

Functional-Group Synthesis

The following table summarizes the synthetic methods by which important functional groups can be prepared. The functional groups are listed alphabetically, followed by reference to the appropriate text section and a brief description of each synthetic method.

Acetals, $R_2C(OR')_2$

(Sec. 19.10) from ketones and aldehydes by acid-catalyzed reaction with alcohols

Acid anhydrides, RCO_2COR'

(Sec. 21.3) from dicarboxylic acids by heating

(Sec. 21.5) from acid chlorides by reaction with carboxylate salts

Acid bromides, $RCOBr$

(Sec. 21.4) from carboxylic acids by reaction with PBr_3

Acid chlorides, $RCOCl$

(Sec. 21.3) from carboxylic acids by reaction with $SOCl_2$

Alcohols, ROH

(Sec. 7.4) from alkenes by oxymercuration/demercuration

(Sec. 7.5) from alkenes by hydroboration/oxidation

(Sec. 7.8) from alkenes by hydroxylation with OsO_4

(Sec. 11.2, 11.3) from alkyl halides and tosylates by S_N2 reaction with hydroxide ion

(Sec. 18.3) from ethers by acid-induced cleavage

(Sec. 18.6) from epoxides by acid-catalyzed ring opening with either H_2O or HX

(Sec. 18.6) from epoxides by base-induced ring opening

(Sec. 17.4, 19.7) from ketones and aldehydes by reduction with $NaBH_4$ or $LiAlH_4$

(Sec. 17.5, 19.7) from ketones and aldehydes by addition of Grignard reagents

(Sec. 21.3) from carboxylic acids by reduction with either $LiAlH_4$ or BH_3

(Sec. 21.4) from acid chlorides by reduction with $LiAlH_4$

(Sec. 21.4) from acid chlorides by reaction with Grignard reagents

(Sec. 21.5) from acid anhydrides by reduction with $LiAlH_4$

(Sec. 17.4, 21.6) from esters by reduction with $LiAlH_4$

(Sec. 17.5, 21.6) from esters by reaction with Grignard reagents

Aldehydes, $RCHO$

(Sec. 7.9) from disubstituted alkenes by ozonolysis

(Sec. 7.9) from 1,2-diols by cleavage with sodium periodate

(Sec. 8.4) from terminal alkynes by hydroboration followed by oxidation

(Sec. 17.7, 19.2) from primary alcohols by oxidation

(Sec. 19.2, 21.6) from esters by reduction with DIBAL $[HAl(i-Bu)_2]$

Alkanes, RH

(Sec. 7.7) from alkenes by catalytic hydrogenation

(Sec. 10.7) from alkyl halides by protonolysis of Grignard reagents

(Sec. 10.8) from alkyl halides by coupling with Gilman reagents

(Sec. 19.9) from ketones and aldehydes by Wolff-Kishner reaction

Alkenes, $R_2C=CR_2$

- (Sec. 7.1, 11.8) from alkyl halides by treatment with strong base (E2 reaction)
- (Sec. 7.1, 17.6) from alcohols by dehydration
- (Sec. 8.5) from alkynes by catalytic hydrogenation using the Lindlar catalyst
- (Sec. 8.5) from alkynes by reduction with lithium in liquid ammonia
- (Sec. 19.11) from ketones and aldehydes by treatment with alkylidenetriphenylphosphoranes (Wittig reaction)
- (Sec. 22.3) from α -bromo ketones by heating with pyridine
- (Sec. 24.7) from amines by methylation and Hofmann elimination

Alkynes, $RC\equiv CR$

- (Sec. 8.2) from dihalides by base-induced double dehydrohalogenation
- (Sec. 8.8) from terminal alkynes by alkylation of acetylide anions

Amides, $RCONH_2$

- (Sec. 21.3) from carboxylic acids by heating with ammonia
- (Sec. 21.4) from acid chlorides by treatment with an amine or ammonia
- (Sec. 21.5) from acid anhydrides by treatment with an amine or ammonia
- (Sec. 21.6) from esters by treatment with an amine or ammonia
- (Sec. 20.7) from nitriles by partial hydrolysis with either acid or base
- (Sec. 26.7) from a carboxylic acid and an amine by treatment with dicyclohexylcarbodiimide (DCC)

Amines, RNH_2

- (Sec. 19.13) from conjugated enones by addition of primary or secondary amines
- (Sec. 21.7, 24.6) from amides by reduction with $LiAlH_4$
- (Sec. 20.7, 24.6) from nitriles by reduction with $LiAlH_4$
- (Sec. 24.6) from primary alkyl halides by treatment with ammonia
- (Sec. 24.6) from primary alkyl halides by Gabriel synthesis
- (Sec. 24.6) from primary alkyl azides by reduction with $LiAlH_4$
- (Sec. 24.6) from acid chlorides by Curtius rearrangement of acyl azides
- (Sec. 24.6) from primary amides by Hofmann rearrangement
- (Sec. 24.6) from ketones and aldehydes by reductive amination with an amine and $NaBH_3CN$

Amino Acids, $RCH(NH_2)CO_2H$

- (Sec. 26.3) from α -bromo acids by S_N2 reaction with ammonia
- (Sec. 26.3) from α -keto acids by reductive amination
- (Sec. 26.3) from primary alkyl halides by alkylation with diethyl acetamidomalonate
- (Sec. 26.3) from (Z)-amido acids by enantioselective hydrogenation

Arenes, $Ar-R$

- (Sec. 16.3) from arenes by Friedel-Crafts alkylation with an alkyl halide
- (Sec. 16.10) from aryl alkyl ketones by catalytic reduction of the keto group
- (Sec. 24.8) from arenediazonium salts by treatment with hypophosphorous acid

Arylamines, $Ar-NH_2$

- (Sec. 16.2, 24.6) from nitroarenes by reduction with either Fe, Sn, or H_2/Pd .

Arenediazonium salts, $Ar-N_2^+ X^-$

- (Sec. 24.8) from arylamines by reaction with nitrous acid

Arenesulfonic acids $\text{Ar-SO}_3\text{H}$

(Sec. 16.2) from arenes by electrophilic aromatic substitution with $\text{SO}_3/\text{H}_2\text{SO}_4$

Azides, R-N_3

(Sec. 11.2, 24.6) from primary alkyl halides by $\text{S}_{\text{N}}2$ reaction with azide ion

Carboxylic acids, RCO_2H

(Sec. 7.9) from mono- and 1,2-disubstituted alkenes by ozonolysis
 (Sec. 16.9) from arenes by side-chain oxidation with $\text{Na}_2\text{Cr}_2\text{O}_7$ or KMnO_4
 (Sec. 19.3) from aldehydes by oxidation
 (Sec. 20.5) from alkyl halides by conversion into Grignard reagents followed by reaction with CO_2
 (Sec. 20.5, 20.7) from nitriles by acid or base hydrolysis
 (Sec. 21.4) from acid chlorides by reaction with aqueous base
 (Sec. 21.5) from acid anhydrides by reaction with aqueous base
 (Sec. 21.6) from esters by hydrolysis with aqueous base
 (Sec. 21.7) from amides by hydrolysis with aqueous base

Cyanohydrins, RCH(OH)CN

(Sec. 19.6) from aldehydes and ketones by reaction with HCN

Cycloalkanes

(Sec. 7.6) from alkenes by addition of dichlorocarbene
 (Sec. 7.6) from alkenes by reaction with CH_2I_2 and Zn/Cu (Simmons–Smith reaction)
 (Sec. 16.10) from arenes by hydrogenation

Disulfides, RS-SR'

(Sec. 18.8) from thiols by oxidation with bromine

Enamines, RCH=CRNR_2

(Sec. 19.8) from ketones or aldehydes by reaction with secondary amines

Epo xides , $\text{R}_2\text{C} \begin{array}{c} \text{O} \\ \diagup \quad \diagdown \\ \text{---} \end{array} \text{CR}_2$

(Sec. 7.8, 18.5) from alkenes by treatment with a peroxyacid
 (Sec. 18.5) from halohydrins by treatment with base

Esters, $\text{RCO}_2\text{R'}$

(Sec. 21.3) from carboxylic acid salts by $\text{S}_{\text{N}}2$ reaction with primary alkyl halides
 (Sec. 21.3) from carboxylic acids by acid-catalyzed reaction with an alcohol (Fischer esterification)
 (Sec. 21.4) from acid chlorides by base-induced reaction with an alcohol
 (Sec. 21.5) from acid anhydrides by base-induced reaction with an alcohol
 (Sec. 22.7) from alkyl halides by alkylation with diethyl malonate
 (Sec. 22.7) from esters by treatment of their enolate ions with alkyl halides

Ethers, $R-O-R'$

- (Sec. 16.7) from activated haloarenes by reaction with alkoxide ions
- (Sec. 16.8) from unactivated haloarenes by reaction with alkoxide ions via benzyne intermediates
- (Sec. 18.2) from primary alkyl halides by S_N2 reaction with alkoxide ions (Williamson ether synthesis)
- (Sec. 18.2) from alkenes by alkoxymercuration/demercuration
- (Sec. 18.5) from alkenes by epoxidation with peroxyacids

Halides, alkyl, R_3C-X

- (Sec. 6.7) from alkenes by electrophilic addition of HX
- (Sec. 7.2) from alkenes by addition of halogen
- (Sec. 7.3) from alkenes by electrophilic addition of hypohalous acid (HOX) to yield halohydrins
- (Sec. 8.3) from alkynes by addition of halogen
- (Sec. 8.3) from alkynes by addition of HX
- (Sec. 10.4) from alkenes by allylic bromination with *N*-bromosuccinimide (NBS)
- (Sec. 10.6) from alcohols by reaction with HX
- (Sec. 10.6) from alcohols by reaction with $SOCl_2$
- (Sec. 10.6) from alcohols by reaction with PBr_3
- (Sec. 11.2, 11.3) from alkyl tosylates by S_N2 reaction with halide ions
- (Sec. 16.9) from arenes by benzylic bromination with *N*-bromosuccinimide (NBS)
- (Sec. 18.3) from ethers by cleavage with either HX
- (Sec. 22.3) from ketones by α -halogenation with bromine
- (Sec. 22.4) from carboxylic acids by α -halogenation with phosphorus and PBr_3 (Hell-Volhard-Zelinskii reaction)

Halides, aryl, $Ar-X$

- (Sec. 16.1, 16.2) from arenes by electrophilic aromatic substitution with halogen
- (Sec. 24.8) from arenediazonium salts by reaction with cuprous halides (Sandmeyer reaction)

Halohydrins, $R_2CXC(OH)R_2$

- (Sec. 7.3) from alkenes by electrophilic addition of hypohalous acid (HOX)
- (Sec. 18.6) from epoxides by acid-induced ring opening with HX

Imines, $R_2C=NR'$

- (Sec. 19.8) from ketones or aldehydes by reaction with primary amines

Ketones, $R_2C=O$

- (Sec. 7.9) from alkenes by ozonolysis
- (Sec. 7.9) from 1,2-diols by cleavage reaction with sodium periodate
- (Sec. 8.4) from alkynes by mercuric-ion-catalyzed hydration
- (Sec. 8.4) from alkynes by hydroboration/oxidation
- (Sec. 16.3) from arenes by Friedel-Crafts acylation reaction with an acid chloride
- (Sec. 17.7, 19.2) from secondary alcohols by oxidation
- (Sec. 19.2, 21.4) from acid chlorides by reaction with lithium diorganocopper (Gilman) reagents
- (Sec. 19.13) from conjugated enones by addition of lithium diorganocopper reagents
- (Sec. 20.7) from nitriles by reaction with Grignard reagents
- (Sec. 22.7) from primary alkyl halides by alkylation with ethyl acetoacetate
- (Sec. 22.7) from ketones by alkylation of their enolate ions with primary alkyl halides

