Fundamentals of Organic Chemistry

CHEM 109

For Students of Health Colleges

Credit hrs.: (2+1)

King Saud University

College of Science, Chemistry Department

CHAPTER 7. CARBOXYLIC ACIDS AND THEIR DERIVATIVES

Learning Objectives

At the end of this chapter, students will able to:

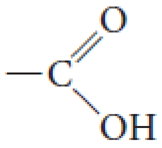
- Identify and name simple carboxylic acids.
- Recognize the properties (structure, physical and chemical properties) of carboxylic acid .
- Suggest preparation reactions from primary alcohols and from Grignard reagents and CO_2.
- Predict the product of the reduction of a carboxylic acid and give the reagents required to perform this reaction.
- Identify carboxylic acid derivatives as esters, amides, acid halides and acid anhydrides
- Predict the products that will be formed when a carboxylic acid derivative is treated with an alcohol or amine.
- Give the reagents required for the interconversion of carboxylic acid derivatives

Structure of Carboxylic Acids

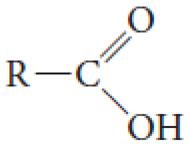
- **The functional group common to all carboxylic acids is the carboxyl group.**

  The name is a contraction of the parts: the carbonyl and hydroxyl groups.

- **The general formula for a carboxylic acid can be written in expanded or abbreviated forms.**

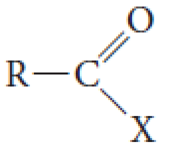


carboxyl group



or RCOOH or RCO_2H

three ways to represent a carboxylic acid



acid derivatives

- **Depending on whether an R or an Ar.** residue is attached to the carboxyl group; **Carboxylic acids are classified** as;
  - **Aliphatic Carboxylic Acids.**
  - **Aromatic Carboxylic Acids.**

$R-COOH$

Aliphatic acid

(R = H or alkyl)

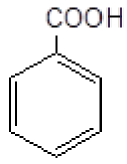
CH_3-COOH

Acetic acid

$Ar-COOH$

Aromatic acid

($R = C_6H_5$-)



Benzoic acid

- **Fatty acids.**

  Long straight-chain carboxylic acids with even numbers of carbons, which were first isolated from fats and waxes.

Nomenclature of Carboxylic Acids

Common Names

- The **common names** of carboxylic acids all end in *-ic acid*.
- These names usually come from some Latin or Greek word that indicates the original source of the acid.
- **Common name**, substituents are located with Greek letters, beginning with the α–carbon atom.

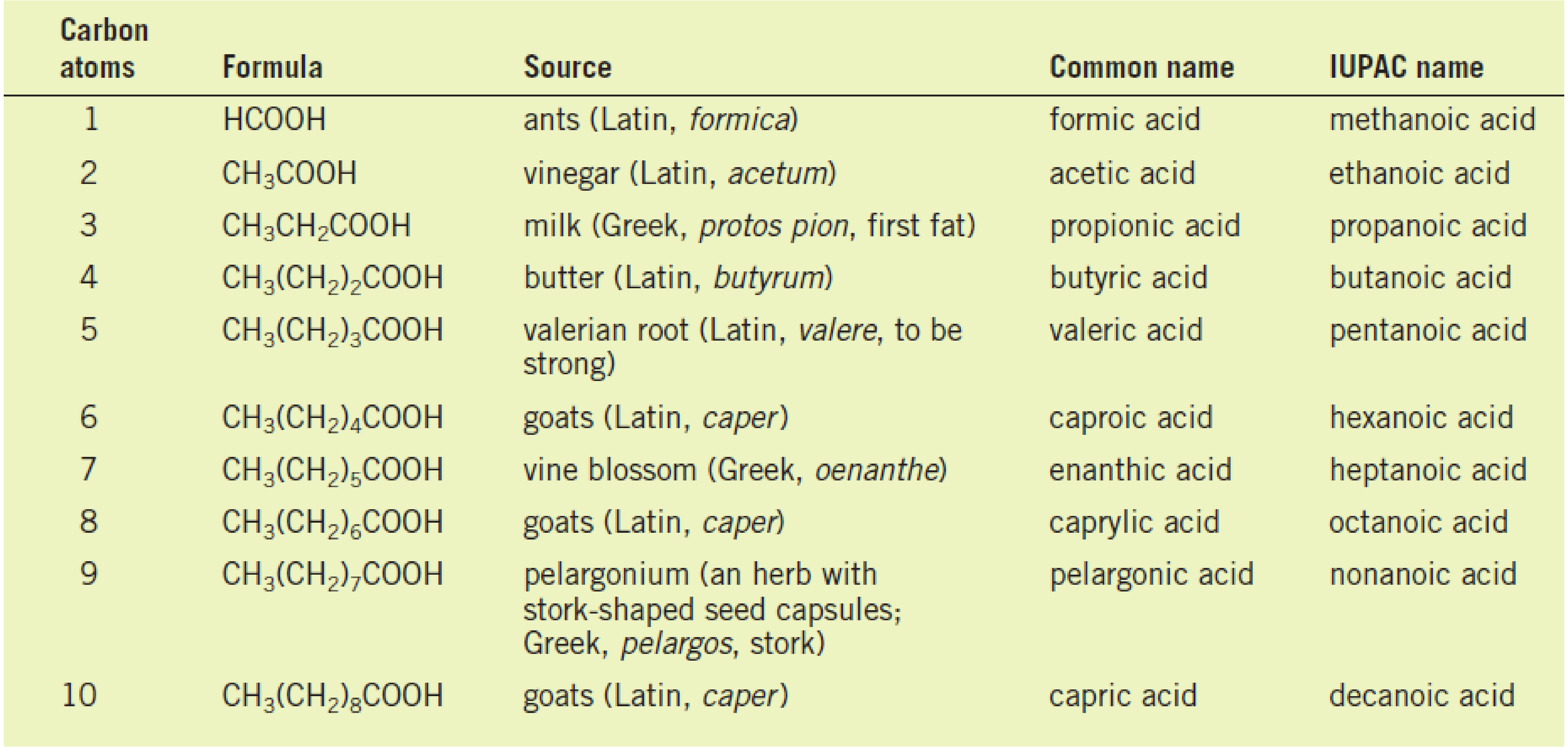
IUPAC System

- We replace the final e in the name of the corresponding alkane with the suffix *-oic* and add the word *acid*.

Alkane- e + *oic acid* = *Alkanoic acid*

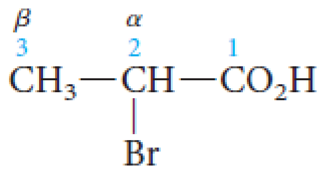
- **IUPAC system**, the chain is numbered beginning with the carboxyl carbon atom, and substituents are located in the usual way.

