CHAPTER 14

CARBOXYLIC ACIDS

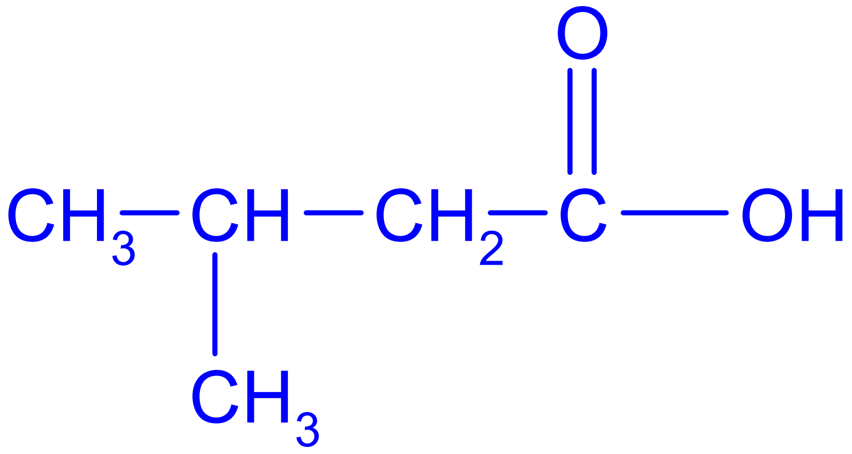
NOMENCLATURE

IUPAC NOMENCLATURE

- **-oic acid**
  IUPAC ending

- **-carboxylic acid**
  IUPAC ending for ring compounds

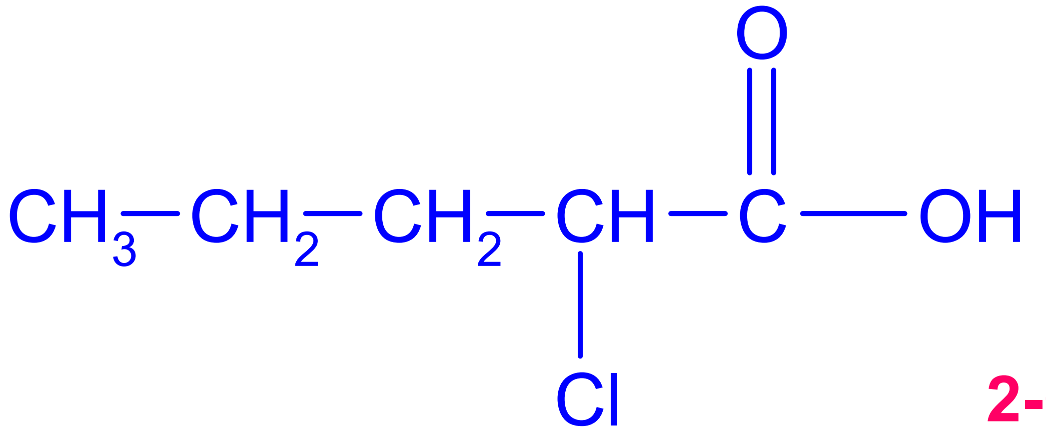
Naming



$CH_3-\underset{CH_3}{\underset{|}{CH}}-CH_2-\overset{O}{\overset{\|}{C}}-OH$

3-Methylbutanoic acid

β-Methylbutyric acid

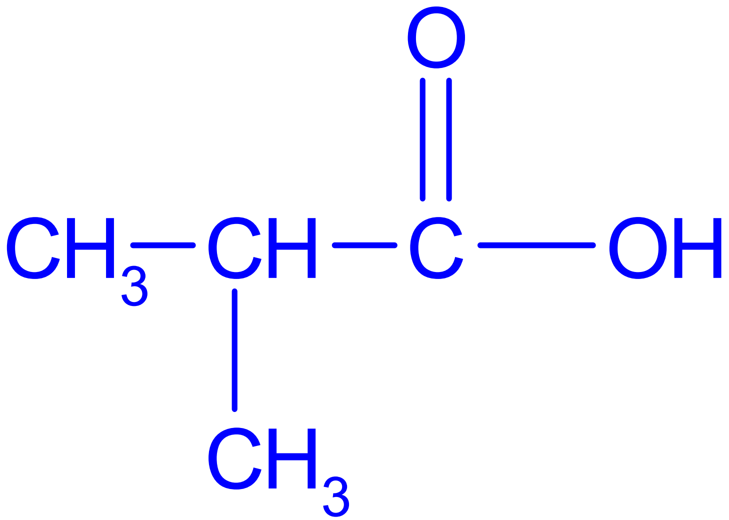


$CH_3-CH_2-CH_2-\underset{Cl}{\underset{|}{CH}}-\overset{O}{\overset{\|}{C}}-OH$

2-Chloropentanoic acid

α-Chlorovaleric acid

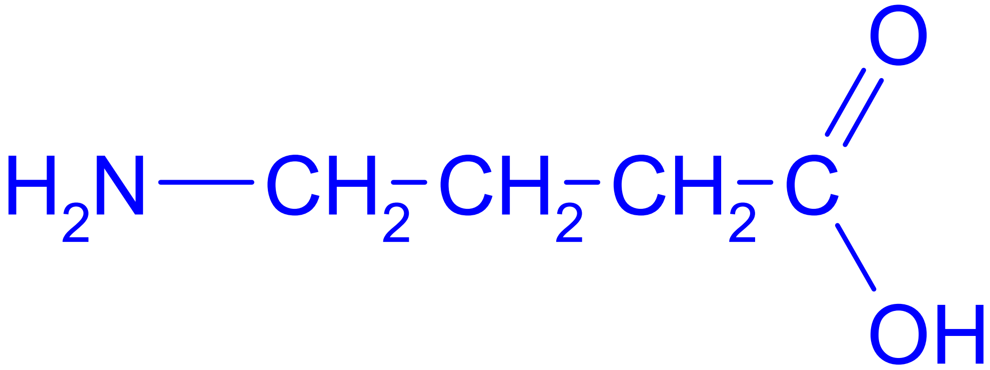
Naming



$$CH_3-\underset{\underset{CH_3}{|}}{CH}-\overset{\overset{O}{\|}}{C}-OH$$

2-Methylpropanoic acid

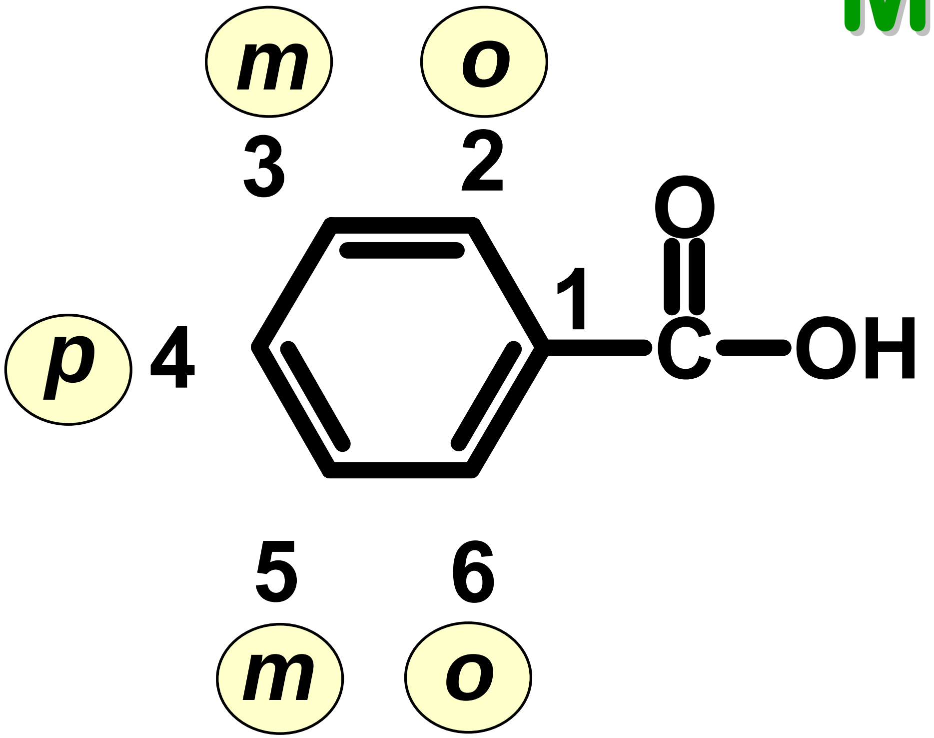
α-Methylpropionic acid



4-Aminobutanoic Acid

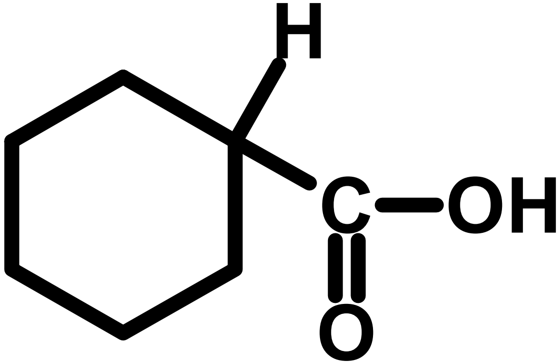
γ-Aminobutyric Acid

More Naming



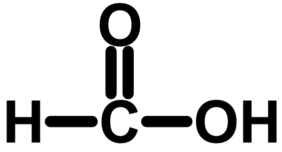
Benzoic acid

Benzenecarboxylic acid



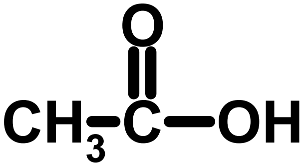