Nitriles, $R-C\equiv N$

- (Sec. 11.3, 20.7) from primary alkyl halides by S_N2 reaction with cyanide ion
 (Sec. 20.7) from primary amides by dehydration with $SOCl_2$
 (Sec. 22.7) from nitriles by alkylation of their α -anions with primary alkyl halides
 (Sec. 24.8) from arenediazonium ions by treatment with $CuCN$

Nitroarenes, $Ar-NO_2$

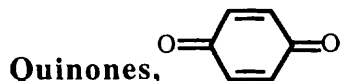
- (Sec. 16.2) from arenes by electrophilic aromatic substitution with nitric/sulfuric acids

Organometallics, $R-M$

- (Sec. 10.7) formation of Grignard reagents from organohalides by treatment with magnesium
 (Sec. 10.8) formation of organolithium reagents from organohalides by treatment with lithium
 (Sec. 10.8) formation of lithium diorganocopper reagents (Gilman reagents) from organolithium reagents by treatment with cuprous halides

Phenols, $Ar-OH$

- (Sec. 24.8) from arenediazonium salts by reaction with Cu_2O and $Cu(NO_3)_2$
 (Sec. 16.7) from aryl halides by nucleophilic aromatic substitution with hydroxide ion



- (Sec. 17.10) from phenols by oxidation with Fremy's salt $[(KSO_3)_2NO]$

Sulfides, $R-S-R'$

- (Sec. 18.8) from thiols by S_N2 reaction of thiolate ions with primary alkyl halides

Sulfones, $R-SO_2-R'$

- (Sec. 18.8) from sulfides or sulfoxides by oxidation with peroxyacids

Sulfoxides, $R-SO-R'$

- (Sec. 18.8) from sulfides by oxidation with H_2O_2

Thiols, $R-SH$

- (Sec. 11.3) from primary alkyl halides by S_N2 reaction with hydrosulfide anion
 (Sec. 18.8) from primary alkyl halides by S_N2 reaction with thiourea, followed by hydrolysis

Functional-Group Reactions

The following table summarizes the reactions of important functional groups. The functional groups are listed alphabetically, followed by a reference to the appropriate text section.

Acetal

1. Hydrolysis to yield a ketone or aldehyde plus alcohol (Sec. 19.10)

Acid anhydride

1. Hydrolysis to yield a carboxylic acid (Sec. 21.5)
2. Alcoholysis to yield an ester (Sec. 21.5)
3. Aminolysis to yield an amide (Sec. 21.5)
4. Reduction to yield a primary alcohol (Sec. 21.5)

Acid chloride

1. Friedel–Crafts reaction with an aromatic compound to yield an aryl ketone (Sec. 16.3)
2. Hydrolysis to yield a carboxylic acid (Sec. 21.4)
3. Alcoholysis to yield an ester (Sec. 21.4)
4. Aminolysis to yield an amide (Sec. 21.4)
5. Reduction to yield a primary alcohol (Sec. 21.4)
6. Grignard reaction to yield a tertiary alcohol (Sec. 21.4)
7. Reaction with a lithium diorganocopper reagent to yield a ketone (Sec. 21.4)

Alcohol

1. Acidity (Sec. 17.2)
2. Oxidation (Sec. 17.7)
 - a. Reaction of a primary alcohol to yield an aldehyde or acid
 - b. Reaction of a secondary alcohol to yield a ketone
3. Reaction with a carboxylic acid to yield an ester (Sec. 21.3)
4. Reaction with an acid chloride to yield an ester (Sec. 21.4)
5. Reaction with an acid anhydride to yield an ester (Sec. 21.5)
6. Dehydration to yield an alkene (Sec. 17.6)
7. Reaction with a primary alkyl halide to yield an ether (Sec. 18.2)
8. Conversion into an alkyl halide (Sec. 17.6)
 - a. Reaction of a tertiary alcohol with HX
 - b. Reaction of a primary or secondary alcohol with SOCl_2
 - c. Reaction of a primary or secondary alcohol with PBr_3

Aldehyde

1. Oxidation to yield a carboxylic acid (Sec. 19.3)
2. Nucleophilic addition reactions
 - a. Reduction to yield a primary alcohol (Secs. 17.4, 19.8)
 - b. Reaction with a Grignard reagent to yield a secondary alcohol (Secs. 17.5, 19.7)
 - c. Grignard reaction of formaldehyde to yield a primary alcohol (Sec. 17.5)
 - d. Reaction with HCN to yield a cyanohydrin (Sec. 19.6)
 - e. Wolff–Kishner reaction with hydrazine to yield an alkane (Sec. 19.9)
 - f. Reaction with an alcohol to yield an acetal (Sec. 19.10)
 - g. Wittig reaction to yield an alkene (Sec. 19.11)
 - h. Reaction with an amine to yield an imine or enamine (Sec. 19.8)
3. Aldol reaction to yield a β -hydroxy aldehyde (Sec. 23.1)
4. Alpha bromination of an aldehyde (Sec. 22.3)

Alkane

1. Radical halogenation to yield an alkyl halide (Secs. 5.3, 10.3)

Alkene

1. Electrophilic addition of HX to yield an alkyl halide (Secs. 6.7–6.11)
Markovnikov regiochemistry is observed.
2. Electrophilic addition of halogen to yield a 1,2-dihalide (Sec. 7.2)
3. Oxymercuration/demercuration to yield an alcohol (Sec. 7.4)
Markovnikov regiochemistry is observed, yielding the more highly substituted alcohol.
4. Hydroboration/oxidation to yield an alcohol (Section 7.5)
5. Hydrogenation to yield an alkane (Sec. 7.7)
6. Hydroxylation to yield a 1,2-diol (Sec. 7.8)
7. Oxidative cleavage to yield carbonyl compounds (Sec. 7.9)
8. Simmons–Smith reaction with CH_2I_2 to yield a cyclopropane (Sec. 7.6)
9. Reaction with dichlorocarbene to yield a dichlorocyclopropane (Sec. 7.6)
10. Allylic bromination with NBS (Sec. 10.4)
11. Alkoxymercuration to yield an ether (Sec. 18.2)
12. Reaction with a peroxyacid to yield an epoxide (Secs. 7.8, 18.5)

Alkyne

1. Electrophilic addition of HX to yield a vinylic halide (Sec. 8.3)
2. Electrophilic addition of halogen to yield a dihalide (Sec. 8.3)
3. Mercuric-sulfate-catalyzed hydration to yield a methyl ketone (Sec. 8.4)
4. Hydroboration/oxidation to yield an aldehyde (Sec. 8.4)
5. Alkylation of an alkyne anion (Sec. 8.8)
6. Reduction (Sec. 8.5)
 - a. Hydrogenation over Lindlar catalyst to yield a cis alkene
 - b. Reduction with Li/NH_3 to yield a trans alkene

Amide

1. Hydrolysis to yield a carboxylic acid (Sec. 21.7)
2. Reduction with LiAlH_4 to yield an amine (Sec. 21.7)
3. Dehydration to yield a nitrile (Section 20.7)

Amine

1. Basicity (Sec. 24.3)
2. $\text{S}_{\text{N}}2$ alkylation of an alkyl halide to yield an amine (Sec. 24.6)
3. Nucleophilic acyl substitution reactions
 - a. Reaction with an acid chloride to yield an amide (Sec. 21.4)
 - b. Reaction with an acid anhydride to yield an amide (Sec. 21.5)
4. Hofmann elimination to yield an alkene (Sec. 24.7)
5. Formation of an arenediazonium salt (Sec. 24.8)

Arene

1. Oxidation of an alkylbenzene side chain to yield a benzoic acid (Sec. 16.9)
2. Catalytic reduction to yield a cyclohexane (Sec. 16.10)
3. Reduction of an aryl alkyl ketone to yield an arene (Sec. 16.10)
4. Electrophilic aromatic substitution (Secs. 16.1–16.3)
 - a. Halogenation (Secs. 16.1–16.2)
 - b. Nitration (Sec. 16.2)
 - c. Sulfonation (Sec. 16.2)
 - d. Friedel–Crafts alkylation (Sec. 16.3)
Aromatic ring must be at least as reactive as a halobenzene
 - e. Friedel–Crafts acylation (Sec. 16.3)

Arenediazonium salt

1. Conversion into an aryl chloride (Sec. 24.8)
2. Conversion into an aryl bromide (Sec. 24.8)
3. Conversion into an aryl iodide (Sec. 24.8)
4. Conversion into an aryl cyanide (Sec. 24.8)
5. Conversion into a phenol (Sec. 24.8)
6. Conversion into an arene (Sec. 24.8)

Carboxylic acid

1. Acidity (Secs. 20.2–20.4)
2. Reduction to yield a primary alcohol (Secs. 17.4, 21.3)
 - a. Reduction with LiAlH_4
 - b. Reduction with BH_3
3. Nucleophilic acyl substitution reactions (Sec. 21.3)
 - a. Conversion into an acid chloride
 - b. Conversion into an acid anhydride
 - c. Conversion into an ester
 - (1) Fischer esterification
 - (2) $\text{S}_\text{N}2$ reaction with an alkyl halide
4. Alpha bromination (Hell–Volhard–Zelinskii reaction) (Sec. 22.4)

Diene

1. Conjugate addition of HX and X_2 (Sec. 14.2)
2. Diels–Alder reaction (Secs. 14.4, 14.5, 30.5)

Epoxide

1. Acid-catalyzed ring opening with HX to yield a halohydrin (Sec. 18.6)
2. Ring opening with aqueous acid to yield a 1,2-diol (Sec. 18.6)

Ester

1. Hydrolysis to yield a carboxylic acid (Sec. 21.6)
2. Aminolysis to yield an amide (Sec. 21.6)
3. Reduction to yield a primary alcohol (Secs. 17.4, 21.6)
4. Partial reduction with DIBAH to yield an aldehyde (Sec. 21.6)
5. Grignard reaction to yield a tertiary alcohol (Secs. 17.5, 21.6)
6. Claisen condensation to yield a β -keto ester (Sec. 23.7)

Ether

1. Acid-induced cleavage to yield an alcohol and an alkyl halide (Sec. 18.3)
2. Claisen rearrangement of an allyl aryl ether to yield an *o*-allyl phenol (Secs. 18.4, 30.8)

Halide, alkyl

1. Reaction with magnesium to form a Grignard reagent (Sec. 10.7)
2. Reduction to yield an alkane (Sec. 10.7)
3. Coupling with a diorganocopper reagent to yield an alkane (Sec. 10.8)
4. Reaction with an alcohol to yield an ether (Sec. 18.2)
5. Nucleophilic substitution ($\text{S}_\text{N}1$ or $\text{S}_\text{N}2$) (Secs. 11.1–11.5)
6. Dehydrohalogenation to yield an alkene ($\text{E}1$ or $\text{E}2$) (Secs. 11.7–11.10)

Halohydrin

1. Conversion into an epoxide (Sec. 18.5)

Ketone

1. Nucleophilic addition reactions
 - a. Reduction to yield a secondary alcohol (Secs. 17.4, 19.7)
 - b. Reaction with a Grignard reagent to yield a tertiary alcohol (Secs. 17.5, 19.7)
 - c. Wolff–Kishner reaction with hydrazine to yield an alkane (Sec. 19.9)
 - d. Reaction with HCN to yield a cyanohydrin (Sec. 19.6)
 - e. Reaction with an alcohol to yield an acetal (Sec. 19.10)
 - f. Wittig reaction to yield an alkene (Sec. 19.11)
 - g. Reaction with an amine to yield an imine or enamine (Sec. 19.8)
2. Aldol reaction to yield a β -hydroxy ketone (Sec. 23.1)
3. Alpha bromination (Sec. 22.3)

Nitrile

1. Hydrolysis to yield a carboxylic acid (Secs. 20.5, 20.7)
2. Reduction to yield a primary amine (Sec. 20.7)
3. Reaction with a Grignard reagent to yield a ketone (Sec. 20.7)

Nitroarene

1. Reduction to yield an arylamine (Secs. 16.2, 24.6)

Organometallic reagent

1. Reduction by treatment with acid to yield an alkane (Sec. 10.7)
2. Nucleophilic addition to a carbonyl compound to yield an alcohol (Secs. 17.5, 19.7)
3. Conjugate addition of a lithium diorganocopper to an α,β -unsaturated ketone (Sec. 19.13)
4. Coupling reaction of a lithium diorganocopper reagent with an alkyl halide to yield an alkane (Sec. 10.8)
5. Coupling reaction of a lithium diorganocopper with an acid chloride to yield a ketone (Sec. 21.4)
6. Reaction with carbon dioxide to yield a carboxylic acid (Sec. 20.5)

Phenol

1. Acidity (Sec. 17.2)
2. Reaction with an acid chloride to yield an ester (Sec. 21.4)
3. Reaction with an alkyl halide to yield an ether (Sec. 18.2)
4. Oxidation to yield a quinone (Sec. 17.10)

Quinone

1. Reduction to yield a hydroquinone (Sec. 17.10)

Sulfide

1. Reaction with an alkyl halide to yield a sulfonium salt (Sec. 18.8)
2. Oxidation to yield a sulfoxide (Sec. 18.8)
3. Oxidation to yield a sulfone (Sec. 18.8)

Thiol

1. Reaction with an alkyl halide to yield a sulfide (Sec. 18.8)
2. Oxidation to yield a disulfide (Sec. 18.8)

Reagents in Organic Chemistry

The following table summarizes the uses of some important reagents in organic chemistry. The reagents are listed alphabetically, followed by a brief description of the uses of each and references to the appropriate text sections.