Nomenclature of Carboxylic Acids



Carbon atoms	Formula	Source	Common name	IUPAC name
1	$HCOOH$	ants (Latin, *formica*)	formic acid	methanoic acid
2	CH_3COOH	vinegar (Latin, *acetum*)	acetic acid	ethanoic acid
3	CH_3CH_2COOH	milk (Greek, *protos pion*, first fat)	propionic acid	propanoic acid
4	$CH_3(CH_2)_2COOH$	butter (Latin, *butyrum*)	butyric acid	butanoic acid
5	$CH_3(CH_2)_3COOH$	valerian root (Latin, *valere*, to be strong)	valeric acid	pentanoic acid
6	$CH_3(CH_2)_4COOH$	goats (Latin, *caper*)	caproic acid	hexanoic acid
7	$CH_3(CH_2)_5COOH$	vine blossom (Greek, *oenanthe*)	enanthic acid	heptanoic acid
8	$CH_3(CH_2)_6COOH$	goats (Latin, *caper*)	caprylic acid	octanoic acid
9	$CH_3(CH_2)_7COOH$	pelargonium (an herb with stork-shaped seed capsules; Greek, *pelargos*, stork)	pelargonic acid	nonanoic acid
10	$CH_3(CH_2)_8COOH$	goats (Latin, *caper*)	capric acid	decanoic acid

Nomenclature of Carboxylic Acids

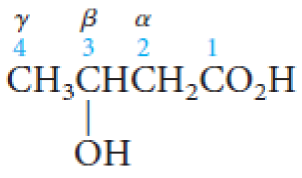


$\overset{\beta}{\overset{3}{CH_3}}-\underset{\mathrm{Br}}{\overset{\alpha}{\overset{2}{CH}}}-\overset{1}{CO_2H}$

2-bromopropanoic acid
(α-bromopropionic acid)

$\overset{3}{CH_2}=\overset{2}{C}H\overset{1}{C}O_2H$

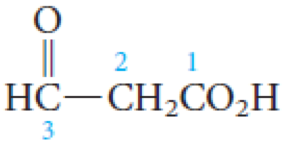
propenoic acid
(acrylic acid)



$\overset{\gamma}{\overset{4}{CH_3}}\underset{\mathrm{OH}}{\overset{\beta}{\overset{3}{CH}}}\overset{\alpha}{\overset{2}{CH_2}}\overset{1}{CO_2H}$

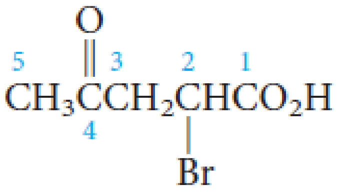
3-hydroxybutanoic acid
(β-hydroxybutyric acid)

- **The carboxyl group has priority over alcohol, aldehyde, or ketone** functionality in naming.
- The prefix **oxo-** is used to locate the carbonyl group of the aldehyde or ketone.



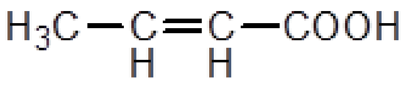
$\underset{3}{\overset{O}{\overset{\|}{HC}}}-\overset{2}{CH_2}\overset{1}{CO_2H}$

3-oxopropanoic acid



$\overset{5}{CH_3}\underset{4}{\overset{O}{\overset{\|}{C}}}\overset{3}{CH_2}\underset{\mathrm{Br}}{\overset{2}{CH}}\overset{1}{CO_2H}$

2-bromo-4-oxopentanoic acid



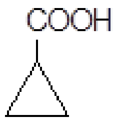
$H_3C-\underset{H}{C}=\underset{H}{C}-COOH$

But-2-enoic acid
(2-Butenoic acid)

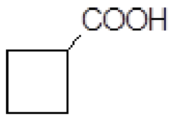
Nomenclature of Carboxylic Acids

- **Cycloalkane carboxylic acid**

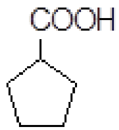
When the carboxyl group is attached to a ring, the ending ***-carboxylic acid*** *is added to the name of the parent* ***cycloalkane****. (****i.e.*** ***Cycloalkanecarboxylic acid****)*



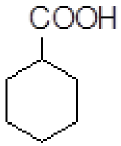
Cyclopropanecarboxylic acid



Cyclobutanecarboxylic acid

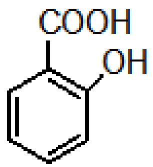


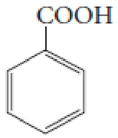
Cyclopentanecarboxylic acid

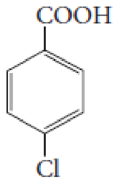


Cyclohexanecarboxylic acid

- **Aromatic acids** are named by attaching the suffix -*oic acid* or *-ic acid* to an appropriate prefix derived from the aromatic hydrocarbon.







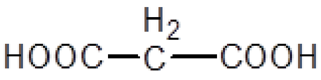
Common name:	Salicylic acid	benzoic acid	*p*-chlorobenzoic acid
IUPAC name :	2-Hydroxybenzenecarboxylic acid	(benzenecarboxylic acid)	(4-chlorobenzenecarboxylic acid)

Nomenclature of Carboxylic Acids

- **Dicarboxylic acids** (*acids that contain two carboxyl groups*) are known almost exclusively by their common names.

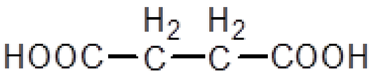
$HOOC-COOH$

Oxalic acid



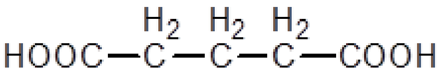
$HOOC-\overset{H_2}{C}-COOH$

Malonic acid



$HOOC-\overset{H_2}{C}-\overset{H_2}{C}-COOH$

Succinic acid



$HOOC-\overset{H_2}{C}-\overset{H_2}{C}-\overset{H_2}{C}-COOH$

Glutaric acid

- **Aliphatic dicarboxylic acids** are given the suffix *-dioic acid* in the IUPAC system.

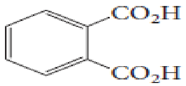
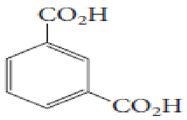
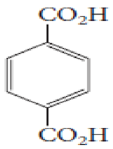
$H\overset{1}{O_2C}-\overset{2}{C}H_2\overset{3}{C}H_2-\overset{4}{C}O_2H$

butanedioic acid

$HO_2C-C\equiv C-CO_2H$

butynedioic acid

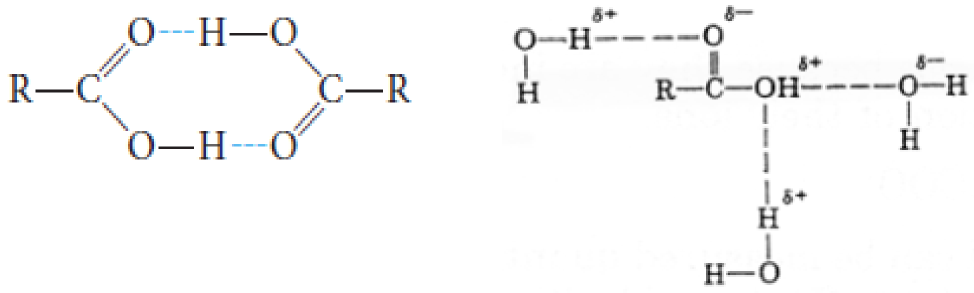
- The three **benzenedicarboxylic acids** are generally known by their common names.

			
Common name:	phthalic acid	isophthalic acid	terephthalic acid
IUPAC name:	Benzene-1,2-dicarboxylic acid	Benzene-1,3-dicarboxylic acid	Benzene-1,4-dicarboxylic acid

Physical Properties of Acids

- **Carboxylic acids** are polar and they form hydrogen bonds with themselves or with other molecules.

- **Carboxylic acids form dimer**, with the individual units held together by two hydrogen bonds between electron-rich oxygens and electron-poor hydrogens.



Boiling Points

Therefore, they have high boiling points for their molecular weights-higher even those of comparable alcohols.

Solubility in water

Hydrogen bonding also explains the water solubility of the lower molecular weight carboxylic acids.