Cyclohexanecarboxylic acid

Common Names



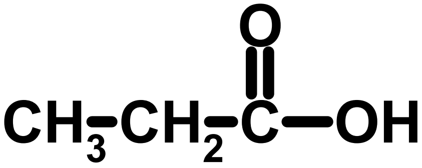
$H-\overset{\overset{O}{\|}}{C}-OH$

Formic acid



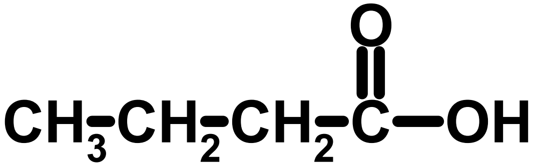
$CH_3-\overset{\overset{O}{\|}}{C}-OH$

Acetic Acid



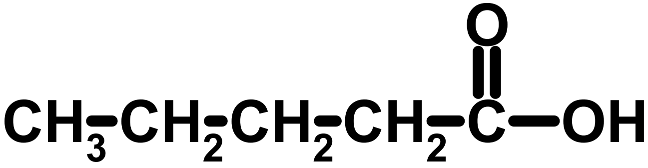
$CH_3-CH_2-\overset{\overset{O}{\|}}{C}-OH$

Propionic Acid



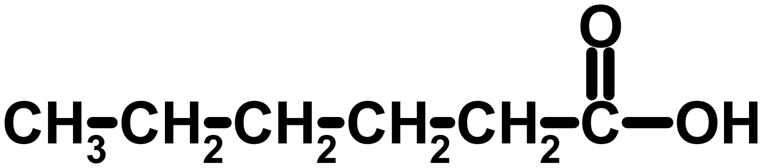
$CH_3-CH_2-CH_2-\overset{\overset{O}{\|}}{C}-OH$

Butyric Acid



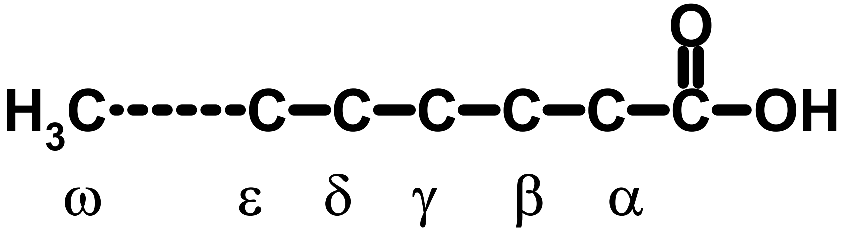
$CH_3-CH_2-CH_2-CH_2-\overset{\overset{O}{\|}}{C}-OH$

Valeric Acid



$CH_3-CH_2-CH_2-CH_2-CH_2-\overset{\overset{O}{\|}}{C}-OH$

Caproic Acid



$H_3C\cdots\cdots C-C-C-C-C-\overset{\overset{O}{\|}}{C}-OH$

SYNTHESIS OF CARBOXYLIC ACIDS

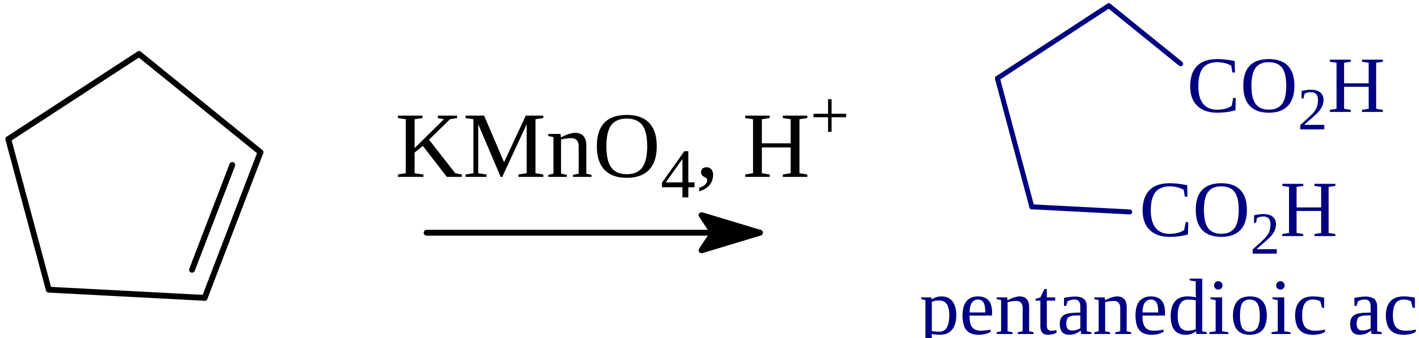
Preparation of Carboxylic Acids

1. By Oxidation of Alkenes

$$\mathrm{RCH{=}CHR'} \xrightarrow[\substack{\text{heat} \\ (2)\ \mathrm{H_3O^+}}]{(1)\ \mathrm{KMnO_4,\ OH^-}} \mathrm{RCO_2H} + \mathrm{R'CO_2H}$$