Acetic acid, $\text{CH}_3\text{CO}_2\text{H}$: Used as a solvent for the reduction of ozonides with zinc (Section 7.9) and the α -bromination of ketones and aldehydes with Br_2 (Section 22.3).

Acetic anhydride, $(\text{CH}_3\text{CO})_2\text{O}$: Reacts with alcohols to yield acetate esters (Sections 21.5 and 25.6) and with amines to yield acetamides (Section 21.5).

Aluminum chloride, AlCl_3 : Acts as a Lewis acid catalyst in Friedel–Crafts alkylation and acylation reactions of aromatic compounds (Section 16.3).

Ammonia, NH_3 : Used as a solvent for the reduction of alkynes by lithium metal to yield trans alkenes (Section 8.5).

- Reacts with acid chlorides and acid anhydrides to yield amides (Sections 21.4 and 21.5).

Borane, BH_3 : Adds to alkenes, giving alkylboranes that can be oxidized with alkaline H_2O_2 to yield alcohols (Section 7.5).

- Adds to alkynes, giving vinylic organoboranes that can be oxidized with H_2O_2 to yield aldehydes (Section 8.4).
- Reduces carboxylic acids to yield primary alcohols (Section 21.3).

Bromine, Br_2 : Adds to alkenes, yielding 1,2-dibromides (Sections 7.2, 14.2).

- Adds to alkynes yielding either 1,2-dibromoalkenes or 1,1,2,2-tetrabromoalkanes (Section 8.3).
- Reacts with arenes in the presence of FeBr_3 catalyst to yield bromoarenes (Section 16.1).
- Reacts with ketones in acetic acid solvent to yield α -bromo ketones (Section 22.3).
- Reacts with carboxylic acids in the presence of PBr_3 to yield α -bromo carboxylic acids (Hell–Volhard–Zelinskii reaction; Section 22.4).
- Oxidizes aldoses to yield aldonic acids (Section 25.6).

***N*-Bromosuccinimide (NBS), $(\text{CH}_2\text{CO})_2\text{NBr}$:** Reacts with alkenes in the presence of aqueous dimethylsulfoxide to yield bromohydrins (Section 7.3).

- Reacts with alkenes in the presence of light to yield allylic bromides (Section 10.4).
- Reacts with alkylbenzenes in the presence of light to yield benzylic bromides; (Section 16.9).

Di-*tert*-butoxy dicarbonate, $(t\text{-BuOCO})_2\text{O}$: Reacts with amino acids to give *t*-Boc protected amino acids suitable for use in peptide synthesis (Section 26.7).

Butyllithium, $\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{Li}$: A strong base; reacts with alkynes to yield acetylide anions, which can be alkylated (Section 8.8).

- Reacts with dialkylamines to yield lithium dialkylamide bases such as LDA [lithium diisopropylamide] (Section 22.5).
- Reacts with alkyltriphenylphosphonium salts to yield alkylidenephosphoranes (Wittig reagents (Section 19.11)).

Carbon dioxide, CO_2 : Reacts with Grignard reagents to yield carboxylic acids (Section 20.5).

Chlorine, Cl_2 : Adds to alkenes to yield 1,2-dichlorides (Sections 7.2 and 14.2).

- Reacts with alkanes in the presence of light to yield chloroalkanes by a radical chain reaction pathway (Section 10.3).
- Reacts with arenes in the presence of FeCl_3 catalyst to yield chloroarenes (Section 16.2).

***m*-Chloroperoxybenzoic acid, $m\text{-ClC}_6\text{H}_4\text{CO}_3\text{H}$:** Reacts with alkenes to yield epoxides (Sections 7.8, 18.5).

Chlorotrimethylsilane, $(\text{CH}_3)_3\text{SiCl}$: Reacts with alcohols to add the trimethylsilyl protecting group (Section 17.8).

Chromium trioxide, CrO_3 : Oxidizes alcohols in aqueous acid to yield carbonyl-containing products. Primary alcohols yield carboxylic acids, and secondary alcohols yield ketones (Sections 17.7 and 19.3).

Cuprous bromide, CuBr : Reacts with arenediazonium salts to yield bromoarenes (Sandmeyer reaction; Section 24.8).

Cuprous chloride, CuCl : Reacts with arenediazonium salts to yield chloroarenes (Sandmeyer reaction; Section 24.8).

Cuprous cyanide, CuCN : Reacts with arenediazonium salts to yield substituted benzonitriles (Sandmeyer reaction; Section 24.8).

Cuprous iodide, CuI : Reacts with organolithiums to yield lithium diorganocopper reagents (Gilman reagents; Section 10.8).

Cuprous oxide, Cu_2O : Reacts with arenediazonium salts to yield phenols (Section 24.8).

Dichloroacetic acid, $\text{Cl}_2\text{CHCO}_2\text{H}$: Cleaves DMT protecting groups in DNA synthesis (Section 28.7).

Dicyclohexylcarbodiimide (DCC), $\text{C}_6\text{H}_{11}\text{-N}=\text{C}=\text{N-C}_6\text{H}_{11}$: Couples an amine with a carboxylic acid to yield an amide. DCC is often used in peptide synthesis (Section 26.7).

Diethyl acetamidomalonate, $\text{CH}_3\text{CONHCH}(\text{CO}_2\text{Et})_2$: Reacts with alkyl halides in a common method of α -amino acid synthesis (Section 26.3).

Diiodomethane, CH_2I_2 : Reacts with alkenes in the presence of zinc–copper couple to yield cyclopropanes (Simmons–Smith reaction; Section 7.6).

Diisobutylaluminum hydride (DIBAL), $(i\text{-Bu})_2\text{AlH}$: Reduces esters to yield aldehydes (Sections 19.2 and 21.6).

2,4-Dinitrophenylhydrazine, $2,4\text{-(NO}_2)_2\text{C}_6\text{H}_3\text{NHNH}_2$: Reacts with aldehydes and ketones to yield 2,4-DNPs that serve as useful crystalline derivatives (Section 19.8).

Ethylene glycol, $\text{HOCH}_2\text{CH}_2\text{OH}$: Reacts with ketones or aldehydes in the presence of an acid catalyst to yield acetals that serve as useful carbonyl protecting groups (Section 19.10).

Ferric bromide, FeBr_3 : Acts as a catalyst for the reaction of arenes with Br_2 to yield bromoarenes (Section 16.1).

Ferric chloride, FeCl_3 : Acts as a catalyst for the reaction of arenes with Cl_2 to yield chloroarenes (Section 16.2).

Grignard reagent, RMgX : Reacts with acids to yield alkanes (Section 10.7).

- Adds to carbonyl-containing compounds (ketones, aldehydes, esters) to yield alcohols (Sections 17.6 and 19.8).
- Adds to nitriles to yield ketones (Section 20.9).

Hydrazine, H_2NNH_2 : Reacts with ketones or aldehydes in the presence of KOH to yield the corresponding alkanes (Wolff–Kishner reaction; Section 19.10).

Hydrogen bromide, HBr : Adds to alkenes with Markovnikov regiochemistry to yield alkyl bromides (Sections 6.7 and 14.2).

- Adds to alkynes to yield either bromoalkenes or 1,1-dibromoalkanes (Section 8.3).
- Reacts with alcohols to yield alkyl bromides (Sections 10.6 and 17.6).
- Cleaves ethers to yield alcohols and alkyl bromides (Section 18.3).

Hydrogen chloride, HCl : Adds to alkenes with Markovnikov regiochemistry to yield alkyl chlorides (Sections 6.7 and 14.2).

- Adds to alkynes to yield either chloroalkenes or 1,1-dichloroalkanes (Section 8.3).
- Reacts with alcohols to yield alkyl chlorides (Sections 10.6 and 17.6).

Hydrogen cyanide, HCN : Adds to ketones and aldehydes to yield cyanohydrins (Section 19.6).

Hydrogen iodide, HI : Reacts with alcohols to yield alkyl iodides (Section 17.6).

- Cleaves ethers to yield alcohols and alkyl iodides (Section 18.3).

Hydrogen peroxide, H_2O_2 : Oxidizes organoboranes to yield alcohols. Used in conjunction with addition of borane to alkenes, the overall transformation effects syn Markovnikov addition of water to an alkene (Section 7.5).

- Oxidizes vinylic boranes to yield aldehydes (Section 8.4).
- Oxidizes sulfides to yield sulfoxides (Section 18.8).

Hydroxylamine, NH_2OH : Reacts with ketones and aldehydes to yield oximes (Section 19.8).

- Reacts with aldoses to yield oximes as the first step in the Wohl degradation of aldoses (Section 25.6).

Hypophosphorous acid, H_3PO_2 : Reacts with arenediazonium salts to yield arenes (Section 24.8).

Iodine, I_2 : Reacts with arenes in the presence of CuCl or H_2O_2 to yield iodoarenes (Section 16.2).

Iodomethane, CH_3I : Reacts with alkoxide anions to yield methyl ethers (Section 18.2).

- Reacts with carboxylate anions to yield methyl esters (Section 21.6).
- Reacts with enolate ions to yield α -methylated carbonyl compounds (Section 22.7).
- Reacts with amines to yield methylated amines (Section 24.6).

Iron, Fe: Reacts with nitroarenes in the presence of aqueous acid to yield anilines (Section 24.6).

Lindlar catalyst: Acts as a catalyst for the partial hydrogenation of alkynes to yield cis alkenes (Section 8.5).

Lithium, Li: Reduces alkynes in liquid ammonia solvent to yield trans alkenes (Section 8.5).
 – Reacts with organohalides to yield organolithium compounds (Section 10.8).

Lithium aluminum hydride, LiAlH_4 : Reduces ketones, aldehydes, esters, and carboxylic acids to yield alcohols (Sections 17.4, 19.7, and 20.6).
 – Reduces amides to yield amines (Section 21.7).
 – Reduces alkyl azides to yield amines (Section 24.6).
 – Reduces nitriles to yield amines (Sections 20.7 and 24.6).

Lithium diisopropylamide (LDA), $\text{LiN}(i\text{-Pr})_2$: Reacts with carbonyl compounds (aldehydes, ketones, esters) to yield enolate ions (Sections 22.5 and 22.7).

Lithium diorganocopper reagent (Gilman reagent), LiR_2Cu : Couples with alkyl halides to yield alkanes (Section 10.8).
 – Adds to α,β -unsaturated ketones to give 1,4-addition products (Section 19.13).
 – Reacts with acid chlorides to give ketones (Section 21.4).

Magnesium, Mg: Reacts with organohalides to yield Grignard reagents (Section 10.7).