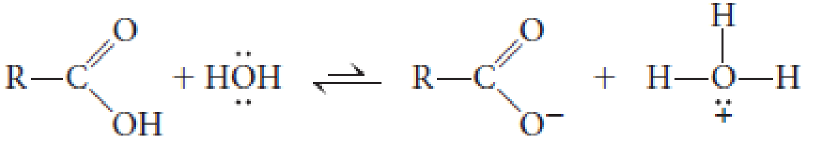
- The first four aliphatic acids (formic through butyric) are completely miscible in water.
- Aromatic acids are insoluble in water.

Physical Properties of Acids

Structure	Name	Mol. Wt.	b.p. °C	Solubility in H_2O at 25°C
HCOOH CH_3CH_2OH	Formic acid Ethyl alcohol	46 46	100 78	Very soluble Very soluble
CH_3COOH $CH_3CH_2CH_2OH$	Acetic acid *n*-Propyl alcohol	60 60	118 97	Very soluble Very soluble
$CH_3(CH_2)_3COOH$ $CH_3(CH_2)_4CH2OH$	Valeric acid *n*-Hexyl alcohol	102 102	187 156	4.0 g/100 g H_2O 0.6 g/100 g H_2O
Ph-COOH Ph-CH_2CH_2OH	Benzoic acid 3-Phenylethanol	122 122	250 250	Insoluble Insoluble

Acid Strength and Structure

- **Carboxylic acids** (RCOOH) dissociate in water, yielding a carboxylate anion ($RCOO^-$) and hydronium ion.

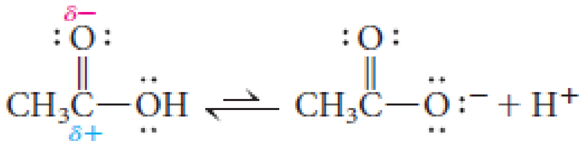


Why carboxylic acids are more acidic than alcohols?

- ➢ In ethoxide ion, the negative charge is localized on a single oxygen atom.
- ➢ In acetate ion, on the other hand, the negative charge can be delocalized through resonance.

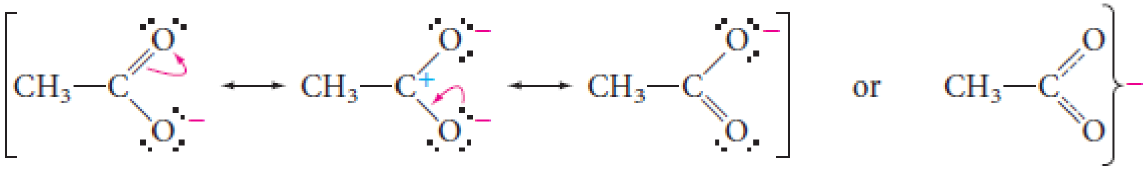
$$CH_3CH_2\ddot{\underset{..}{O}}H \rightleftharpoons CH_3CH_2\ddot{\underset{..}{O}}:^- + H^+$$

ethoxide ion



$$CH_3\overset{\overset{\delta-}{:O:}}{\underset{\delta+}{\overset{\|}{C}}}-\ddot{\underset{..}{O}}H \rightleftharpoons CH_3\overset{:O:}{\overset{\|}{C}}-\ddot{\underset{..}{O}}:^- + H^+$$

acetate ion

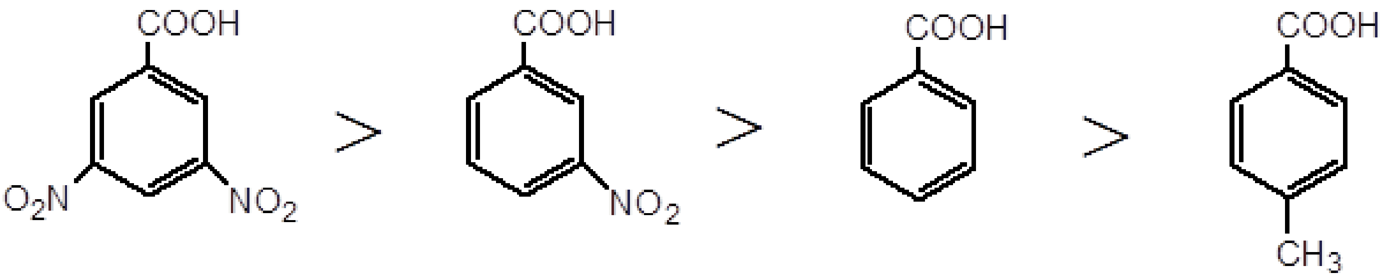


resonance in a carboxylate ion (acetate ion)

Acid Strength and Structure

Effect of Structure on Acidity; the Inductive Effect

- Acidities can vary depending on what other groups are attached to the molecule.
- Recall that *electron-withdrawing groups (-I) enhance acidity*, *and* *electron-releasing groups (+I) reduce acidity*.
  This effect relays charge through bonds, by displacing bonding electrons toward electronegative atoms, or away from electropositive atoms.



Acid Strength and Structure

Effect of Structure on Acidity; the Inductive Effect

- **Formic acid is a substantially stronger acid than acetic acid.**

  This suggests that the methyl group is more electron-releasing (hence anion-destabilizing and acidity-reducing) than hydrogen.

$$HCOOH > CH_3COOH > CH_3CH_2COOH > CH_3CH_2CH_2COOH$$

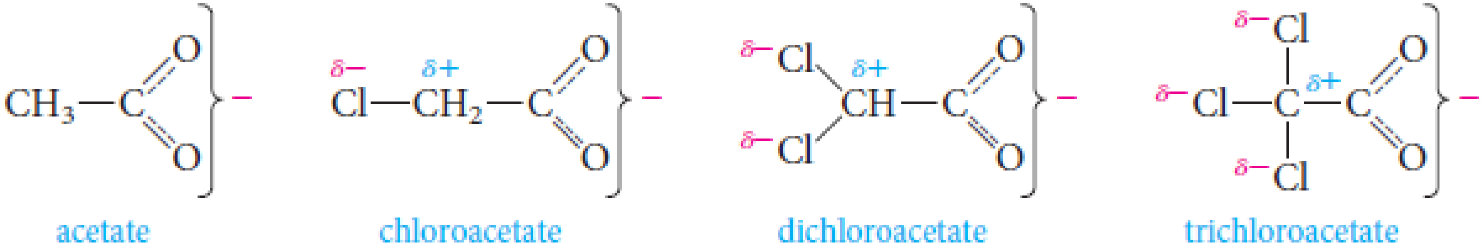
- **Example:** acetic acid with those of mono-, di-, and trichloroacetic acids.

  Comparison of acid strengths of acetic Acid and chlorinated acetic acids

$$Cl_3CCOOH > Cl_2CHCOOH > ClCH_2COOH > CH_3COOH$$

Acid Strength and Structure

Effect of Structure on Acidity; the Inductive Effect

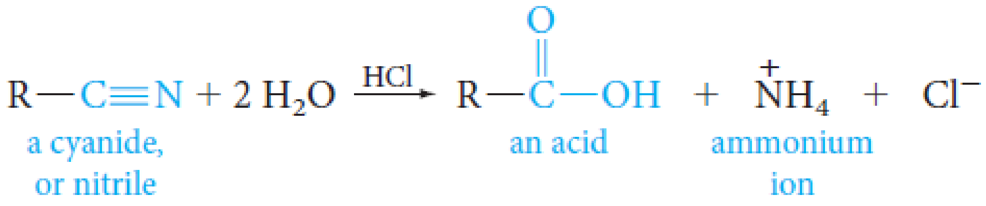


The more chlorines, the greater the effect and the greater the strength of the acid.