$$\mathrm{RCH{=}CHR'} \xrightarrow[(2)\ \mathrm{H_2O_2}]{(1)\ \mathrm{O_3}} \mathrm{RCO_2H} + \mathrm{R'CO_2H}$$

eg



pentanedioic acid

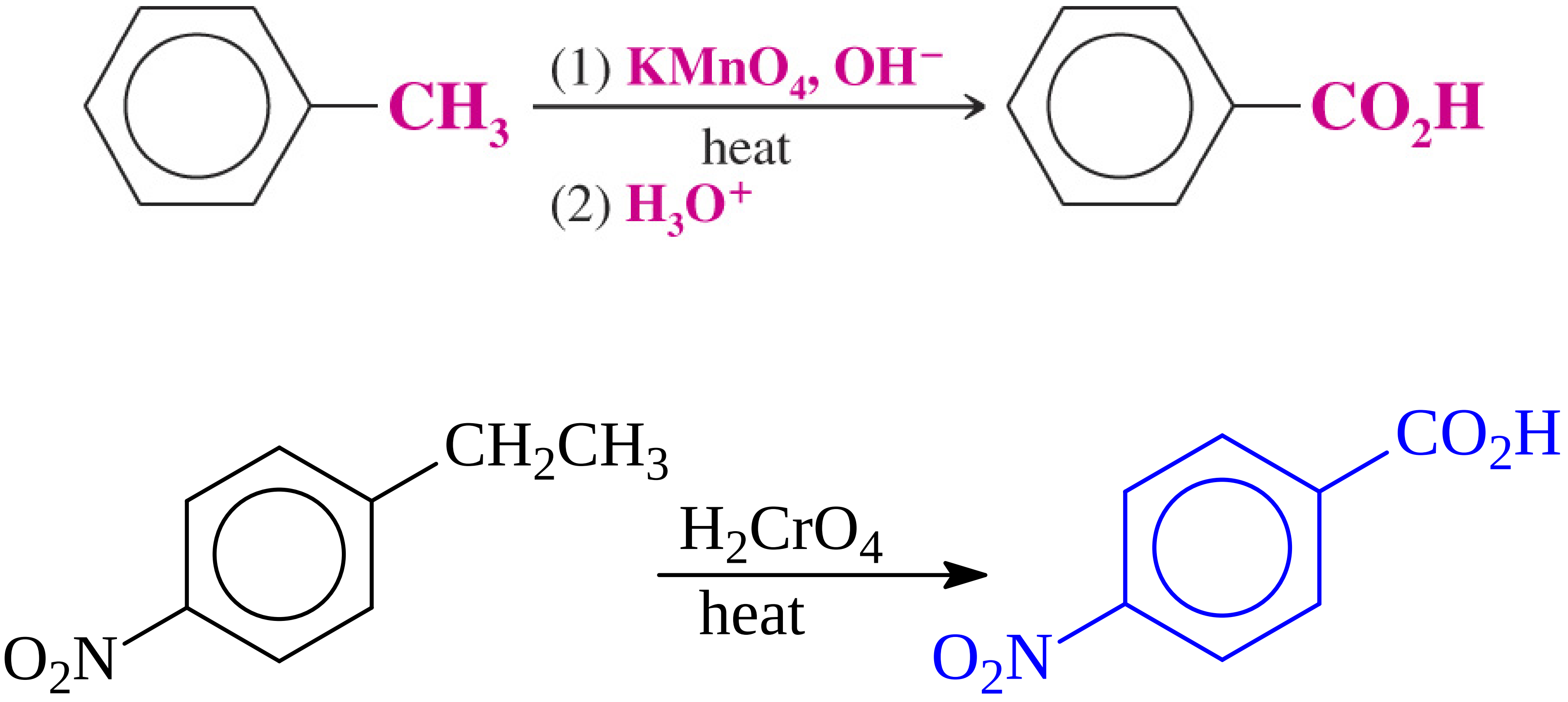
2. By Oxidation of Aldehydes and Primary Alcohols

$$R{-}CHO \xrightarrow[\text{(2) } H_3O^+]{\text{(1) } Ag_2O \text{ or } Ag(NH_3)_2{}^+OH^-} RCO_2H$$

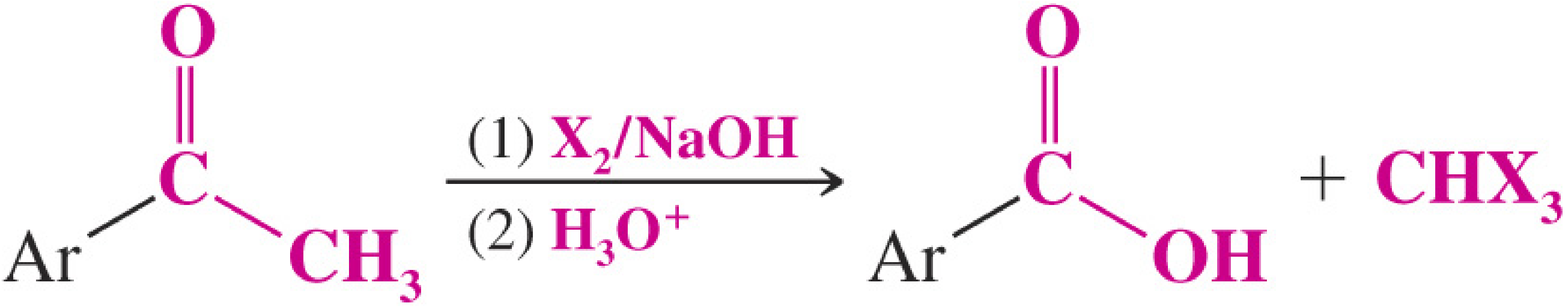
$$RCH_2OH \xrightarrow[\substack{\text{heat} \\ \text{(2) } H_3O^+}]{\text{(1) } KMnO_4,\ OH^-} RCO_2H$$