Mercuric acetate, $\text{Hg}(\text{O}_2\text{CCH}_3)_2$: Adds to alkenes in the presence of water, giving α -hydroxy organomercury compounds that can be reduced with NaBH_4 to yield alcohols. The overall effect is the Markovnikov hydration of an alkene (Section 7.4).

Mercuric sulfate, HgSO_4 : Acts as a catalyst for the addition of water to alkynes in the presence of aqueous sulfuric acid, yielding ketones (Section 8.4).

Mercuric trifluoroacetate, $\text{Hg}(\text{O}_2\text{CCF}_3)_2$: Adds to alkenes in the presence of alcohol, giving α -alkoxy organomercury compounds that can be reduced with NaBH_4 to yield ethers. The overall reaction effects a net addition of an alcohol to an alkene (Section 18.2).

Nitric acid, HNO_3 : Reacts with arenes in the presence of sulfuric acid to yield nitroarenes (Section 16.2).
 – Oxidizes aldoses to yield aldaric acids (Section 25.6).

Nitrous acid, HNO_2 : Reacts with amines to yield diazonium salts (Section 24.8).

Osmium tetroxide, OsO_4 : Adds to alkenes to yield 1,2-diols (Section 7.8).
 – Reacts with alkenes in the presence of periodic acid to cleave the carbon–carbon double bond, yielding ketone or aldehyde fragments (Section 7.9).

Ozone, O_3 : Adds to alkenes to cleave the carbon–carbon double bond and give ozonides, which can be reduced with zinc in acetic acid to yield carbonyl compounds (Section 7.9).

Palladium on barium sulfate, Pd/BaSO_4 : Acts as a hydrogenation catalyst for nitriles in the Kiliani–Fischer chain-lengthening reaction of carbohydrates (Section 25.6).

Palladium on carbon, Pd/C: Acts as a hydrogenation catalyst for reducing carbon–carbon multiple bonds. Alkenes and alkynes are reduced to yield alkanes (Sections 7.7 and 8.5).

- Acts as a hydrogenation catalyst for reducing aryl ketones to yield alkylbenzenes (Section 16.10).
- Acts as a hydrogenation catalyst for reducing nitroarenes to yield anilines (Section 24.6).

Periodic acid, HIO₄: Reacts with 1,2-diols to yield carbonyl-containing cleavage products (Section 7.9).

Peroxyacetic acid, CH₃CO₃H: Oxidizes sulfoxides to yield sulfones (Section 18.8)

Phenylisothiocyanate, C₆H₅–N=C=S: Used in the Edman degradation of peptides to identify N-terminal amino acids (Section 26.6).

Phosphorus oxychloride, POCl₃: Reacts with secondary and tertiary and alcohols to yield alkene dehydration products (Section 17.6).

Phosphorus tribromide, PBr₃: Reacts with alcohols to yield alkyl bromides (Section 10.6).

- Reacts with carboxylic acids to yield acid bromides (Section 21.4).
- Reacts with carboxylic acids in the presence of bromine to yield α-bromo carboxylic acids (Hell–Volhard–Zelinskii reaction; Section 22.4).

Platinum oxide (Adam's catalyst), PtO₂: Acts as a hydrogenation catalyst in the reduction of alkenes and alkynes to yield alkanes (Sections 7.7 and 8.5).

Potassium hydroxide, KOH: Reacts with alkyl halides to yield alkenes by an elimination reaction (Sections 7.1 and 11.11).

- Reacts with 1,1- or 1,2-dihaloalkanes to yield alkynes by a twofold elimination reaction (Section 8.2).

Potassium nitrosodisulfonate (Fremy's salt), K(SO₃)₂NO: Oxidizes phenols to yield quinones (Section 17.10).

Potassium permanganate, KMnO₄: Oxidizes alkenes under neutral or acidic conditions to give carboxylic acid double-bond cleavage products (Sections 7.9).

- Oxidizes alkynes to give carboxylic acid triple-bond cleavage products (Section 8.6).
- Oxidizes aromatic side chains to yield benzoic acids (Section 16.9).

Potassium phthalimide, C₆H₄(CO)₂NK: Reacts with alkyl halides to yield *N*-alkyl-phthalimides, which are hydrolyzed by aqueous sodium hydroxide to yield amines (Gabriel amine synthesis; Section 24.6).

Potassium *tert*-butoxide, KO-*t*-Bu: Reacts with alkyl halides to yield alkenes (Sections 11.7 and 11.8).

- Reacts with allylic halides to yield conjugated dienes (Section 14.1).
- Reacts with chloroform in the presence of an alkene to yield a dichlorocyclopropane (Section 7.6).

Pyridine, C₅H₅N: Acts as a basic catalyst for the reaction of alcohols with acid chlorides to yield esters (Section 21.4).

- Acts as a basic catalyst for the reaction of alcohols with acetic anhydride to yield acetate esters (Section 21.5).
- Reacts with α-bromo ketones to yield α,β-unsaturated ketones (Section 22.3).

Pyridinium chlorochromate (PCC), $C_5H_6NCrO_3Cl$: Oxidizes primary alcohols to yield aldehydes and secondary alcohols to yield ketones (Section 17.7).

Pyrrolidine, C_4H_8N : Reacts with ketones to yield enamines for use in the Stork enamine reaction (Sections 19.8 and 23.11).

Rhodium on carbon, Rh/C: Acts as a hydrogenation catalyst in the reduction of benzene rings to yield cyclohexanes (Section 16.10).

Silver oxide, Ag_2O : Oxidizes primary alcohols in aqueous ammonia solution to yield aldehydes (Tollens oxidation; Section 19.3).

- Catalyzes the reaction of monosaccharides with alkyl halides to yield ethers (Section 25.6).
- Reacts with tetraalkylammonium salts to yield alkenes (Hofmann elimination; Section 24.7).

Sodium amide, $NaNH_2$: Reacts with terminal alkynes to yield acetylide anions (Section 8.7).

- Reacts with 1,1- or 1,2-dihalides to yield alkynes by a twofold elimination reaction (Section 8.2).
- Reacts with aryl halides to yield anilines by a benzyne aromatic substitution mechanism (Section 16.8).

Sodium azide, NaN_3 : Reacts with alkyl halides to yield alkyl azides (Section 24.6).

- Reacts with acid chlorides to yield acyl azides. On heating in the presence of water, acyl azides yield amines and carbon dioxide (Section 24.6).

Sodium bisulfite, $NaHSO_3$: Reduces osmate esters, prepared by treatment of an alkene with osmium tetroxide, to yield 1,2-diols (Section 7.8).

Sodium borohydride, $NaBH_4$: Reduces organomercury compounds, prepared by oxymercuration of alkenes, to convert the C–Hg bond to C–H (Section 7.4).

- Reduces ketones and aldehydes to yield alcohols (Sections 17.4 and 19.7).
- Reduces quinones to yield hydroquinones (Section 17.10).

Sodium cyanide, $NaCN$: Reacts with alkyl halides to yield alkanenitriles (Sections 20.6 and 20.7).

Sodium cyanoborohydride, $NaBH_3CN$: Reacts with ketones and aldehydes in the presence of ammonia to yield an amine by a reductive amination process (Section 24.6).

Sodium dichromate, $Na_2Cr_2O_7$: Oxidizes primary alcohols to yield carboxylic acids and secondary alcohols to yield ketones (Sections 17.7 and 19.2).

- Oxidizes alkylbenzenes to yield benzoic acids (Section 16.9).

Sodium hydride, NaH : Reacts with alcohols to yield alkoxide anions (Section 17.2).

Sodium hydroxide, $NaOH$: Reacts with aryl halides to yield phenols by a benzyne aromatic substitution mechanism (Section 16.8).

Sodium iodide, NaI : Reacts with arenediazonium salts to yield aryl iodides (Section 24.8).

Stannous chloride, SnCl_2 : Reduces nitroarenes to yield anilines (Sections 16.2 and 24.6).

- Reduces quinones to yield hydroquinones (Section 17.10).

Sulfur trioxide, SO_3 : Reacts with arenes in sulfuric acid solution to yield arenesulfonic acids (Section 16.2).

Sulfuric acid, H_2SO_4 : Reacts with alcohols and water to yield alkenes (Section 7.4).

- Reacts with alkynes in the presence of water and mercuric sulfate to yield ketones (Section 8.4).
- Catalyzes the reaction of nitric acid with aromatic rings to yield nitroarenes (Section 16.2).
- Catalyzes the reaction of SO_3 with aromatic rings to yield arenesulfonic acids (Section 16.2).

Tetrazole: Acts as a coupling reagent for use in DNA synthesis (Section 28.7).

Thionyl chloride, SOCl_2 : Reacts with primary and secondary alcohols to yield alkyl chlorides (Section 10.6).

- Reacts with carboxylic acids to yield acid chlorides (Section 21.4).

Thiourea, H_2NCSNH_2 : Reacts with primary alkyl halides to yield thiols (Section 18.8).

***p*-Toluenesulfonyl chloride, $p\text{-CH}_3\text{C}_6\text{H}_4\text{SO}_2\text{Cl}$:** Reacts with alcohols to yield tosylates (Sections 11.1 and 17.6).

Trifluoroacetic acid, $\text{CF}_3\text{CO}_2\text{H}$: Acts as a catalyst for cleaving *tert*-butyl ethers, yielding alcohols and 2-methylpropene (Section 18.3).

- Acts as a catalyst for cleaving the *t*-Boc protecting group from amino acids in peptide synthesis (Section 26.7).

Triphenylphosphine, $(\text{C}_6\text{H}_5)_3\text{P}$: Reacts with primary alkyl halides to yield the alkyltriphenylphosphonium salts used in Wittig reactions (Section 19.11).

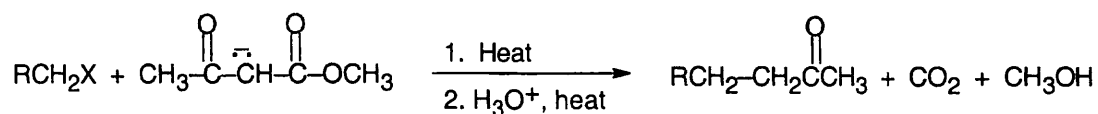
Zinc, Zn : Reduces ozonides, produced by addition of ozone to alkenes, to yield ketones and aldehydes (Section 7.9).

- Reduces disulfides to yield thiols (Section 18.8).

Zinc–copper couple, Zn–Cu : Reacts with diiodomethane in the presence of alkenes to yield cyclopropanes (Simmons–Smith reaction; Section 7.6).

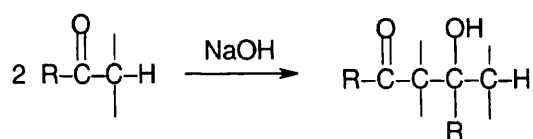
Name Reactions

Acetoacetic ester synthesis (Section 22.7): a multistep reaction sequence for converting a primary alkyl halide into a methyl ketone having three more carbon atoms in the chain.

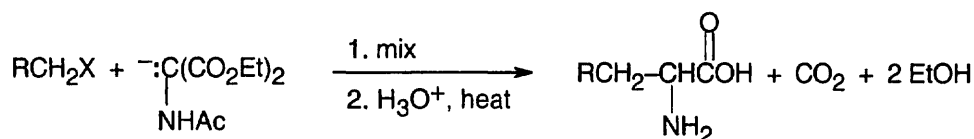


Adams' catalyst (Section 7.7): PtO_2 , a catalyst used for the hydrogenation of carbon-carbon double bonds.

Aldol condensation reaction (Section 23.1): the nucleophilic addition of an enol or enolate ion to a ketone or aldehyde, yielding a β -hydroxy ketone.

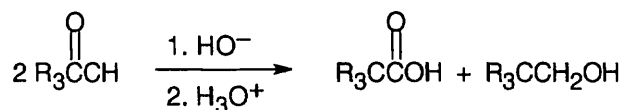


Amidomalonate amino acid synthesis (Section 26.3): a multistep reaction sequence, similar to the malonic ester synthesis, for converting a primary alkyl halide into an amino acid.

