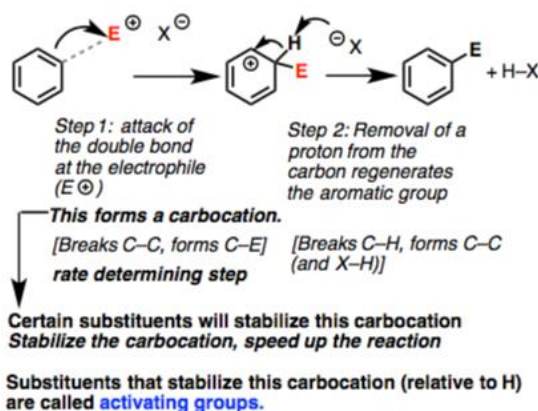


[USNCO Examples – N2015P1-Q57]

Which of the following is a difference between benzene and cyclooctatetraene?

- (A) Benzene reacts rapidly with bromine and cyclooctatetraene does not.
- (B) Benzene contains sp^2 -hybridized carbon atoms and cyclooctatetraene does not.
- (C) Benzene has the formula C_nH_n and cyclooctatetraene does not.
- (D) Benzene is planar and cyclooctatetraene is not.

Mechanism and reactions

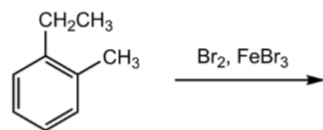


Source: MasterOrganicChemistry

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[USNCO Example – L2019-Q58]

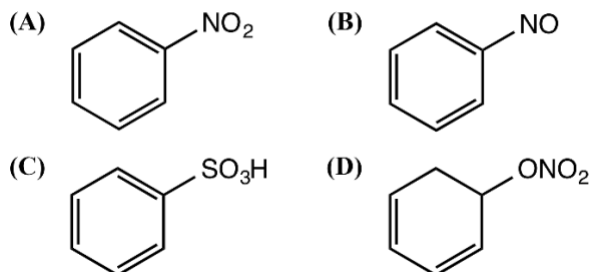
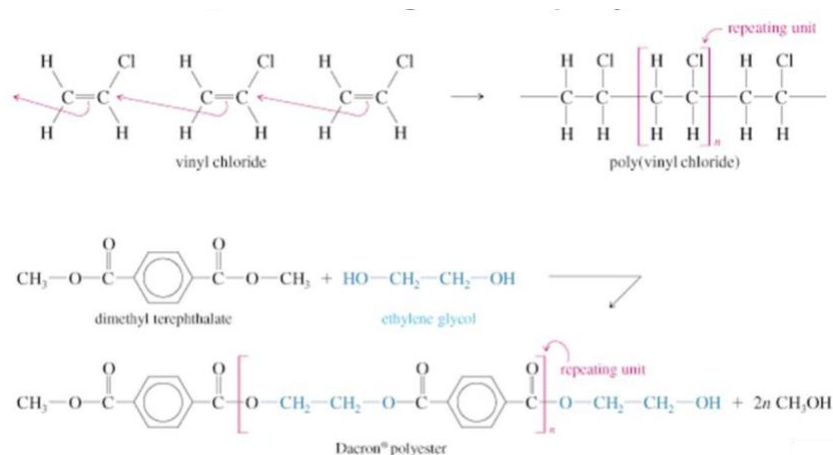
What is the maximum number of monosubstitution products of the aromatic substitution reaction shown?



- (A) 1 (B) 2 (C) 3 (D) 4

[USNCO Example – N2016P1-Q58]

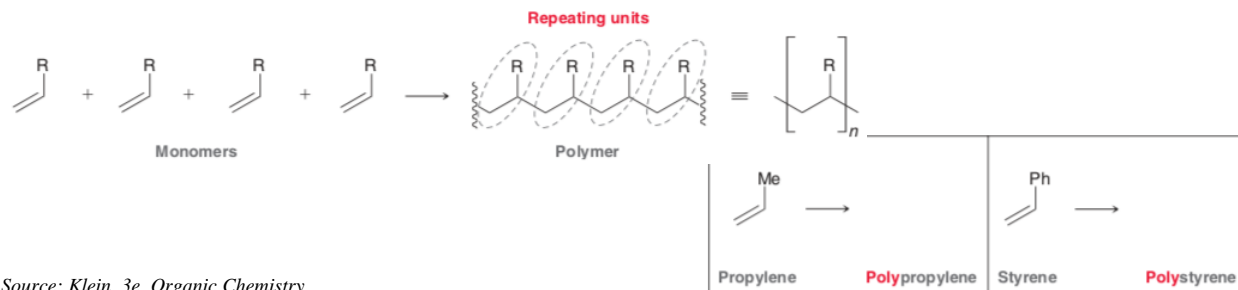
What is the product of the reaction of benzene with a solution of nitric acid in sulfuric acid at 50°C ?