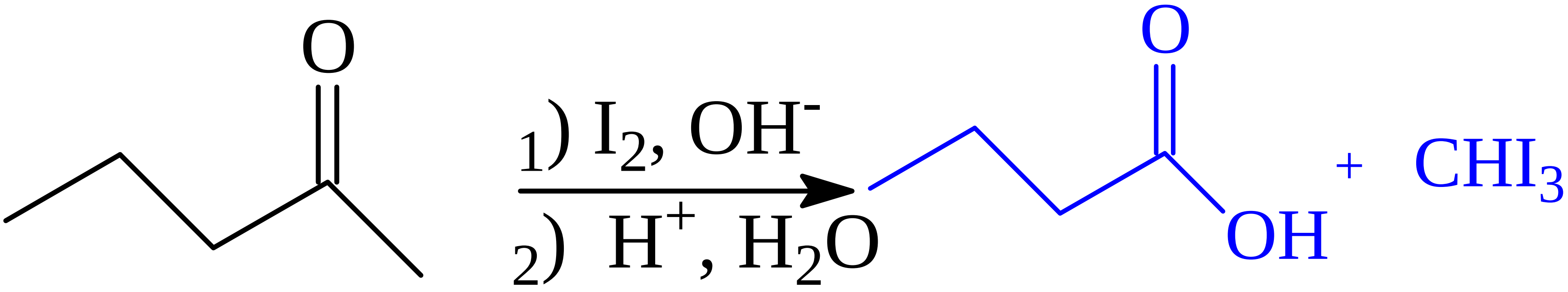
$$R{-}CHO \text{ or } RCH_2OH \xrightarrow{H_2CrO_4} RCO_2H$$

3. By Oxidation of Alkylbenzenes

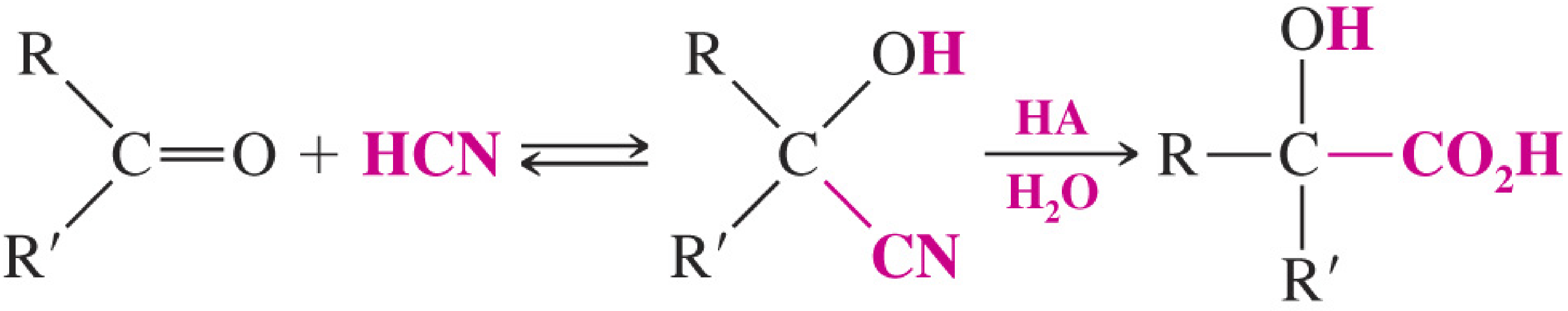


4. By Oxidation of Methyl Ketones (The Haloform Reaction)





5. By Hydrolysis of Cyanohydrins and Other Nitriles



$$\mathrm{HOCH_2CH_2Cl} \xrightarrow[(80\%)]{\mathrm{NaCN}} \mathrm{HOCH_2CH_2CN} \xrightarrow[\substack{(2)\ \mathrm{H_3O^+} \\ (75\text{–}80\%)}]{(1)\ \mathrm{OH^-,\ H_2O}} \mathrm{HOCH_2CH_2CO_2H}$$

3-Hydroxypropanoic acid

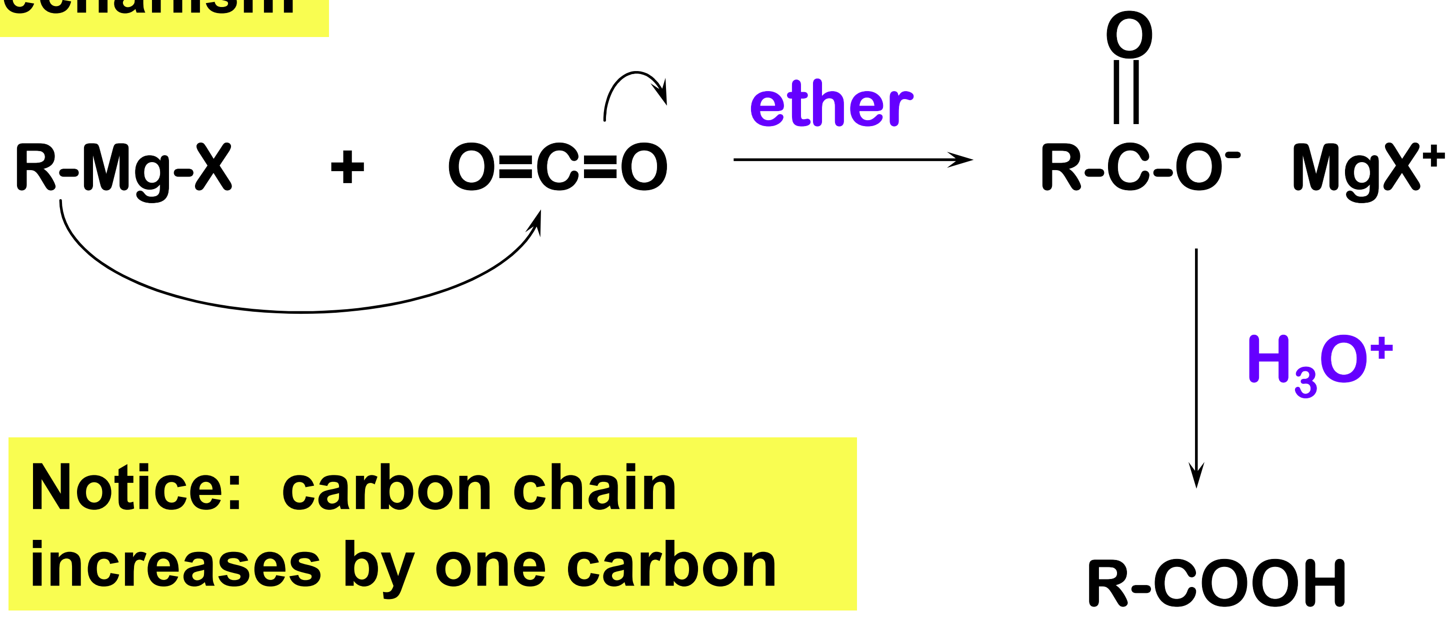
$$\mathrm{BrCH_2CH_2CH_2Br} \xrightarrow[(77\text{–}86\%)]{\mathrm{NaCN}} \mathrm{NCCH_2CH_2CH_2CN} \xrightarrow[(77\text{–}86\%)]{\mathrm{H_3O^+}} \mathrm{HO_2CCH_2CH_2CH_2CO_2H}$$

Glutaric acid

6.By Reaction of Grignard Reagents with carbondioxide

$$\mathrm{RMgX} \xrightarrow[\text{2)}\ \mathrm{H+,\ H_2O}]{\text{1)}\ \mathrm{CO_2}} \mathrm{RCO_2H}$$