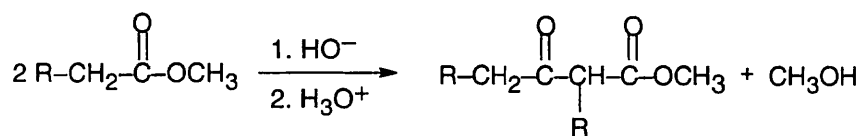


Benedict's test (Section 25.6): a chemical test for aldehydes, involving treatment with cupric ion in aqueous sodium citrate.

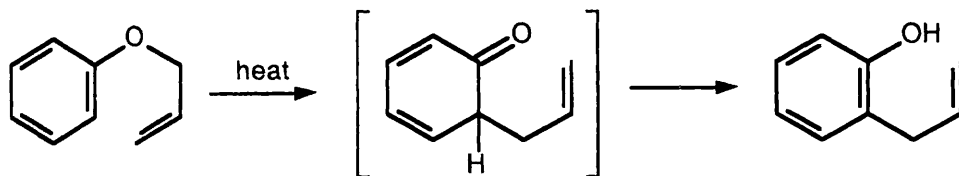
Cannizzaro reaction (Section 19.12): the disproportionation reaction that occurs when a nonenolizable aldehyde is treated with base.



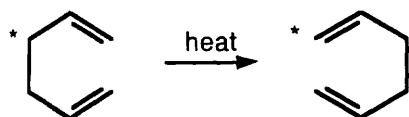
Claisen condensation reaction (Section 23.7): a nucleophilic acyl substitution reaction that occurs when an ester enolate ion attacks the carbonyl group of a second ester molecule. The product is a β -keto ester.



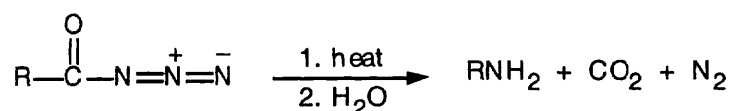
Claisen rearrangement (Sections 18.4 and 30.8): the thermal [3,3] sigmatropic rearrangement of an allyl vinyl ether or an allyl phenyl ether.



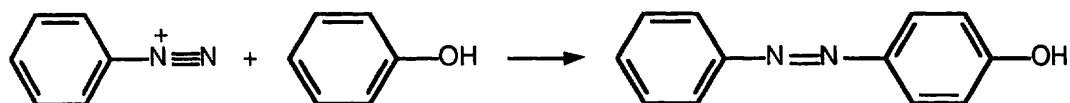
Cope rearrangement (Section 30.8): the thermal [3,3] sigmatropic rearrangement of a 1,5-diene to a new 1,5-diene.



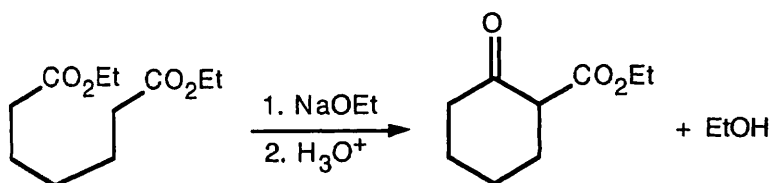
Curtius rearrangement (Section 24.6): the thermal rearrangement of an acyl azide to an isocyanate, followed by hydrolysis to yield an amine.



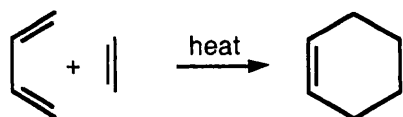
Diazonium coupling reaction (Section 24.8): the coupling reaction between an aromatic diazonium salt and a phenol or aniline.



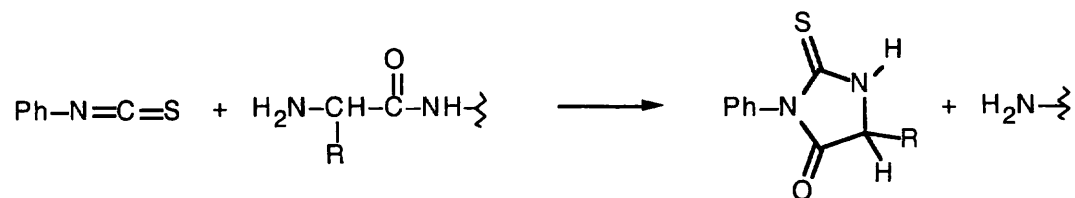
Dieckmann reaction (Section 23.9): the intramolecular Claisen condensation reaction of a 1,6- or 1,7-diester, yielding a cyclic β -keto ester.



Diels-Alder cycloaddition reaction (Sections 14.4–14.5 and 30.5): the reaction between a diene and a dienophile to yield a cyclohexene ring.

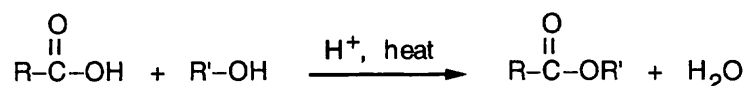


Edman degradation (Section 26.6): a method for cleaving the N-terminal amino acid from a peptide by treatment of the peptide with *N*-phenylisothiocyanate.

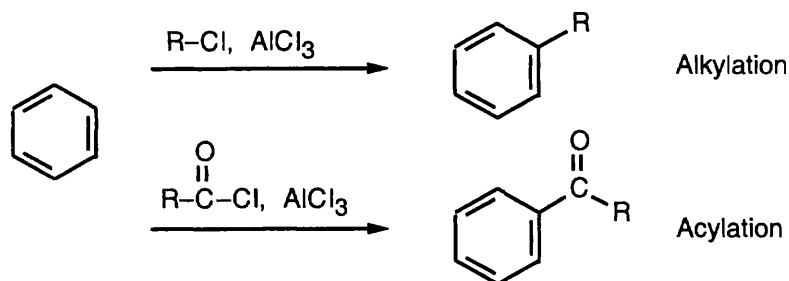


Fehling's test (Section 25.6): a chemical test for aldehydes, involving treatment with cupric ion in aqueous sodium tartrate.

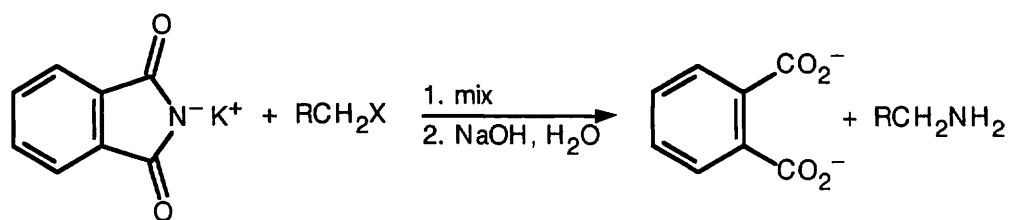
Fischer esterification reaction (Section 21.3): the acid-catalyzed reaction between a carboxylic acid and an alcohol, yielding the ester.



Friedel-Crafts reaction (Section 16.3): the alkylation or acylation of an aromatic ring by treatment with an alkyl- or acyl chloride in the presence of a Lewis-acid catalyst.

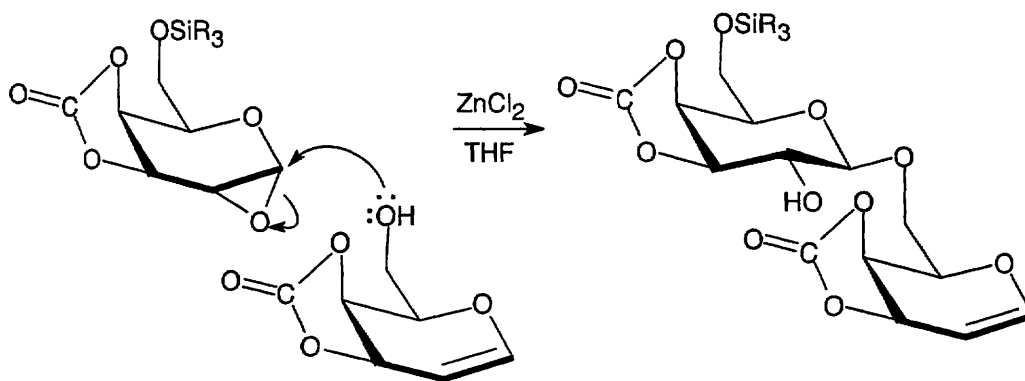


Gabriel amine synthesis (Section 24.6): a multistep sequence for converting a primary alkyl halide into a primary amine by alkylation with potassium phthalimide, followed by hydrolysis.

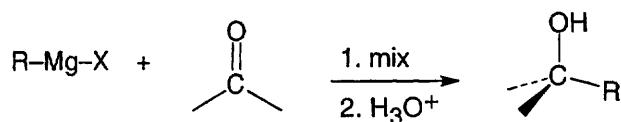


Gilman reagent (Section 10.8): a lithium dialkylcopper reagent, R_2CuLi , prepared by treatment of a cuprous salt with an alkyllithium. Gilman reagents undergo a coupling reaction with alkyl halides, a 1,4-addition reaction with α,β -unsaturated ketones, and a coupling reaction with acid chlorides to yield ketones.

Glycal assembly method (Section 25.9): a method of polysaccharide synthesis in which a glycal is converted into its epoxide, which is then opened by reaction with an alcohol.

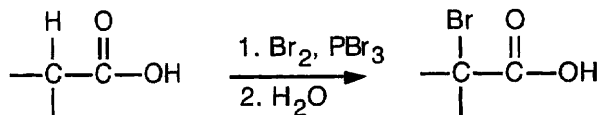


Grignard reaction (Section 19.7): the nucleophilic addition reaction of an alkylmagnesium halide to a ketone, aldehyde, or ester carbonyl group.

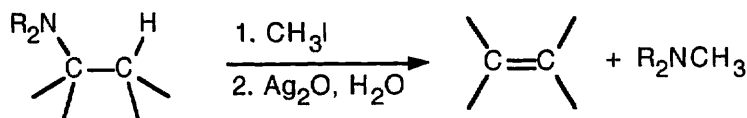


Grignard reagent (Section 10.7): an organomagnesium halide, RMgX , prepared by reaction between an organohalide and magnesium metal. Grignard reagents add to carbonyl compounds to yield alcohols.

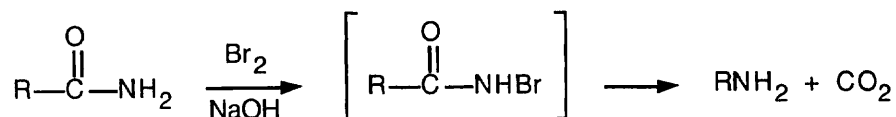
Hell-Volhard-Zelinskii reaction (Section 22.4): the α -bromination of a carboxylic acid by treatment with bromine and phosphorus tribromide.



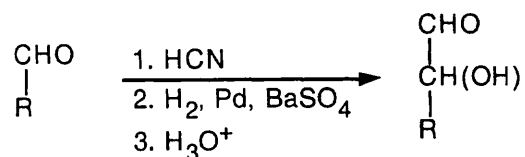
Hofmann elimination (Section 24.7): a method for effecting the elimination reaction of an amine to yield an alkene. The amine is first treated with excess iodomethane, and the resultant quaternary ammonium salt is heated with silver oxide.



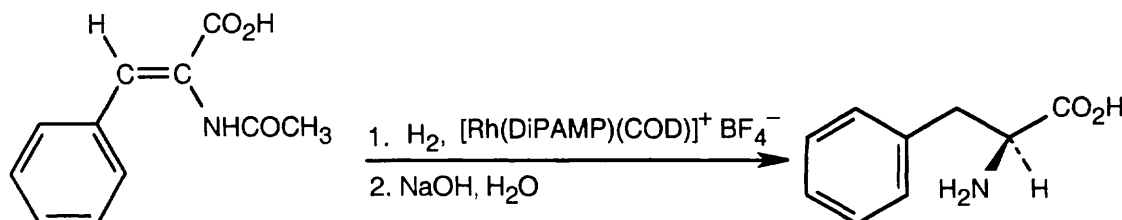
Hofmann rearrangement (Section 24.6): the rearrangement of an *N*-bromoamide to a primary amine by treatment with aqueous base.