1) Hydrolysis of Cyanides (Nitriles)

- **The reaction requires either acid or base.**

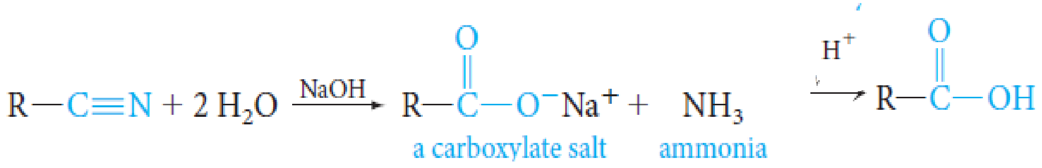
- **In acid**, the nitrogen atom of the cyanide is converted to an ammonium ion.



$$R{-}C{\equiv}N + 2\,H_2O \xrightarrow{HCl} R{-}\overset{\overset{\displaystyle O}{\|}}{C}{-}OH + \overset{+}{N}H_4 + Cl^-$$

a cyanide, or nitrile — an acid — ammonium ion

- **In base**, the nitrogen atom is converted to ammonia and the organic product is the carboxylate salt, which must be neutralized in a separate step to give the acid.



$$R{-}C{\equiv}N + 2\,H_2O \xrightarrow{NaOH} R{-}\overset{\overset{\displaystyle O}{\|}}{C}{-}O^-Na^+ + NH_3 \xrightarrow{H^+} R{-}\overset{\overset{\displaystyle O}{\|}}{C}{-}OH$$

a carboxylate salt — ammonia

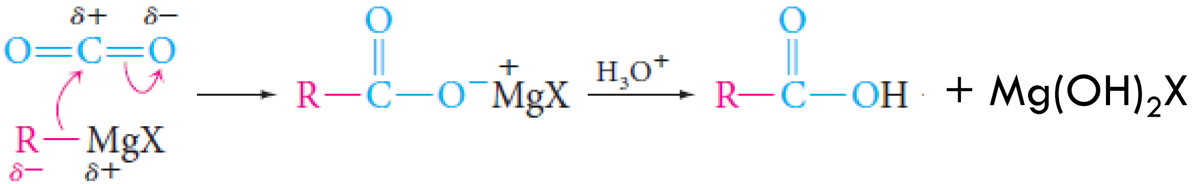
- **Alkyl cyanides** are generally made from the corresponding alkyl halide.

$$CH_3CH_2CH_2Br \xrightarrow{NaCN} CH_3CH_2CH_2CN \xrightarrow[H^+]{H_2O} CH_3CH_2CH_2CO_2H + NH_4^+$$

propyl bromide (1-bromopropane) — butyronitrile (butanenitrile) — butyric acid (butanoic acid)

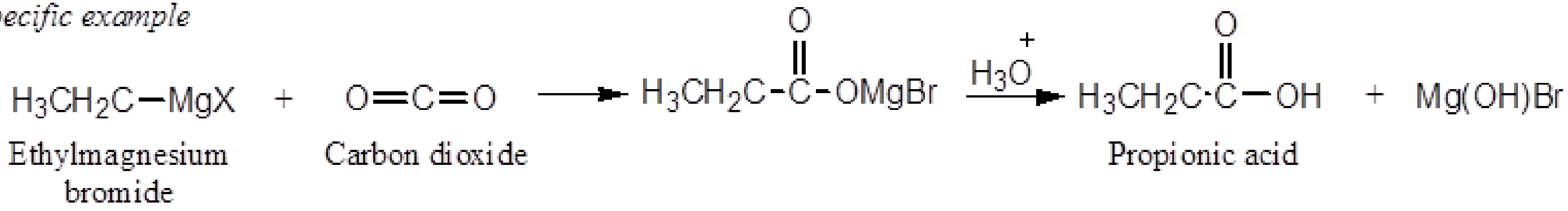
2) Reaction of Grignard Reagents with Carbon Dioxide (Carbonation of Grignard Reagent)

- **Grignard reagents** add to the carbonyl group of carbon dioxide to give acids, after protonation of the intermediate carboxylate salt with a mineral acid like aqueous HCl.
- **The acid obtained has one more carbon atom** (*the reaction provides a way to increase the length of a carbon chain*).



$$\overset{\delta+}{\ } \ O{=}C{=}O + \overset{\delta-}{R}{-}\overset{\delta+}{MgX} \longrightarrow R{-}\overset{O}{\overset{\|}{C}}{-}O^{-}\overset{+}{Mg}X \xrightarrow{H_3O^+} R{-}\overset{O}{\overset{\|}{C}}{-}OH + Mg(OH)_2X$$

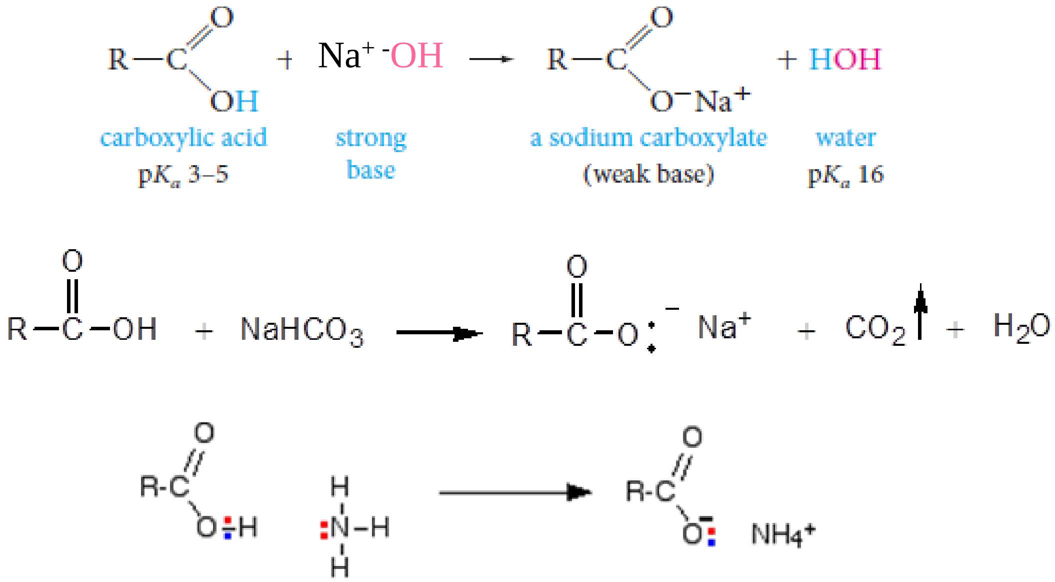
Specific example



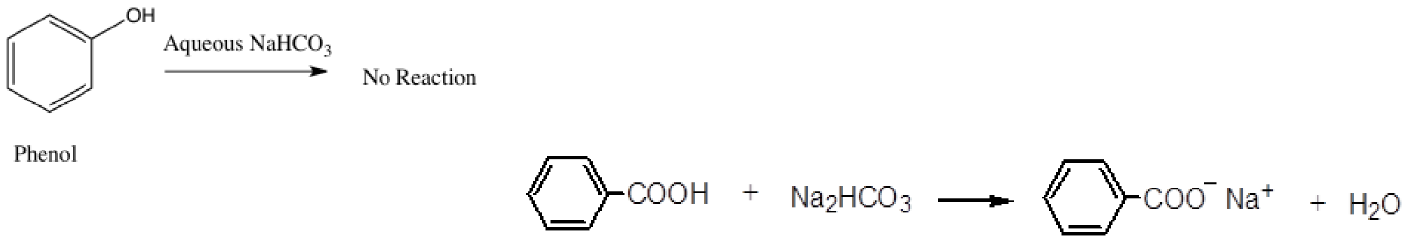
$$\underset{\text{Ethylmagnesium bromide}}{H_3CH_2C{-}MgX} + \underset{\text{Carbon dioxide}}{O{=}C{=}O} \longrightarrow H_3CH_2C{-}\overset{O}{\overset{\|}{C}}{-}OMgBr \xrightarrow{H_3\overset{+}{O}} \underset{\text{Propionic acid}}{H_3CH_2C{-}\overset{O}{\overset{\|}{C}}{-}OH} + Mg(OH)Br$$