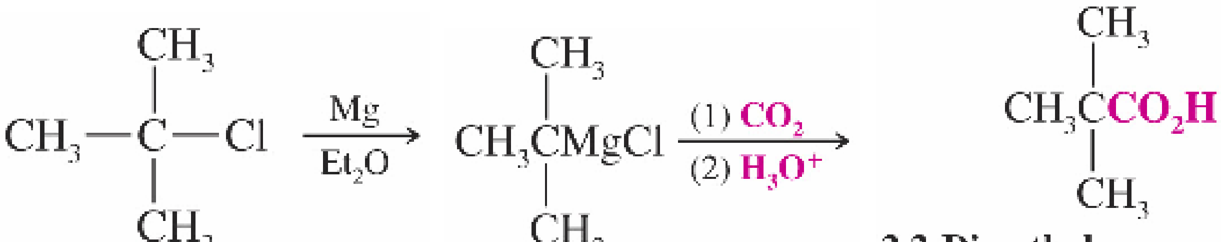
Mechanism



$$\mathrm{R\text{-}Mg\text{-}X} + \mathrm{O{=}C{=}O} \xrightarrow{\text{ether}} \mathrm{R\text{-}\overset{\overset{\displaystyle O}{\|}}{C}\text{-}O^-}\ \mathrm{MgX^+} \xrightarrow{\mathrm{H_3O^+}} \mathrm{R\text{-}COOH}$$

Notice: carbon chain increases by one carbon

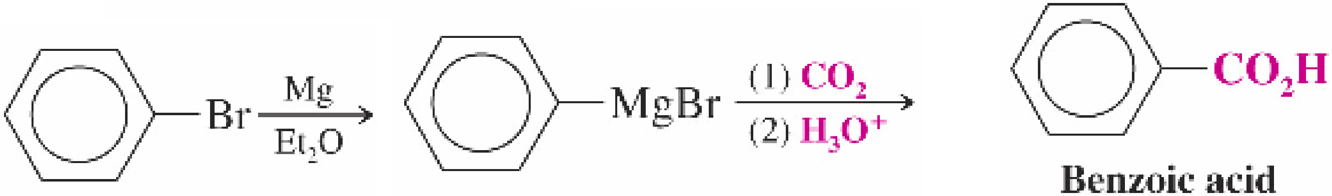
Examples



$$CH_3-\overset{\displaystyle CH_3}{\underset{\displaystyle CH_3}{C}}-Cl \xrightarrow[Et_2O]{Mg} CH_3\overset{\displaystyle CH_3}{\underset{\displaystyle CH_3}{C}}MgCl \xrightarrow[(2)\ H_3O^+]{(1)\ CO_2} CH_3\overset{\displaystyle CH_3}{\underset{\displaystyle CH_3}{C}}CO_2H$$

tert-Butyl chloride

2,2-Dimethylpropanoic acid
(79–80% overall)

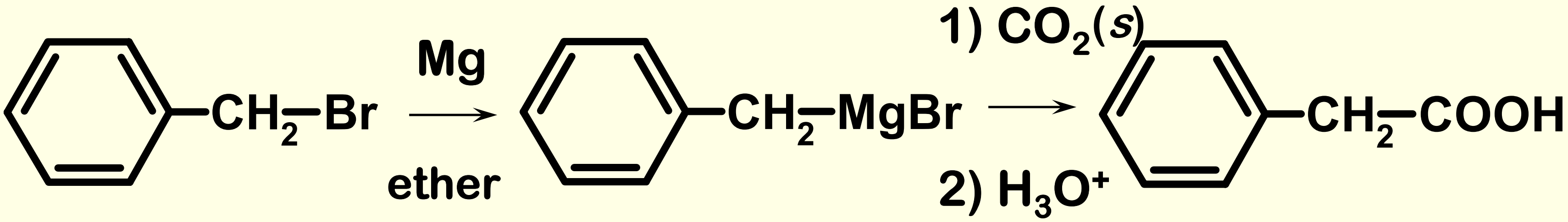


Benzoic acid
(85%)

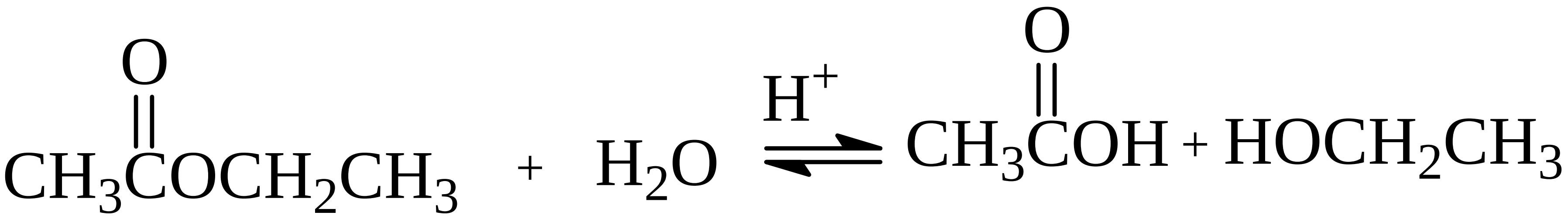
$$CH_3CH_2CH_2CH_2Cl \xrightarrow[Et_2O]{Mg} CH_3CH_2CH_2CH_2MgCl \xrightarrow[(2)\ H_3O^+]{(1)\ CO_2} CH_3CH_2CH_2CH_2CO_2H$$

Butyl chloride

Pentanoic acid
(80% overall)



7. By Hydrolysis of Acid Derivatives

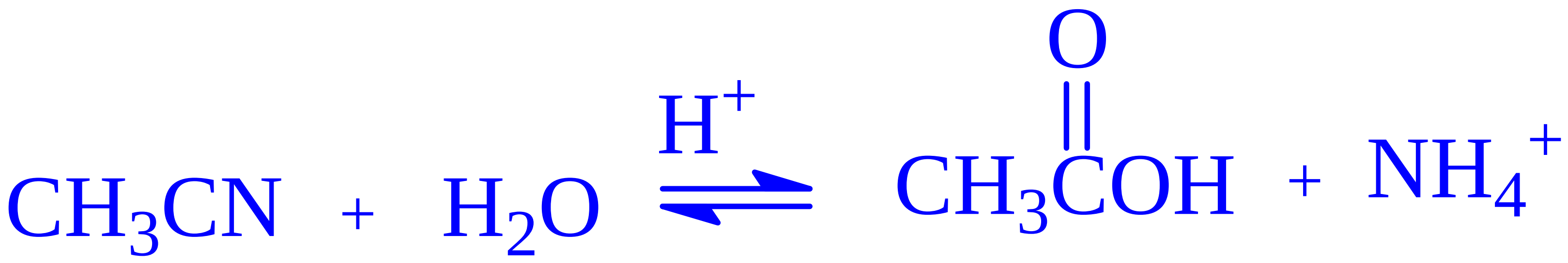


$$CH_3\overset{O}{\overset{\|}{C}}OCH_2CH_3 + H_2O \xrightleftharpoons{H^+} CH_3\overset{O}{\overset{\|}{C}}OH + HOCH_2CH_3$$