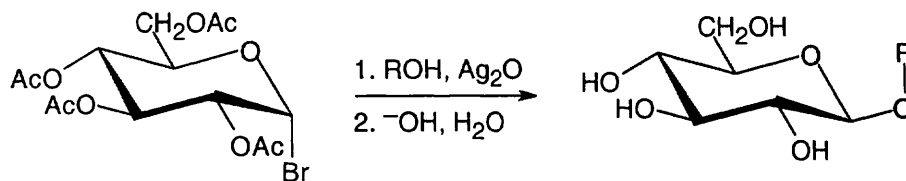
Kiliani–Fischer synthesis (Section 25.6): a multistep sequence for chain-lengthening an aldose into the next higher homolog.



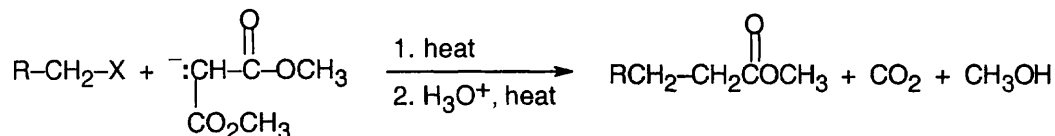
Knowles amino acid synthesis (Section 26.3): an enantioselective method of amino acid synthesis by hydrogenation of a *Z* enamido acid with a chiral hydrogenation catalyst.



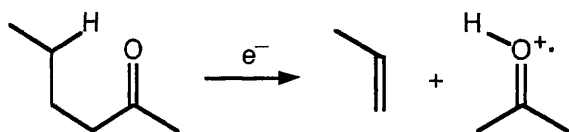
Koenigs–Knorr reaction (Section 25.6): a method for synthesizing a glycoside by reaction of a pyranosyl bromide with an alcohol and Ag_2O .



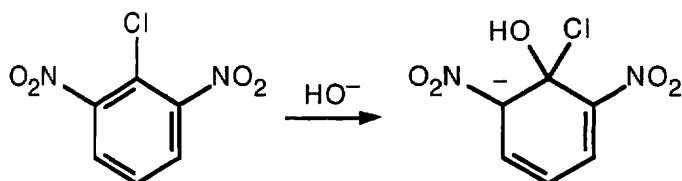
Malonic ester synthesis (Section 22.7): a multistep sequence for converting an alkyl halide into a carboxylic acid with the addition of two carbon atoms to the chain.



McLafferty rearrangement (Section 19.14): a mass spectral fragmentation pathway for carbonyl compounds having a hydrogen three carbon atoms away from the carbonyl carbon.

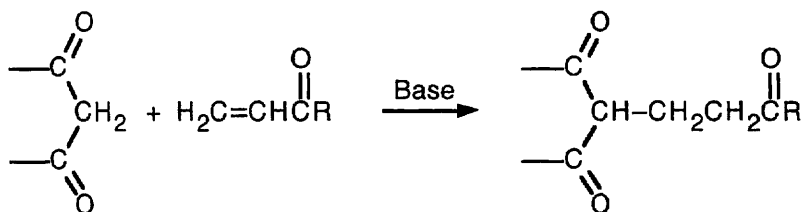


Meisenheimer complex (Section 16.7): an intermediate formed in the nucleophilic aryl substitution reaction of a base with a nitro-substituted aromatic ring.

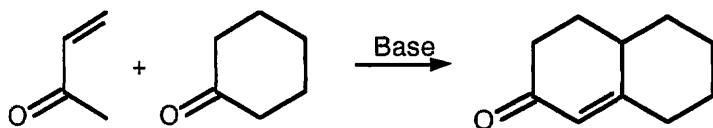


Merrifield solid-phase peptide synthesis (Section 26.8): a rapid and efficient means of peptide synthesis in which the growing peptide chain is attached to an insoluble polymer support.

Michael reaction (Section 23.10): the 1,4-addition reaction of a stabilized enolate anion such as that from a 1,3-diketone to an α,β -unsaturated carbonyl compound.



Robinson annulation reaction (Section 23.12): a multistep sequence for building a new cyclohexenone ring onto a ketone. The sequence involves an initial Michael reaction of the ketone followed by an internal aldol cyclization.

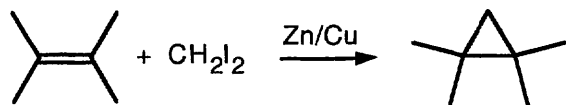


Sandmeyer reaction (Section 24.8): a method for converting an aryl diazonium salt into an aryl halide by treatment with a cuprous halide.

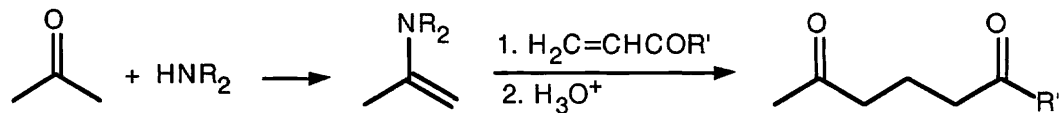


Sanger dideoxy method (Section 28.6): an enzymatic method for DNA sequencing.

Simmons-Smith reaction (Section 7.6): a method for preparing a cyclopropane by treating an alkene with diiodomethane and zinc-copper.



Stork enamine reaction (Section 23.11): a multistep sequence whereby a ketone is converted into an enamine by treatment with a secondary amine, and the enamine is then used in Michael reactions.



Tollen's test (Section 19.3): a chemical test for detecting aldehydes by treatment with ammoniacal silver nitrate. A positive test is signaled by formation of a silver mirror on the walls of the reaction vessel.

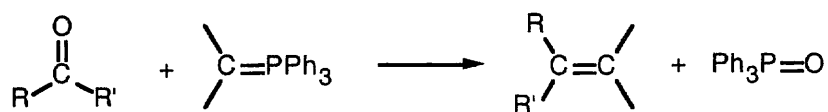
Walden inversion (Section 11.1): the inversion of stereochemistry at a chirality center during an $\text{S}_{\text{N}}2$ reaction.



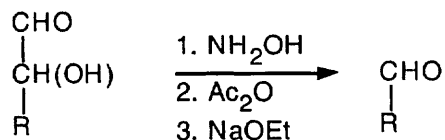
Williamson ether synthesis (Section 18.2): a method for preparing an ether by treatment of a primary alkyl halide with an alkoxide ion.



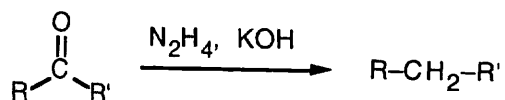
Wittig reaction (Section 19.11): a general method of alkene synthesis by treatment of a ketone or aldehyde with an alkylidenetriphenylphosphorane.



Wohl degradation (Section 25.6): a multistep reaction sequence for degrading an aldose into the next lower homolog.



Wolff-Kishner reaction (Section 19.9): a method for converting a ketone or aldehyde into the corresponding hydrocarbon by treatment with hydrazine and strong base.

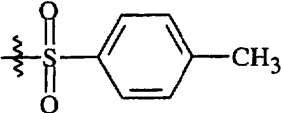









Woodward-Hoffmann orbital symmetry rules (Section 30.9): a series of rules for predicting the stereochemistry of pericyclic reactions. Even-electron species react thermally through either antarafacial or conrotatory pathways, whereas odd-electron species react thermally through either suprafacial or disrotatory pathways.

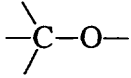

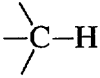
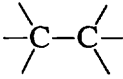
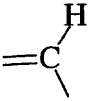
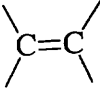
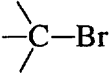
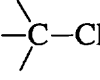
Abbreviations

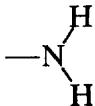

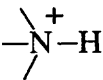




Å	symbol for Angstrom unit (10^{-8} cm = 10^{-10} m)
Ac-	Acetyl group, $\text{CH}_3\text{C}(=\text{O})-$
Ar-	aryl group
at. no.	atomic number
at. wt.	atomic weight
$[\alpha]_D$	specific rotation
Boc	<i>tert</i> -butoxycarbonyl group, $(\text{CH}_3)_3\text{COC}(=\text{O})-$
bp	boiling point
<i>n</i> -Bu	<i>n</i> -butyl group, $\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2-$
<i>sec</i> -Bu	<i>sec</i> -butyl group, $\text{CH}_3\text{CH}_2\text{CH}(\text{CH}_3)-$
<i>t</i> -Bu	<i>tert</i> -butyl group, $(\text{CH}_3)_3\text{C}-$
cm	centimeter
cm^{-1}	wavenumber, or reciprocal centimeter
D	stereochemical designation of carbohydrates and amino acids
DCC	dicyclohexylcarbodiimide, $\text{C}_6\text{H}_{11}-\text{N}=\text{C}=\text{N}-\text{C}_6\text{H}_{11}$
δ	chemical shift in ppm downfield from TMS
Δ	symbol for heat; also symbol for change
ΔH	heat of reaction
dm	decimeter (0.1 m)
DMF	dimethylformamide, $(\text{CH}_3)_2\text{NCHO}$
DMSO	dimethyl sulfoxide, $(\text{CH}_3)_2\text{SO}$
DNA	deoxyribonucleic acid
DNP	dinitrophenyl group, as in 2,4-DNP (2,4-dinitrophenylhydrazine)
(<i>E</i>)	entgegen, stereochemical designation of double bond geometry
E_{act}	activation energy
E1	unimolecular elimination reaction
E1cB	unimolecular elimination that takes place through a carbanion intermediate
E2	bimolecular elimination reaction
Et	ethyl group, CH_3CH_2-
g	gram
h ν	symbol for light
Hz	Hertz, or cycles per second (s^{-1})

<i>i</i> -	iso
IR	infrared
J	Joule
<i>J</i>	symbol for coupling constant
K	Kelvin temperature
K_a	acid dissociation constant
kJ	kilojoule
L	stereochemical designation of carbohydrates and amino acids
LAH	lithium aluminum hydride, LiAlH_4
Me	methyl group, CH_3 -
mg	milligram (0.001 g)
MHz	megahertz (10^6 s^{-1})
mL	milliliter (0.001 L)
mm	millimeter (0.001 m)
mp	melting point
μg	microgram (10^{-6} g)
m μ	millimicron (nanometer, 10^{-9} m)
MW	molecular weight
<i>n</i> -	normal, straight-chain alkane or alkyl group
ng	nanogram (10^{-9} gram)
nm	nanometer (10^{-9} meter)
NMR	nuclear magnetic resonance
-OAc	acetate group, $\text{-O}\overset{\text{O}}{\parallel}\text{CCH}_3$
PCC	pyridinium chlorochromate
Ph	phenyl group, $\text{-C}_6\text{H}_5$
pH	measure of acidity of aqueous solution
$\text{p}K_a$	measure of acid strength ($= -\log K_a$)
pm	picometer (10^{-12} m)
ppm	parts per million
<i>n</i> -Pr	<i>n</i> -propyl group, $\text{CH}_3\text{CH}_2\text{CH}_2$ -
<i>i</i> -Pr	isopropyl group, $(\text{CH}_3)_2\text{CH}$ -
<i>pro-R</i>	designation of a prochirality center
<i>pro-S</i>	designation of a prochirality center
R-	symbol for a generalized alkyl group
(<i>R</i>)	<i>rectus</i> , designation of chirality center