1) Reactions with Bases: Salt Formation

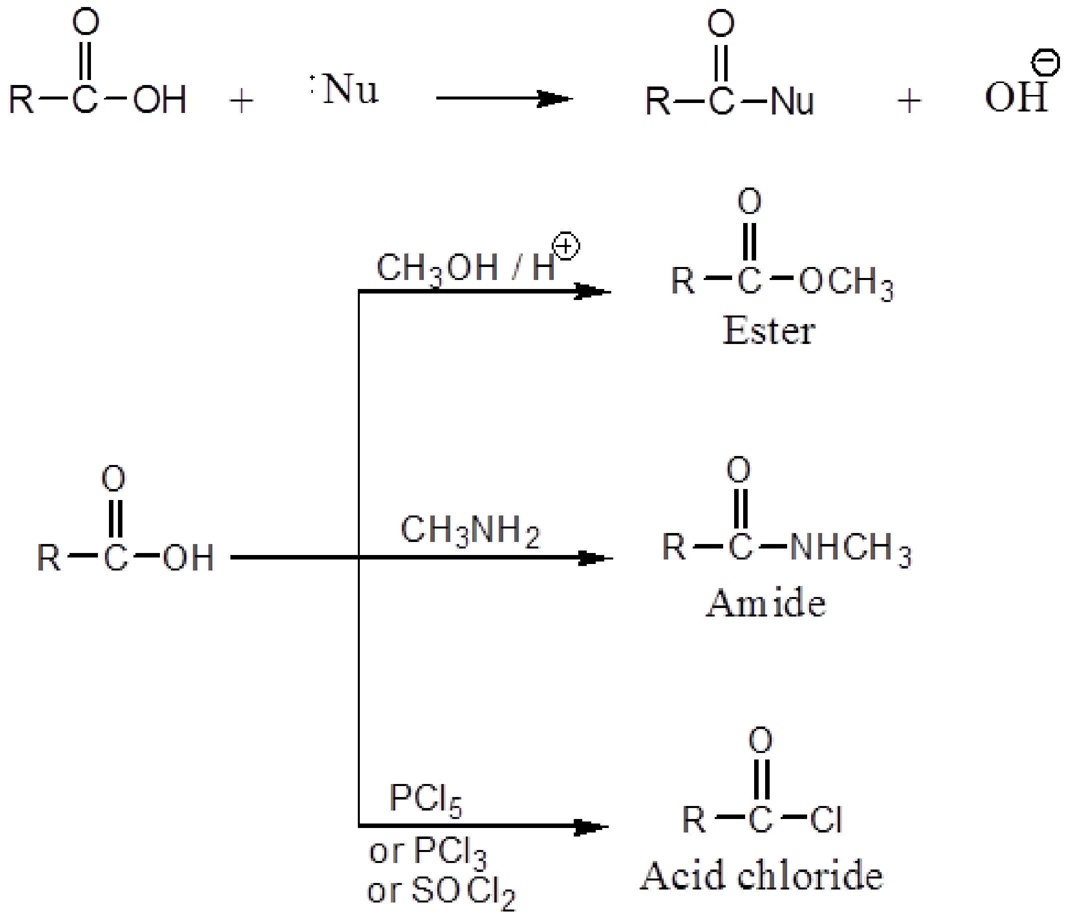
- Carboxylic acids, when treated with a strong base, form carboxylate salts.



- Examples.



2) Nucleophilic Substitution Reactions



$$R-\overset{O}{\overset{\|}{C}}-OH + :Nu \longrightarrow R-\overset{O}{\overset{\|}{C}}-Nu + OH^{\ominus}$$

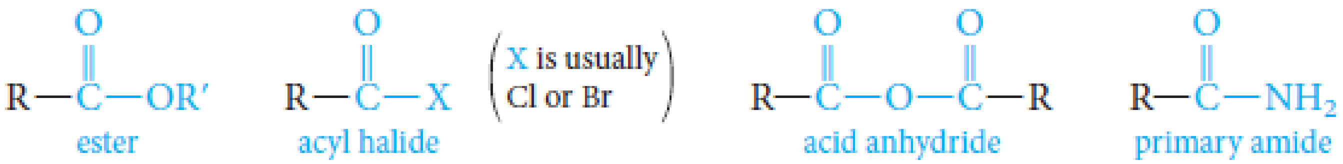
$$R-\overset{O}{\overset{\|}{C}}-OH \xrightarrow{CH_3OH\ /\ H^{\oplus}} R-\overset{O}{\overset{\|}{C}}-OCH_3$$

$$R-\overset{O}{\overset{\|}{C}}-OH \xrightarrow{CH_3NH_2} R-\overset{O}{\overset{\|}{C}}-NHCH_3$$

$$R-\overset{O}{\overset{\|}{C}}-OH \xrightarrow[\text{or } PCl_3 \text{ or } SOCl_2]{PCl_5} R-\overset{O}{\overset{\|}{C}}-Cl$$

Carboxylic Acid Derivatives

- **Carboxylic acid derivatives** are compounds in which the hydroxyl part of the carboxyl group is replaced by various other groups.



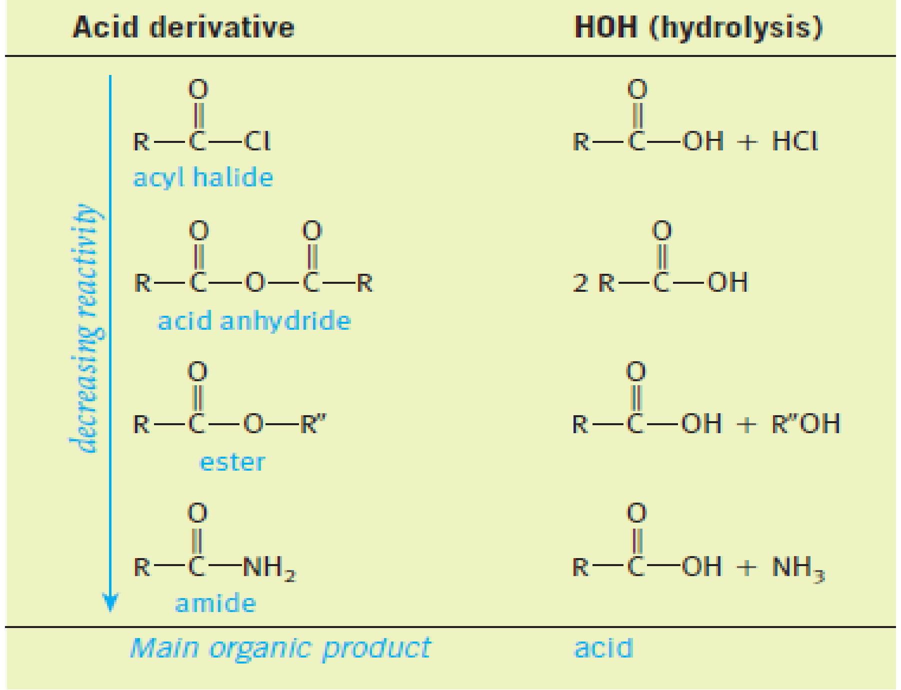
$\mathrm{R-\overset{O}{\overset{\|}{C}}-OR'}$ ester

$\mathrm{R-\overset{O}{\overset{\|}{C}}-X}$ acyl halide (X is usually Cl or Br)

$\mathrm{R-\overset{O}{\overset{\|}{C}}-O-\overset{O}{\overset{\|}{C}}-R}$ acid anhydride

$\mathrm{R-\overset{O}{\overset{\|}{C}}-NH_2}$ primary amide

- All acid derivatives can be hydrolyzed to the corresponding carboxylic acid.