an ester

Carboxylic acid

alcohol

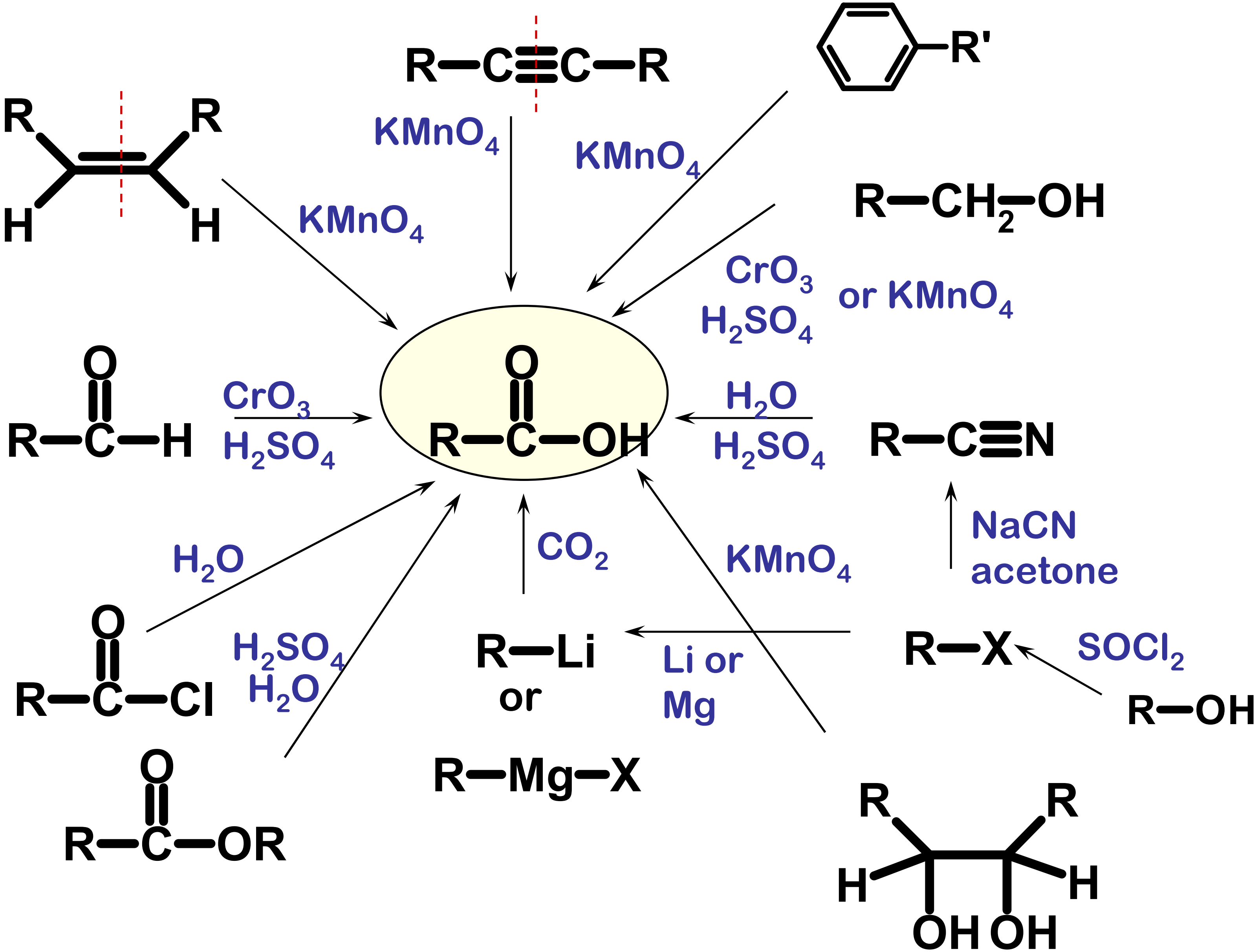


$$CH_3CN + H_2O \xrightleftharpoons{H^+} CH_3\overset{O}{\overset{\|}{C}}OH + NH_4^+$$

a nitrile

acetic acid

SYNTHESIS OF CARBOXYLIC ACIDS



How structure Affects Acid Strength

	RCH_3	RNH_2	$RC\equiv CH$	ROH	H_2O	$ArOH$	RCO_2H
pKa	45	35	25	15-19	16	10	5

Increasing acid strength

Acid Strength

$$HA + H_2O \rightleftharpoons H_3O^+ + A^-$$

The greater the amount of ionization ➔ the stronger the acid (HA)

The more stable the conjugate base (A^-) ➔ the stronger the acid (HA)

Factors affect the stability of the conjugate base (A^-)

1. Electronegative of the atom carrying the negative charge in A^-.

C N O F

Increasing electronegativity of elements

$R_3C\text{-}H$ $H_2N\text{-}H$ $RO\text{-}H$ $F\text{-}H$

Increasing acid strength

2. Size of A^-

A larger atom is better able to disperse the negative charge than a smaller one → stabilization

F^- Cl^- Br^- I^-

Increasing ionic radii

	HF	**HCl**	**HBr**	**HI**
pKa	3.45	-7	-9	-9.5

Increasing acid strength

3. Hybridization of the atom carrying the negative charge in A^-.

Increasing s character ➔ increasing electronegativity of the carbon ➔ increasing acid strength

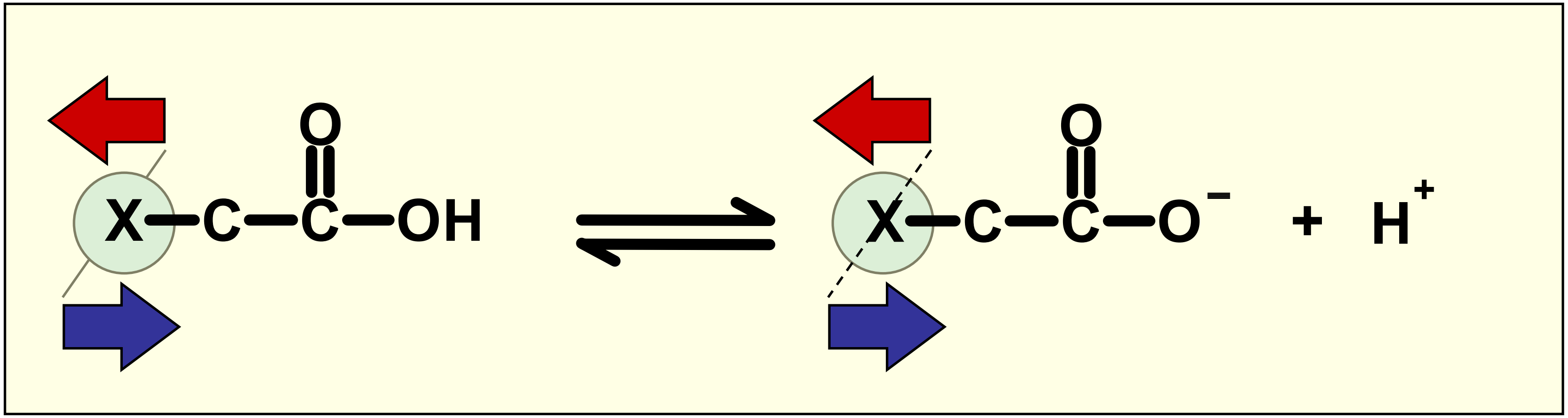
	CH_3CH_3	$CH_2{=}CH_2$	$CH{\equiv}CH$
Percentage of s	25	33	50
pka	~50	~45	~26