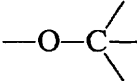

<i>Re</i> face	a face of a planar, sp^2 -hybridized carbon atom
RNA	ribonucleic acid
(<i>S</i>)	<i>sinister</i> , designation of chirality center
<i>sec</i> -	secondary
<i>Si</i> face	a face of a planar, sp^2 -hybridized carbon atom
S_N1	unimolecular substitution reaction
S_N2	bimolecular substitution reaction
<i>tert</i> -	tertiary
THF	tetrahydrofuran
TMS	tetramethylsilane nmr standard, $(CH_3)_4Si$
Tos	tosylate group, 
UV	ultraviolet
X-	halogen group ($-F$, $-Cl$, $-Br$, $-I$)
(<i>Z</i>)	<i>zusammen</i> , stereochemical designation of double bond geometry
	chemical reaction in direction indicated
	reversible chemical reaction
	resonance symbol
	curved arrow indicating direction of electron flow
\equiv	is equivalent to
$>$	greater than
$<$	less than
\approx	approximately equal to
$R-\text{>}$	indicates that the organic fragment shown is a part of a larger molecule
	single bond coming out of the plane of the paper
	single bond receding into the plane of the paper
	partial bond
$\delta+$, $\delta-$	partial charge
\ddagger	denoting the transition state

Infrared Absorption Frequencies

Functional Group		Frequency (cm ⁻¹)	Text Section
Alcohol	-O-H	3300–3600 (s)	17.11
		1050 (s)	
Aldehyde	-CO-H	2720, 2820 (m)	19.14
<i>aliphatic</i>		1725 (s)	
<i>aromatic</i>		1705 (s)	
Alkane			12.8
		2850–2960 (s)	
		800–1300 (m)	
Alkene			12.8
		3020–3100 (s)	
		1650–1670 (m)	
	RCH=CH ₂	910, 990 (m)	
	R ₂ C=CH ₂	890 (m)	
Alkyne	≡C-H	3300 (s)	12.8
	-C≡C-	2100–2260 (m)	
Alkyl bromide			12.8
		500–600 (s)	
Alkyl chloride			12.8
		600–800 (s)	

Amine, <i>primary</i>			24.10
		3400, 3500 (s)	
<i>secondary</i>		3350 (s)	
Ammonium salt			24.10
		2200–3000 (broad)	
Aromatic ring	Ar–H	3030 (m)	15.8
<i>monosubstituted</i>	Ar–R	690–710 (s) 730–770 (s)	
<i>o</i> -disubstituted		735–770 (s)	
<i>m</i> -disubstituted		690–710 (s) 810–850 (s)	
<i>p</i> -disubstituted		810–840 (s)	
Carboxylic acid	–O–H	2500–3300 (broad)	20.8
<i>associated</i>		1710 (s)	
<i>free</i>		1760 (s)	
Acid anhydride		1760, 1820 (s)	21.10
Acid chloride			21.10
<i>aliphatic</i>		1810 (s)	
<i>aromatic</i>		1770 (s)	
Amide			21.10
<i>aliphatic</i>		1810 (s)	
<i>aromatic</i>		1770 (s)	
<i>N</i> -substituted		1680 (s)	
<i>N,N</i> -disubstituted		1650 (s)	

890 Infrared Absorptions

Ester				21.10
<i>aliphatic</i>		1735 (s)		
<i>aromatic</i>		1720 (s)		
Ether		1050–1150 (s)		18.9
Ketone				19.14
<i>aliphatic</i>		1715 (s)		
<i>aromatic</i>		1690 (s)		
<i>6-memb. ring</i>		1715 (s)		
<i>5-memb. ring</i>		1750 (s)		
Nitrile				20.8
<i>aliphatic</i>	$\text{--C}\equiv\text{N}$	2250 (m)		
<i>aromatic</i>		2230 (m)		
Phenol	--O--H	3500 (s)		17.11

(s) = strong; (m) = medium intensity

Proton NMR Chemical Shifts

Type of Proton		Chemical Shift (δ)	Text Section
Alkyl, primary	$\text{R}-\text{CH}_3$	0.7–1.3	13.9
Alkyl, secondary	$\text{R}-\text{CH}_2-\text{R}$	1.2–1.4	13.9
Alkyl tertiary	$\text{R}_3\text{C}-\text{H}$	1.4–1.7	13.9
Allylic	$\begin{array}{c} \quad \quad \\ -\text{C}=\text{C}-\text{C}-\text{H} \\ \end{array}$	1.6–1.9	13.9
α to carbonyl	$\begin{array}{c} \text{O} \\ \\ -\text{C}-\text{C}-\text{H} \\ \end{array}$	2.0–2.3	19.14
Benzylic	$\begin{array}{c} \\ \text{Ar}-\text{C}-\text{H} \\ \end{array}$	2.3–3.0	15.8
Acetylenic	$\text{R}-\text{C}\equiv\text{C}-\text{H}$	2.5–2.7	13.9
Alkyl chloride	$\begin{array}{c} \\ \text{Cl}-\text{C}-\text{H} \\ \end{array}$	3.0–4.0	13.9
Alkyl bromide	$\begin{array}{c} \\ \text{Br}-\text{C}-\text{H} \\ \end{array}$	2.5–4.0	13.9
Alkyl iodide	$\begin{array}{c} \\ \text{I}-\text{C}-\text{H} \\ \end{array}$	2.0–4.0	13.9
Amine	$\begin{array}{c} \diagup \quad \diagdown \\ \text{N}-\text{C}-\text{H} \\ \end{array}$	2.2–2.6	24.10
Epoxide	$\begin{array}{c} \quad \text{O} \quad \text{H} \\ \diagdown \quad \diagup \\ \text{C}-\text{C} \\ \diagup \quad \diagdown \end{array}$	2.5–3.5	18.9
Alcohol	$\begin{array}{c} \\ \text{HO}-\text{C}-\text{H} \\ \end{array}$	3.5–4.5	17.11
Ether	$\begin{array}{c} \\ \text{RO}-\text{C}-\text{H} \\ \end{array}$	3.5–4.5	18.9
Vinylic	$\begin{array}{c} \quad \\ -\text{C}=\text{C}-\text{H} \end{array}$	5.0–6.0	13.9
Aromatic	$\text{Ar}-\text{H}$	6.5–8.0	15.8
Aldehyde	$\begin{array}{c} \text{O} \\ \\ \text{R}-\text{C}-\text{H} \end{array}$	9.7–10.0	19.14
Carboxylic acid	$\begin{array}{c} \text{O} \\ \\ \text{R}-\text{C}-\text{O}-\text{H} \end{array}$	11.0–12.0	20.8
Alcohol	$\text{R}-\text{O}-\text{H}$	3.5–4.5	17.11
Phenol	$\text{Ar}-\text{O}-\text{H}$	2.5–6.0	17.11

Nobel Prizes in Chemistry

- 1901 **Jacobus H. van't Hoff** (The Netherlands):
"for the discovery of laws of chemical dynamics and of osmotic pressure"
- 1902 **Emil Fischer** (Germany):
"for syntheses in the groups of sugars and purines"
- 1903 **Svante A. Arrhenius** (Sweden):
"for his theory of electrolytic dissociation"
- 1904 **Sir William Ramsey** (Britain):
"for the discovery of gases in different elements in the air and for the determination of their place in the periodic system"
- 1905 **Adolf von Baeyer** (Germany):
"for his researches on organic dyestuffs and hydroaromatic compounds"
- 1906 **Henri Moissan** (France):
"for his research on the isolation of the element fluorine and for placing at the service of science the electric furnace that bears his name"
- 1907 **Eduard Buchner** (Germany):
"for his biochemical researches and his discovery of cell-less formation"
- 1908 **Ernest Rutherford** (Britain):
"for his investigation into the disintegration of the elements and the chemistry of radioactive substances"
- 1909 **Wilhelm Ostwald** (Germany):
"for his work on catalysis and on the conditions of chemical equilibrium and velocities of chemical reactions"
- 1910 **Otto Wallach** (Germany):
"for his services to organic chemistry and the chemical industry by his pioneer work in the field of alicyclic substances"
- 1911 **Marie Curie** (France):
"for her services to the advancement of chemistry by the discovery of the elements radium and polonium"
- 1912 **Victor Grignard** (France):
"for the discovery of the so-called Grignard reagent, which has greatly helped in the development of organic chemistry"
- Paul Sabatier** (France):
"for his method of hydrogenating organic compounds in the presence of finely divided metals"

- 1913 **Alfred Werner** (Switzerland):
"for his work on the linkage of atoms in molecules by which he has thrown new light on earlier investigations and opened up new fields of research especially in inorganic chemistry"
- 1914 **Theodore W. Richards** (U.S.):
"for his accurate determinations of the atomic weights of a great number of chemical elements"
- 1915 **Richard M. Willstätter** (Germany):
"for his research on plant pigments, principally on chlorophyll"
- 1916 No award
- 1917 No award
- 1918 **Fritz Haber** (Germany):
"for the synthesis of ammonia from its elements, nitrogen and hydrogen"
- 1919 No award
- 1920 **Walther H. Nernst** (Germany):
"for his thermochemical work"
- 1921 **Frederick Soddy** (Britain):
"for his contributions to the chemistry of radioactive substances and his investigations into the origin and nature of isotopes"
- 1922 **Francis W. Aston** (Britain):
"for his discovery, by means of his mass spectrograph, of the isotopes of a large number of nonradioactive elements, as well as for his discovery of the whole-number rule"
- 1923 **Fritz Pregl** (Austria):
"for his invention of the method of microanalysis of organic substances"
- 1924 No award
- 1925 **Richard A. Zsigmondy** (Germany):
for his demonstration of the heterogeneous nature of colloid solutions, and for the methods he used, which have since become fundamental in modern colloid chemistry"
- 1926 **Theodor Svedberg** (Sweden):
"for his work on disperse systems"
- 1927 **Heinrich O. Wieland** (Germany):
"for his research on bile acids and related substances"
- 1928 **Adolf O. R. Windaus** (Germany):
"for his studies on the constitution of the sterols and their connection with the vitamins"
- 1929 **Arthur Harden** (Britain):
Hans von Euler-Chelpin (Sweden):
"for their investigation on the fermentation of sugar and of fermentative enzymes"

- 1930 **Hans Fischer** (Germany):
"for his researches into the constitution of hemin and chlorophyll, and especially for his synthesis of hemin"
- 1931 **Frederich Bergius** (Germany):
Carl Bosch (Germany):
"for their contributions to the invention and development of chemical high-pressure methods"
- 1932 **Irving Langmuir** (U.S.):
"for his discoveries and investigations in surface chemistry"
- 1933 No award
- 1934 **Harold C. Urey** (U.S.):
"for his discovery of heavy hydrogen"
- 1935 **Frederic Joliot** (France):
Irene Joliot-Curie (France):
"for their synthesis of new radioactive elements"
- 1936 **Peter J. W. Debye** (Netherlands/U.S.):
"for his contributions our knowledge of molecular structure through his investigations on dipole moments and on the diffraction of X rays and electrons in gases"
- 1937 **Walter N. Haworth** (Britain):
"for his researches into the constitution of carbohydrates and vitamin C"
- Paul Karrer** (Switzerland):
"for his researches into the constitution of carotenoids, flavins, and vitamins A and B"
- 1938 **Richard Kuhn** (Germany):
"for his work on carotenoids and vitamins"
- 1939 **Adolf F. J. Butenandt** (Germany):
"for his work on sex hormones"
- Leopold Ruzicka** (Switzerland):
"for his work on polymethylenes and higher terpenes"
- 1940 No award
- 1941 No award
- 1942 No award
- 1943 **Georg de Hevesy** (Hungary):
"for his work on the use of isotopes as tracer elements in researches on chemical processes"
- 1944 **Otto Hahn** (Germany):
"for his discovery of the fission of heavy nuclei"