Acid derivative	HOH (hydrolysis)
$\mathrm{R-\overset{O}{\overset{\|}{C}}-Cl}$ acyl halide	$\mathrm{R-\overset{O}{\overset{\|}{C}}-OH + HCl}$
$\mathrm{R-\overset{O}{\overset{\|}{C}}-O-\overset{O}{\overset{\|}{C}}-R}$ acid anhydride	$\mathrm{2\ R-\overset{O}{\overset{\|}{C}}-OH}$
$\mathrm{R-\overset{O}{\overset{\|}{C}}-O-R''}$ ester	$\mathrm{R-\overset{O}{\overset{\|}{C}}-OH + R''OH}$
$\mathrm{R-\overset{O}{\overset{\|}{C}}-NH_2}$ amide	$\mathrm{R-\overset{O}{\overset{\|}{C}}-OH + NH_3}$
Main organic product	acid

Acid Chloride

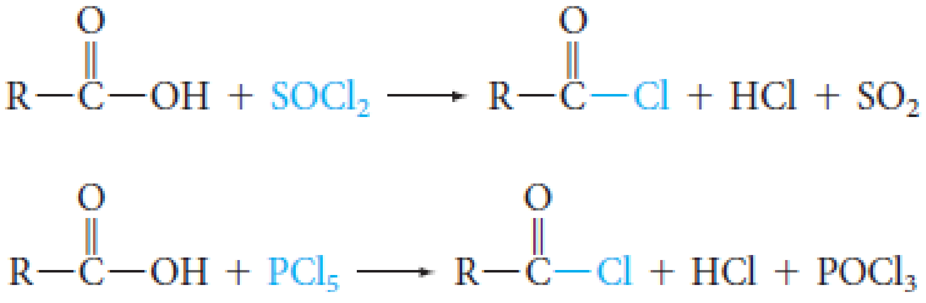
- **Acyl chlorides** have the general formula RCOCl.
- **Acyl chlorides** are more common and less expensive than bromides or iodides.
- **Nomenclature:**

  Acyl chlorides, or acid chlorides, are named by replacing the *-ic acid* ending of the parent acid by *-yl chloride*.

$CH_3-\overset{\overset{\displaystyle O}{\|}}{C}-Cl$ acetyl chloride $\quad CH_3\overset{\overset{\displaystyle O}{\|}}{C}-Cl$ acetyl chloride

- **Preparation:**

  They can be prepared from acids by reaction with thionyl chloride or phosphorous pentachloride.

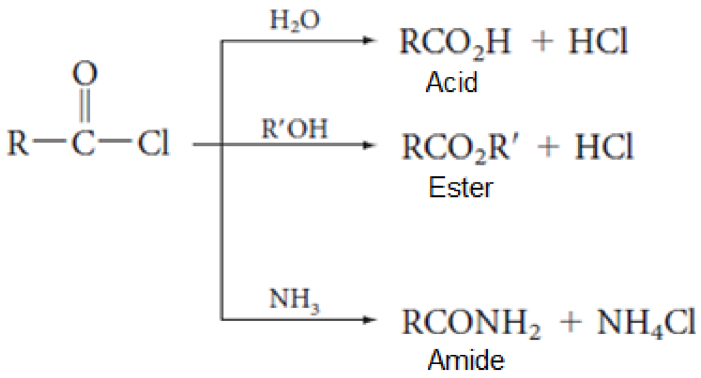


$$R-\overset{\overset{\displaystyle O}{\|}}{C}-OH + SOCl_2 \longrightarrow R-\overset{\overset{\displaystyle O}{\|}}{C}-Cl + HCl + SO_2$$

$$R-\overset{\overset{\displaystyle O}{\|}}{C}-OH + PCl_5 \longrightarrow R-\overset{\overset{\displaystyle O}{\|}}{C}-Cl + HCl + POCl_3$$

Acid Chloride

- **Reactions:** *They can react rapidly with most nucleophile.*



$$R-\overset{\overset{O}{\|}}{C}-Cl \xrightarrow{H_2O} RCO_2H + HCl$$

Acid

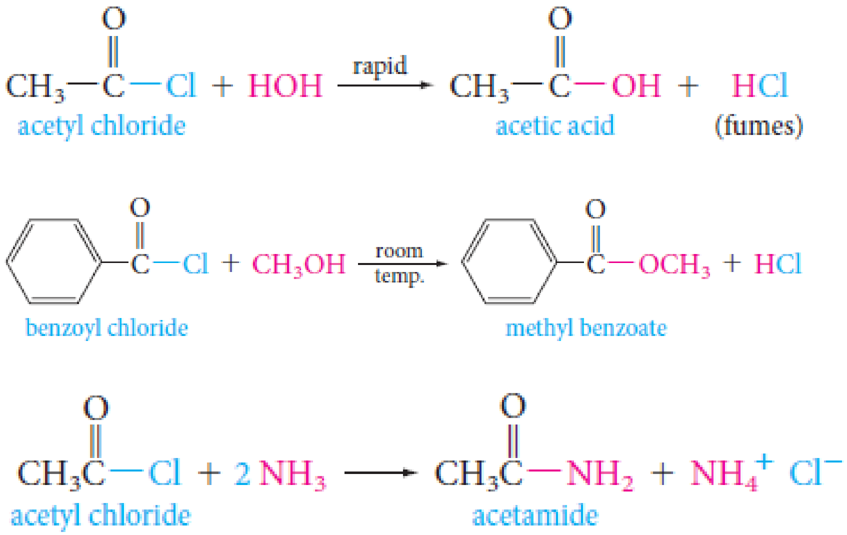
$$R-\overset{\overset{O}{\|}}{C}-Cl \xrightarrow{R'OH} RCO_2R' + HCl$$

Ester

$$R-\overset{\overset{O}{\|}}{C}-Cl \xrightarrow{NH_3} RCONH_2 + NH_4Cl$$

Amide

- **Examples:**



$$CH_3-\overset{\overset{O}{\|}}{C}-Cl + HOH \xrightarrow{\text{rapid}} CH_3-\overset{\overset{O}{\|}}{C}-OH + HCl$$

acetyl chloride, acetic acid, (fumes)

$$C_6H_5-\overset{\overset{O}{\|}}{C}-Cl + CH_3OH \xrightarrow[\text{temp.}]{\text{room}} C_6H_5-\overset{\overset{O}{\|}}{C}-OCH_3 + HCl$$

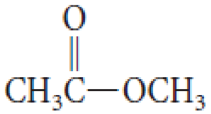
benzoyl chloride, methyl benzoate

$$CH_3\overset{\overset{O}{\|}}{C}-Cl + 2\,NH_3 \longrightarrow CH_3\overset{\overset{O}{\|}}{C}-NH_2 + NH_4^+\ Cl^-$$

acetyl chloride, acetamide

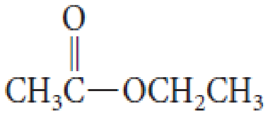
Esters

- **Esters** are derived from acids by replacing the –OH group by an –OR group and have the general formula R/COOR.
- **Nomenclature:**
  - They are named in a manner analogous to carboxylic acid salts.
  - The **R part of the –OR group is name first**, followed by the name of the acid, with the ***–ic acid*** ending changed to ***–ate***.