Increasing acid strength

CH_3CH^- $\quad$ $CH_2{=}CH^-$ $\quad$ $CH{\equiv}C^-$

Increasing base strength

4. Inductive effect



$$X-C-\overset{\overset{\displaystyle O}{\|}}{C}-OH \rightleftharpoons X-C-\overset{\overset{\displaystyle O}{\|}}{C}-O^{-} + H^{+}$$

⬅ - Electron-withdrawing Groups:
    - – strengthen acids
    - – weaken bases

➡ - Electron-releasing Groups:
    - – weaken acids
    - – strengthen bases

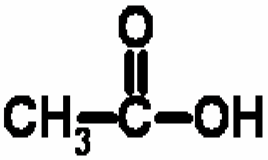
Electron-withdrawal power groups

CH_3- H- CH_2=CH- C_6H_5- HO- CH_3O- I- Br- Cl-

Increasing power of electron-withdrawal

	$CH_3CH_2CO_2H$	**CH_3CO_2H**	**$C_6H_5CH_2CO_2H$**	**$HOCH_2CO_2H$**	**$ClCH_2CO_2H$**
pka	**4.87**	**4.75**	**4.31**	**3.87**	**2.81**

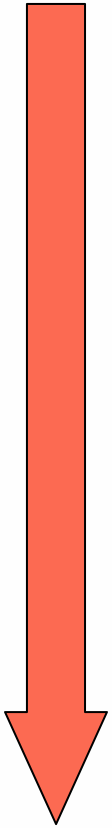
Increasing acid strength

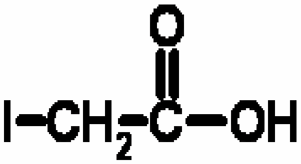


$CH_3-\overset{O}{\overset{\|}{C}}-OH$

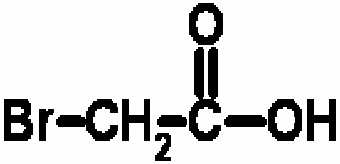
pK_a = 4.75

increasing acidity

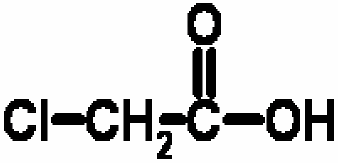




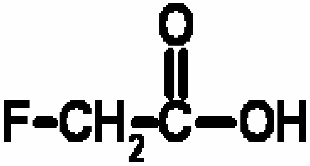
$I-CH_2-\overset{O}{\overset{\|}{C}}-OH$ 3.12



$Br-CH_2-\overset{O}{\overset{\|}{C}}-OH$ 2.86

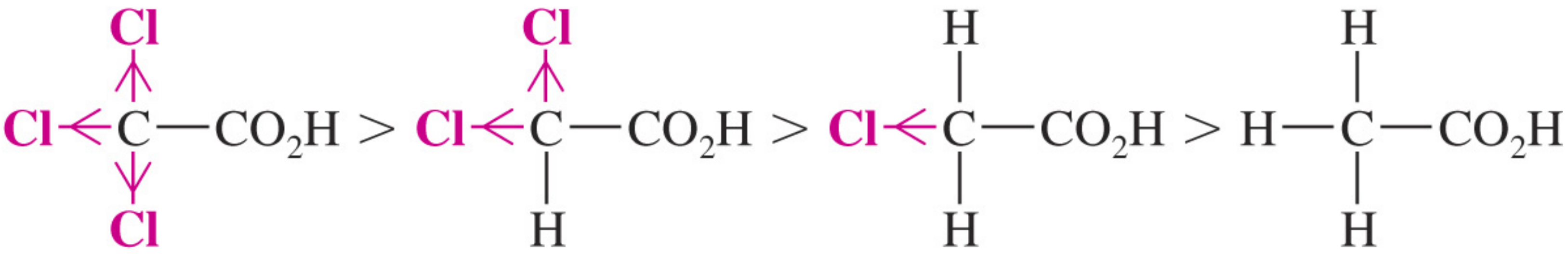


$Cl-CH_2-\overset{O}{\overset{\|}{C}}-OH$ 2.86



$F-CH_2-\overset{O}{\overset{\|}{C}}-OH$ 2.66

- Presence of more than one electron-withdrawing groups ➔ **amplify the inductive effect**



$$Cl_3C-CO_2H > Cl_2CH-CO_2H > ClCH_2-CO_2H > H_3C-CO_2H$$

pK_a 0.70 1.48 2.86 4.76

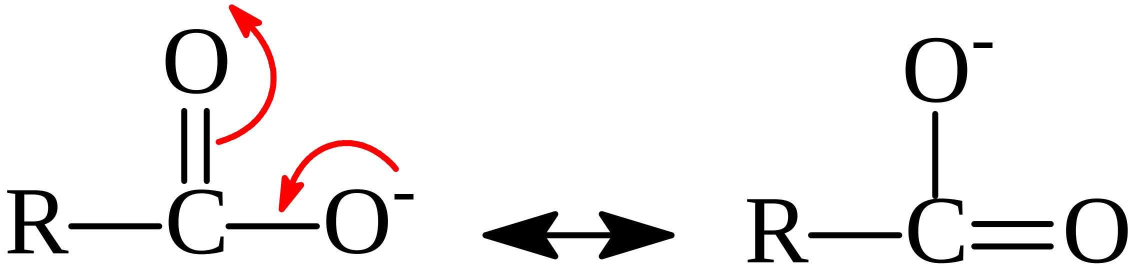
- Inductive effect decrease with an increasing number of atoms between CO_2H and the electronegative group.