- 1945 **Artturi I. Virtanen** (Finland):
"for his researches and inventions in agricultural and nutritive chemistry, especially for his fodder preservation method"
- 1946 **James B. Sumner** (U.S.):
"for his discovery that enzymes can be crystallized"
- John H. Northrop** (U.S.):
Wendell M. Stanley (U.S.):
for their preparation of enzymes and virus proteins in a pure form"
- 1947 **Sir Robert Robinson** (Britain):
"for his investigations on plant products of biological importance, particularly the alkaloids"
- 1948 **Arne W. K. Tiselius** (Sweden):
"for his researches on electrophoresis and adsorption analysis, especially for his discoveries concerning the complex nature of the serum proteins"
- 1949 **William F. Giauque** (U.S.):
"for his contributions in the field of chemical thermodynamics, particularly concerning the behavior of substances at extremely low temperatures"
- 1950 **Kurt Alder** (Germany):
Otto P. H. Diels (Germany):
"for their discovery and development of the diene synthesis"
- 1951 **Edwin M. McMillan** (U.S.):
Glenn T. Seaborg (U.S.):
"for their discoveries in the chemistry of the transuranium elements"
- 1952 **Archer J. P. Martin** (Britain):
Richard L. M. Synge (Britain):
"for their development of partition chromatography"
- 1953 **Hermann Staudinger** (Germany):
"for his discoveries in the field of macromolecular chemistry"
- 1954 **Linus C. Pauling** (U.S.):
"for his research into the nature of the chemical bond and its application to the elucidation of the structure of complex substances"
- 1955 **Vincent du Vigneaud** (U.S.):
"for his work on biochemically important sulfur compounds, especially for the first synthesis of a polypeptide hormone"
- 1956 **Sir Cyril N. Hinshelwood** (Britain):
Nikolai N. Semenov (U.S.S.R.):
"for their research in clarifying the mechanisms of chemical reactions in gases"
- 1957 **Sir Alexander R. Todd** (Britain):
"for his work on nucleotides and nucleotide coenzymes"

- 1958 **Frederick Sanger** (Britain):
"for his work on the structure of proteins, particularly insulin"
- 1959 **Jaroslav Heyrovsky** (Czechoslovakia):
"for his discovery and development of the polarographic method of analysis"
- 1960 **Willard F. Libby** (U.S.):
"for his method to use carbon-14 for age determination in archaeology, geology, geophysics, and other branches of science"
- 1961 **Melvin Calvin** (U.S.):
"for his research on the carbon dioxide assimilation in plants"
- 1962 **John C. Kendrew** (Britain):
Max F. Perutz (Britain):
"for their studies of the structures of globular proteins"
- 1963 **Giulio Natta** (Italy):
Karl Ziegler (Germany):
"for their work in the controlled polymerization of hydrocarbons through the use of organometallic catalysts"
- 1964 **Dorothy C. Hodgkin** (Britain):
"for her determinations by X-ray techniques of the structures of important biochemical substances, particularly vitamin B₁₂ and penicillin"
- 1965 **Robert B. Woodward** (U.S.):
"for his outstanding achievements in the 'art' of organic synthesis"
- 1966 **Robert S. Mulliken** (U.S.):
"for his fundamental work concerning chemical bonds and the electronic structure of molecules by the molecular orbital method"
- 1967 **Manfred Eigen** (Germany):
Ronald G. W. Norrish (Britain):
George Porter (Britain):
"for their studies of extremely fast chemical reactions, effected by disturbing the equilibrium with very short pulses of energy"
- 1968 **Lars Onsager** (U.S.):
"for his discovery of the reciprocal relations bearing his name, which are fundamental for the thermodynamics of irreversible processes"
- 1969 **Sir Derek H. R. Barton** (Britain):
Odd Hassel (Norway):
"for their contributions to the development of the concept of conformation and its application in chemistry"
- 1970 **Luis F. Leloir** (Argentina):
"for his discovery of sugar nucleotides and their role in the biosynthesis of carbohydrates"

- 1971 **Gerhard Herzberg** (Canada):
"for his contributions to the knowledge of electronic structure and geometry of molecules, particularly free radicals"
- 1972 **Christian B. Anfinsen** (U.S.):
"for his work on ribonuclease, especially concerning the connection between the amino acid sequence and the biologically active conformation"
- Stanford Moore** (U.S.):
William H. Stein (U.S.):
"for their contribution to the understanding of the connection between chemical structure and catalytic activity of the active center of the ribonuclease molecule"
- 1973 **Ernst Otto Fischer** (Germany):
Geoffrey Wilkinson (Britain):
"for their pioneering work, performed independently, on the chemistry of the organo-metallic sandwich compounds"
- 1974 **Paul J. Flory** (U.S.):
"for his fundamental achievements, both theoretical and experimental, in the physical chemistry of macromolecules"
- 1975 **John Cornforth** (Australia/Britain):
"for his work on the stereochemistry of enzyme-catalyzed reactions"
- Vladimir Prelog** (Yugoslavia/Switzerland):
"for his work on the stereochemistry of organic molecules and reactions"
- 1976 **William N. Lipscomb** (U.S.):
"for his studies on the structures of boranes illuminating problems of chemical bonding"
- 1977 **Ilya Prigogine** (Belgium):
"for his contributions to nonequilibrium thermodynamics, particularly the theory of dissipative structures"
- 1978 **Peter Mitchell** (Britain):
"for his contribution to the understanding of biological energy transfer through the formulation of the chemiosmotic theory"
- 1979 **Herbert C. Brown** (U.S.):
"for his application of boron compounds to synthetic organic chemistry"
- Georg Wittig** (Germany):
"for developing phosphorus reagents, presently bearing his name"
- 1980 **Paul Berg** (U.S.):
"for his fundamental studies of the biochemistry of nucleic acids, with particular regard to recombinant DNA"
- Walter Gilbert** (U.S.)
Frederick Sanger (Britain):
"for their contributions concerning the determination of base sequences in nucleic acids"

- 1981 **Kenichi Fukui** (Japan)
Roald Hoffmann (U.S.):
for their theories, developed independently, concerning the course of chemical reactions"
- 1982 **Aaron Klug** (Britain):
"for his development of crystallographic electron microscopy and his structural elucidation of biologically important nucleic acid – protein complexes"
- 1983 **Henry Taube** (U.S.):
"for his work on the mechanisms of electron transfer reactions, especially in metal complexes"
- 1984 **R. Bruce Merrifield** (U.S.):
"for his development of methodology for chemical synthesis on a solid matrix"
- 1985 **Herbert A. Hauptman** (U.S.):
Jerome Karle (U.S.):
"for their outstanding achievements in the development of direct methods for the determination of crystal structures"
- 1986 **John C. Polanyi** (Canada):
"for his pioneering work in the use of infrared chemiluminescence in studying the dynamics of chemical reactions"
- Dudley R. Herschbach** (U.S.):
Yuan T. Lee (U.S.):
"for their contributions concerning the dynamics of chemical elementary processes"
- 1987 **Donald J. Cram** (U.S.):
Jean-Marie Lehn (France):
Charles J. Pedersen (U.S.):
"for their development and use of molecules with structure-specific interactions of high selectivity"
- 1988 **Johann Deisenhofer** (Germany):
Robert Huber (Germany):
Hartmut Michel (Germany):
"for their determination of the structure of the photosynthetic reaction center of bacteria"
- 1989 **Sidney Altman** (U.S.):
Thomas R. Cech (U.S.):
"for their discovery of catalytic properties of RNA"
- 1990 **Elias J. Corey** (U.S.):
"for his development of the theory and methodology of organic synthesis"
- 1991 **Richard R. Ernst** (Switzerland):
"for his contributions to the development of the methodology of high resolution NMR spectroscopy"

- 1992 **Rudolph A. Marcus** (U.S.):
"for his contributions to the theory of electron-transfer reactions in chemical systems"
- 1993 **Kary B. Mullis** (U.S.):
"for his development of the polymerase chain reaction"
- Michael Smith** (Canada):
"for his fundamental contributions to the establishment of oligonucleotide-based site-directed mutagenesis and its development for protein studies"
- 1994 **George A Olah** (U.S.):
"for pioneering research on carbocations and their role in the chemical reactions of hydrocarbons"
- 1995 **F. Sherwood Rowland** (U.S.)
Mario Molina (U.S.)
Paul Crutzen (Germany)
"for their work in atmospheric chemistry, particularly concerning the formation and decomposition of ozone"
- 1996 **Robert F. Curl, Jr.** (U.S.)
Harold W. Kroto (U.K.)
Richard E. Smalley (U.S.)
"for their discovery of carbon atoms bound in the form of a ball (fullerenes)."
- 1997 **Paul D. Boyer** (U.S.)
John E. Walker (U.K.)
"for having elucidated the mechanism by which ATP synthase catalyzes the synthesis of adenosine triphosphate, the energy currency of living cells"
- Jens C. Skou** (Denmark)
"for his discovery of the ion-transporting enzyme $\text{Na}^+\text{--K}^+$ ATPase, the first molecular pump"
- 1998 **Walter Kohn** (U.S.)
John A. Pople (U.S.)
"to Walter Kohn for his development of the density-functional theory and to John Pople for his development of computational methods in quantum chemistry"
- 1999 **Ahmed H. Zewail** (Egypt, U.S.)
"for his studies of the transition states of chemical reactions using femtosecond spectroscopy."
- 2000 **Alan J. Heeger** (U.S.)
Alan G. MacDiarmid (U.S.)
Hideki Shirakawa (Japan)
"for opening and developing the important new field of electrically conductive polymers"
- 2001 **William S. Knowles** (U.S.)
Ryoji Noyori (Japan)
K. Barry Sharpless (U.S.)
"for their work on chirally catalysed hydrogenation and oxidation reactions"

- 2002 **John B. Fenn** (U.S.)
Koichi Tanaka (Japan)
"for their development of soft desorption ionisation methods for mass spectrometric analyses of biological macromolecules"
- Kurt Wüthrich** (Switzerland)
"for his development of nuclear magnetic resonance spectroscopy for determining the three-dimensional structure of biological macromolecules in solution"
- 2003 **Peter Agre** (U.S.)
"for the discovery of water channels in cell membranes"
Roderick MacKinnon (U.S.)
"for structural and mechanistic studies of ion channels in cell membranes"
- 2004 **Aaron Ciechanover** (Israel)
Avram Hershko (Israel)
Irwin Rose (U.S.)
"for the discovery of ubiquitin-mediated protein degradation"
- 2005 **Yves Chauvin** (France)
Robert H. Grubbs (U.S.)
Richard R. Schrock (U.S.)
"for the development of the metathesis method in organic synthesis"
- 2006 **Roger D. Kornberg** (U.S.)
"for his studies of the molecular basis of eukaryotic transcription"

<p>Answers to Multiple-Choice Questions in Review Units 1–12</p>

Review Unit 1:	1. d 2. b 3. a 4. c 5. d 6. b 7. a 8. d 9. a 10. c
Review Unit 2:	1. c 2. a 3. d 4. c 5. d 6. b 7. a 8. b 9. c 10. b
Review Unit 3:	1. c 2. b 3. a 4. b 5. a 6. d 7. d 8. c 9. d 10. b
Review Unit 4:	1. d 2. b 3. c 4. c 5. b 6. a 7. d 8. c 9. a 10. d
Review Unit 5:	1. b 2. b 3. c 4. a 5. d 6. d 7. c 8. a 9. b 10. c 11. c
Review Unit 6:	1. c 2. a 3. b 4. d 5. c 6. c 7. a 8. b 9. d 10. a
Review Unit 7:	1. d 2. c 3. b 4. b 5. a 6. d 7. b 8. a 9. c 10. c
Review Unit 8:	1. a 2. b 3. a 4. b 5. c 6. a 7. c 8. d 9. c 10. b
Review Unit 9:	1. b 2. d 3. a 4. a 5. c 6. d 7. b 8. c 9. b 10. d
Review Unit 10:	1. b 2. a 3. d 4. b 5. c 6. a 7. d 8. b 9. a 10. d
Review Unit 11:	1. c 2. d 3. a 4. b 5. d 6. a 7. d 8. b 9. c 10. a
Review Unit 12:	1. d 2. a 3. c 4. c 5. a 6. d 7. b 8. a 9. b 10. c