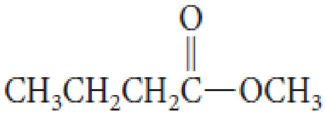
$CH_3C(=O)-OCH_3$

methyl acetate
(methyl ethanoate)



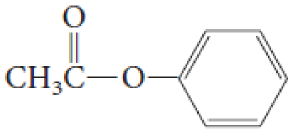
$CH_3C(=O)-OCH_2CH_3$

ethyl acetate
(ethyl ethanoate)

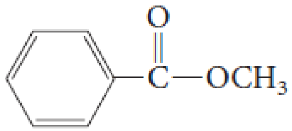


$CH_3CH_2CH_2C(=O)-OCH_3$

methyl butanoate
bp 102.3°C



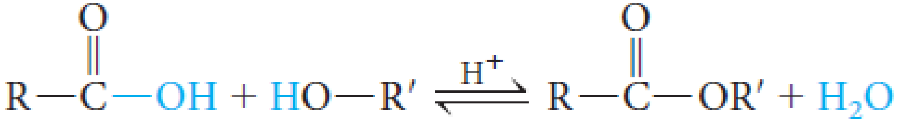
phenyl acetate



methyl benzoate

- **Preparation:**

When a carboxylic acid and an alcohol are heated in the presence of an acid catalyst (HCl or H_2SO_4), an equilibrium is established with the ester and water.

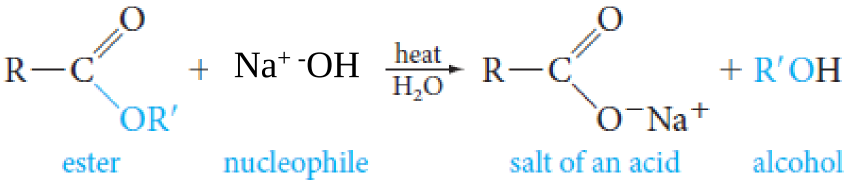


$$R-\overset{O}{\overset{\|}{C}}-OH + HO-R' \underset{}{\overset{H^+}{\rightleftharpoons}} R-\overset{O}{\overset{\|}{C}}-OR' + H_2O$$

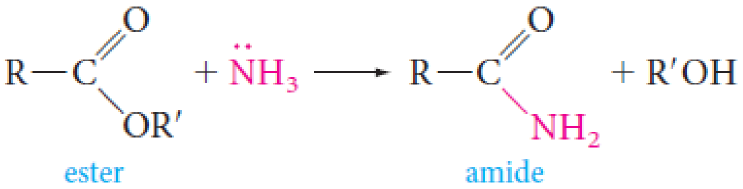
Esters

Reactions

- **Saponification;** esters are commonly hydrolyzed with base.



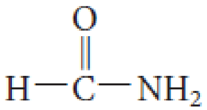
- Ammonia converts esters to **amides**.



Amides

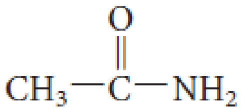
- **Amides** are the least reactive of the common carboxylic acid derivatives.
- Primary amides have general formula $RCONH_2$.
- **Nomenclature:**

  Amides are named by replacing the *–oic acid* ending of the acid name with the *–amide* ending, This will be either for the common or the IUPAC name.



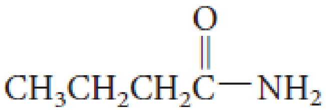
$\mathrm{H-\overset{O}{\overset{\|}{C}}-NH_2}$

formamide
(methanamide)



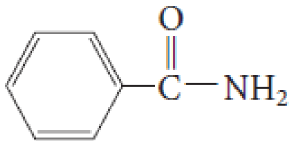
$\mathrm{CH_3-\overset{O}{\overset{\|}{C}}-NH_2}$

acetamide
(ethanamide)

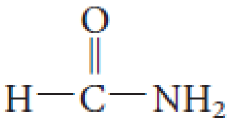


$\mathrm{CH_3CH_2CH_2\overset{O}{\overset{\|}{C}}-NH_2}$

butanamide

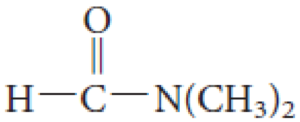


benzamide
(benzenecarboxamide)



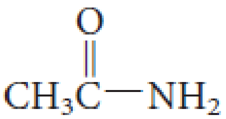
$\mathrm{H-\overset{O}{\overset{\|}{C}}-NH_2}$

formamide



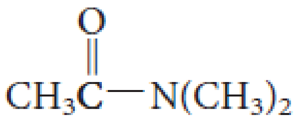
$\mathrm{H-\overset{O}{\overset{\|}{C}}-N(CH_3)_2}$

N,*N*-dimethylformamide



$\mathrm{CH_3\overset{O}{\overset{\|}{C}}-NH_2}$

acetamide

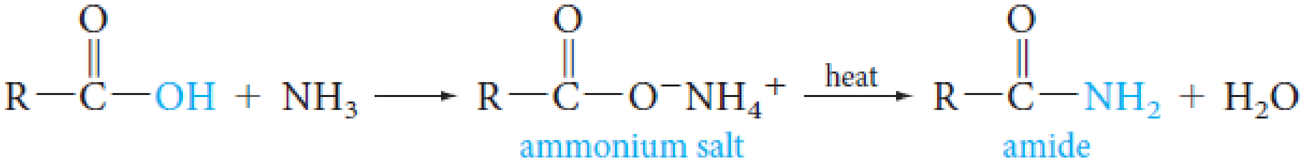


$\mathrm{CH_3\overset{O}{\overset{\|}{C}}-N(CH_3)_2}$

N,*N*-dimethylacetamide

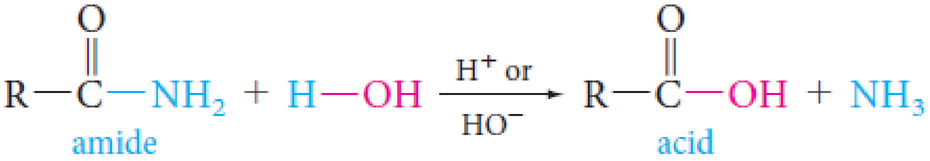
Amides

- **Preparation:**
  - They can be prepared by the reaction of ammonia with esters, with acyl halides, or with acid anhydrides.
  - Amides can also prepared by heating the ammonium salts of acids as shown in the following scheme.



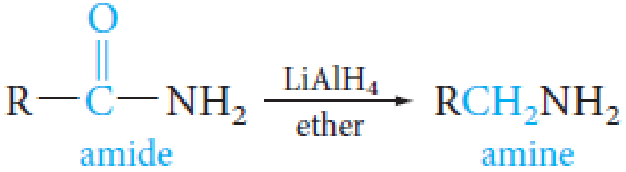
$$R-\overset{\overset{O}{\|}}{C}-OH + NH_3 \longrightarrow \underset{\text{ammonium salt}}{R-\overset{\overset{O}{\|}}{C}-O^-NH_4^+} \xrightarrow{\text{heat}} \underset{\text{amide}}{R-\overset{\overset{O}{\|}}{C}-NH_2} + H_2O$$

- **Reactions**
  - **Amides** react with nucleophiles and they can be hydrolyzed by water.



$$\underset{\text{amide}}{R-\overset{\overset{O}{\|}}{C}-NH_2} + H-OH \xrightarrow[HO^-]{H^+ \text{ or}} \underset{\text{acid}}{R-\overset{\overset{O}{\|}}{C}-OH} + NH_3$$

  - **Amides** can be reduced by lithium aluminums hydride to give amines.