**2.8 Polymerization****Addition vs Condensation**

Source: Wade 7th, Organic Chemistry

_____ polymerization	_____ polymerization
<ul style="list-style-type: none"> ○ It is formed by _____ reaction of large number of _____ having double bond without any loss of small molecules. ○ It is chain growth polymerization, e. g. polythene 	<ul style="list-style-type: none"> ○ It is formed by the combination of large number of monomer having <i>multifunctional</i> groups to form polymers with loss of small molecules like H_2O, NH_3, etc. ○ It is step growth polymerization, e.g. Nylon-6,6

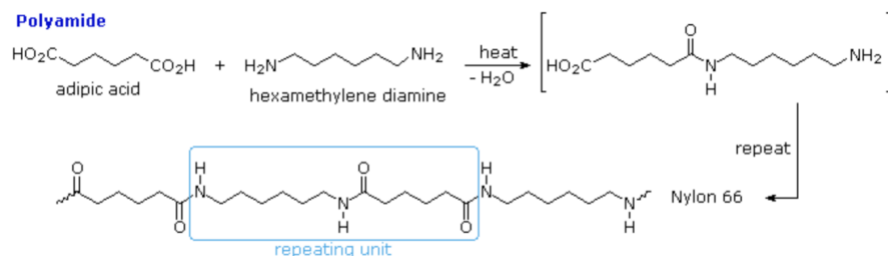
[Practice Example] Draw the structures of the polypropylene and polystyrene following the example.



Source: Klein, 3e, Organic Chemistry

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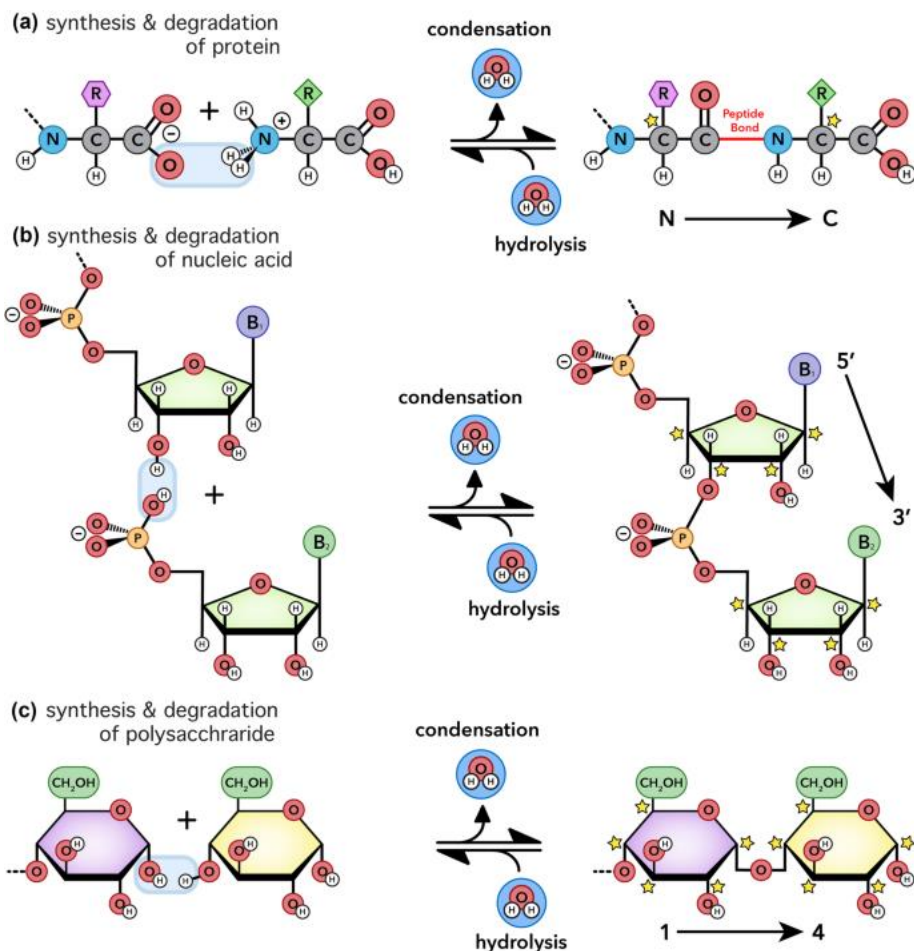
Examples of condensation polymers – polyamide



source: Libretxts

Biopolymers and their hydrolysis

Biopolymers are natural polymers produced by the cells of living organisms. There are three main classes of biopolymers, classified according to the monomers used and the structure of the biopolymer formed: *polynucleotides*, *polypeptides*, and *polysaccharides*. Polynucleotides, such as RNA and DNA, are long polymers composed of 13 or more nucleotide monomers. Polypeptides and proteins, are polymers of amino acids and some major examples include collagen, actin, and fibrin. Polysaccharides are linear or branched polymeric carbohydrates and examples include starch, cellulose and alginate. Other examples of biopolymers include *natural rubbers* (polymers of isoprene).



source: [springer](#)