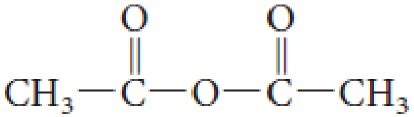


$$\underset{\text{amide}}{R-\overset{\overset{O}{\|}}{C}-NH_2} \xrightarrow[\text{ether}]{LiAlH_4} \underset{\text{amine}}{RCH_2NH_2}$$

Acid Anhydrides

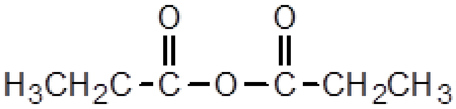
- **Acid anhydrides** have general formula RCOOCOR.
- **Nomenclature:**

  The name of an anhydrides is obtained by naming the acid from which is derived and replacing the word acid with anhydride.



$$CH_3-\overset{O}{\overset{\|}{C}}-O-\overset{O}{\overset{\|}{C}}-CH_3$$

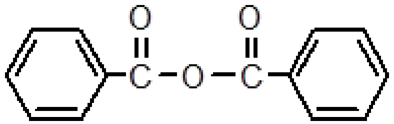
ethanoic anhydride or acetic anhydride



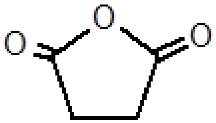
$$H_3CH_2C-\overset{O}{\overset{\|}{C}}-O-\overset{O}{\overset{\|}{C}}-CH_2CH_3$$

IUPAC name: Propanoic anhydride

Common name: Propionic anhydride



Benzoic anhydride

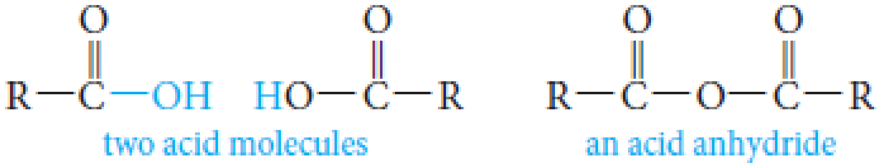


Succinic anhydride

Acid Anhydrides

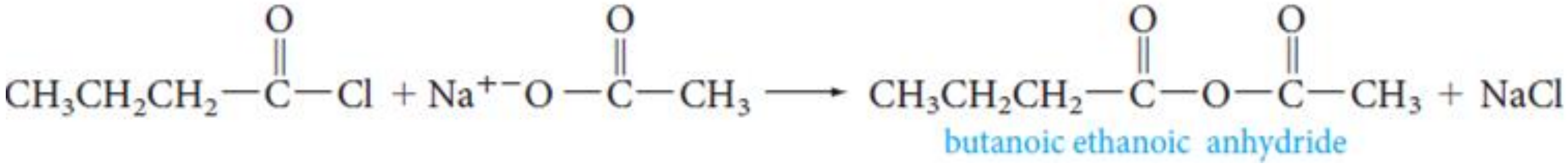
Preparation

- **Acid anhydrides** are derived from acids by removing water from two carboxyl groups under heating and effect of suitable catalyst.



$$R-\overset{\overset{O}{\|}}{C}-OH \quad HO-\overset{\overset{O}{\|}}{C}-R \qquad R-\overset{\overset{O}{\|}}{C}-O-\overset{\overset{O}{\|}}{C}-R$$

- **Anhydrides** can also be prepared from acid chlorides and carboxylate salts. *This method is used for preparing anhydrides derived from two different carboxylic acids (mixed anhydrides).*

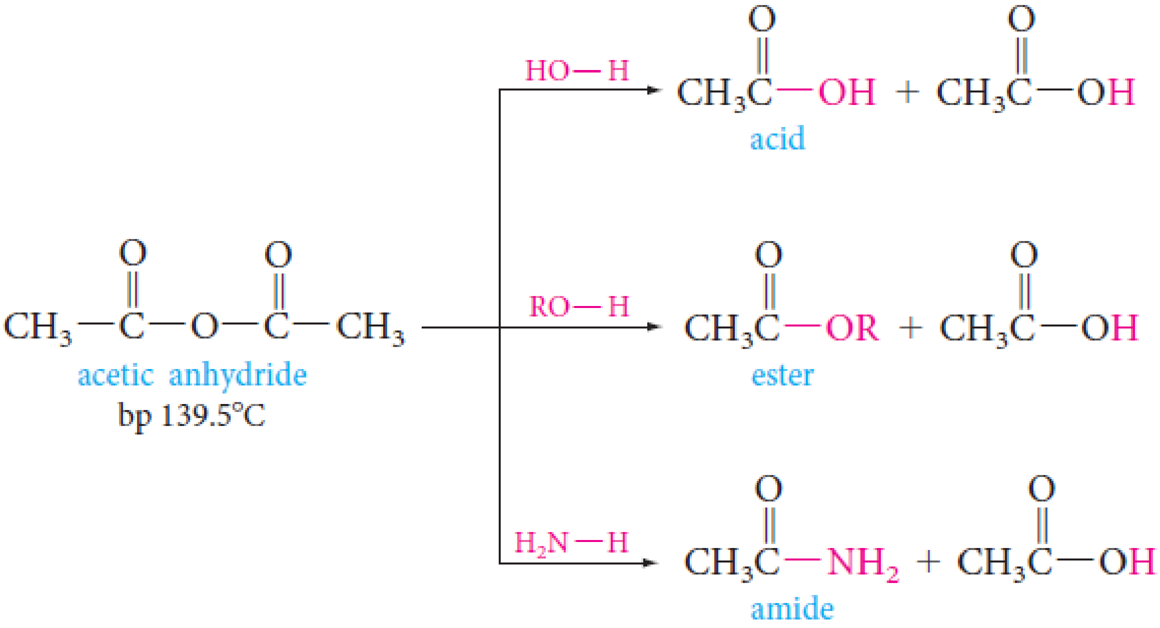


$$CH_3CH_2CH_2-\overset{\overset{O}{\|}}{C}-Cl + Na^{+}\,{}^{-}O-\overset{\overset{O}{\|}}{C}-CH_3 \longrightarrow CH_3CH_2CH_2-\overset{\overset{O}{\|}}{C}-O-\overset{\overset{O}{\|}}{C}-CH_3 + NaCl$$

Acid Anhydrides

➢ Reactions

- **Anhydrides** undergo nucleophilic acyl substitution reactions (*They are more reactive than esters, but less reactive than acyl halides*).



Uses of Carboxylic Acids

- **Salicylic acid**
  - It can be used to create acne medications.
  - Therefore, It is used frequently in cleansers, liquid foundations, moisturizers, anti-aging hydrating creams, eye gels, and sun screens.
- **Acetylsalicylic Acid in Aspirin**
  - Acetic acid acts as the precursor for the formation of an ester of salicylic acid which is used for aspirin (Acetyl Salicylic acid) production.
- **Citric Acid**
  - Citric acid has a sour taste and is often used to add flavor to sour candies (covered in a white powder).
  - Because citric acid is non-toxic and acidic, it is an ideal preservative. (it causes the pH to drop to a point where it is difficult for bacteria to survive).
- **Industrial uses**
  - Manufacturing of soaps and detergents (oleic acid, Palmitic acid and stearic acid).