	$ClCH_2CH_2CH_2CO_2H$	$CH_3CHClCH_2CO_2H$	$CH_3CH_2CHClCO_2H$
pK_a	**4.4**	**4.0**	**2.9**

5. Resonance Stabilization

	ROH	ArOH	RCO_2H
pK_a	15-19	10	5

No resonance

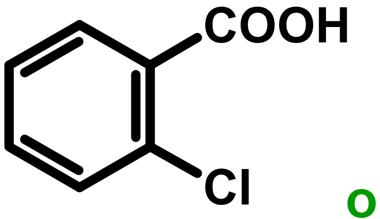


6. Substituted Acid Strength

- Electron-withdrawing groups in the *meta* or *para* position ➔ **increases acid strength.**

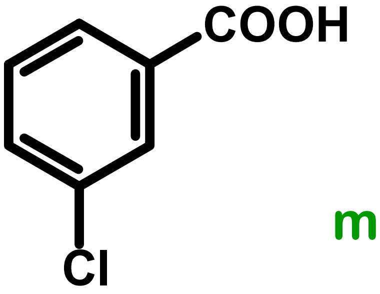
- An electron-releasing groups in the same positions ➔ **decreases acid strength.**

- **All *ortho*-substituents (**electron-releasing or electron-withdrawing)➔ **increases acid strength (*ortho*-effect)**



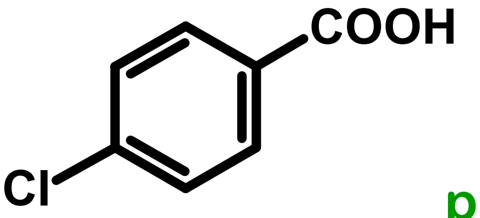
pK_a = 2.92

ortho



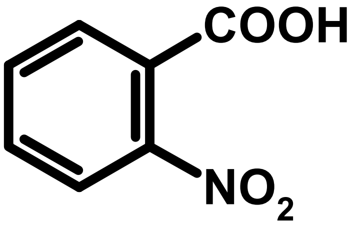
3.82

meta



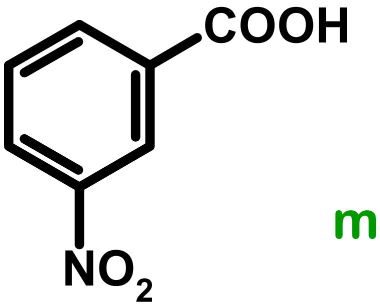
3.98

para



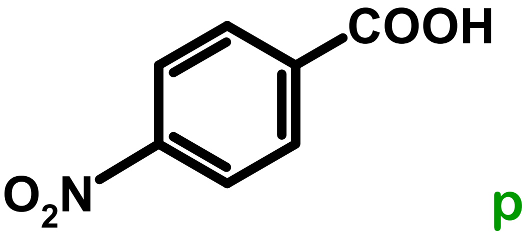
2.16

ortho



3.47

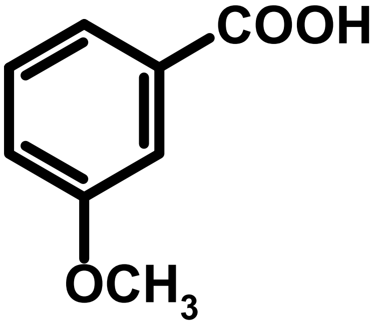
meta



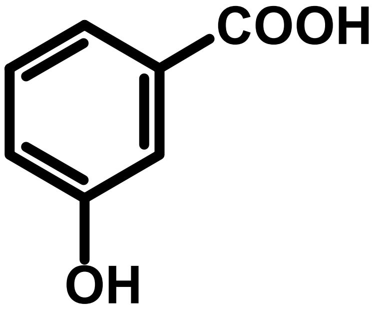
3.41

para

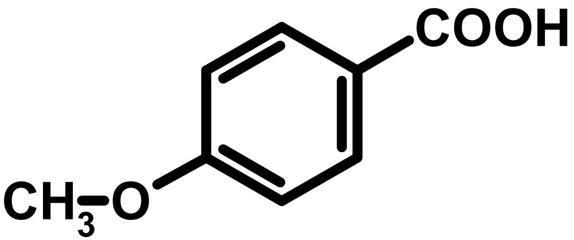
Benzoic Acid: pK_a = 4.19



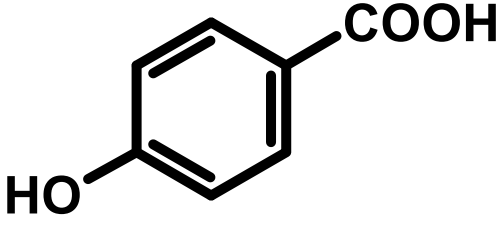
4.08



4.06

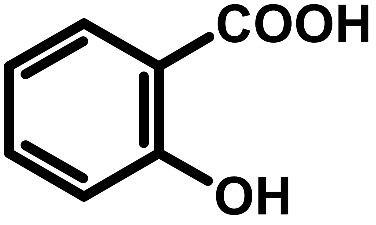


4.46

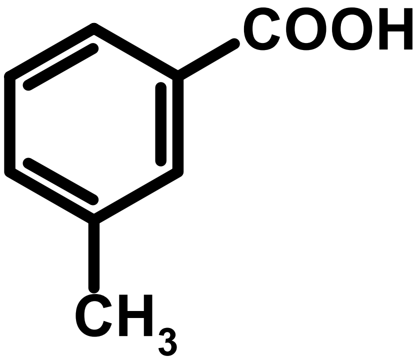


4.48

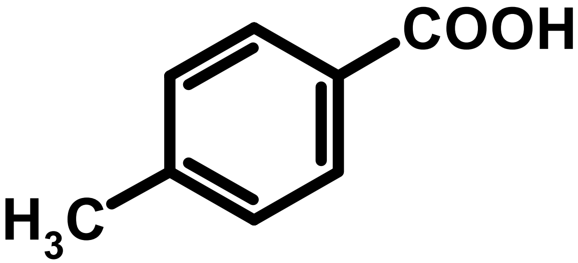
Benzoic Acid: pK_a = 4.19



2.97



pK_a = 4.27



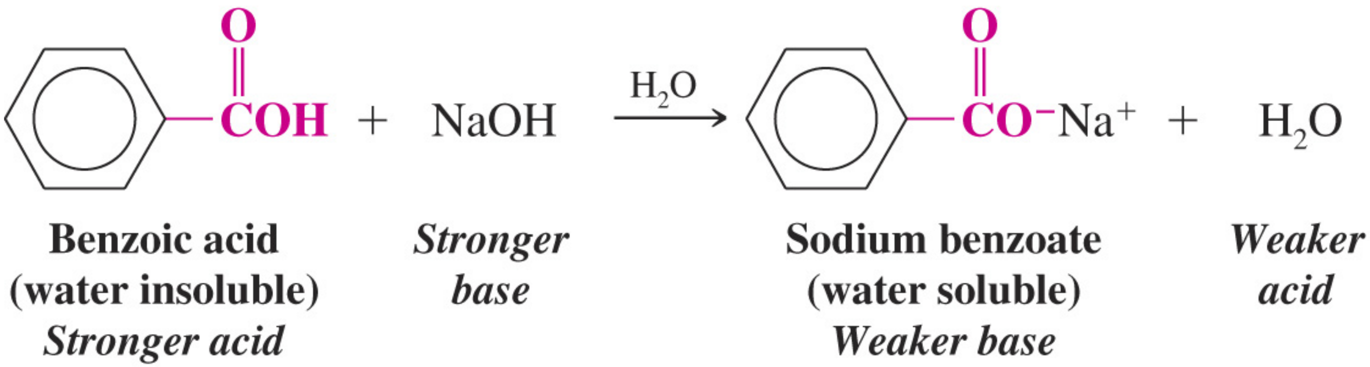
4.36

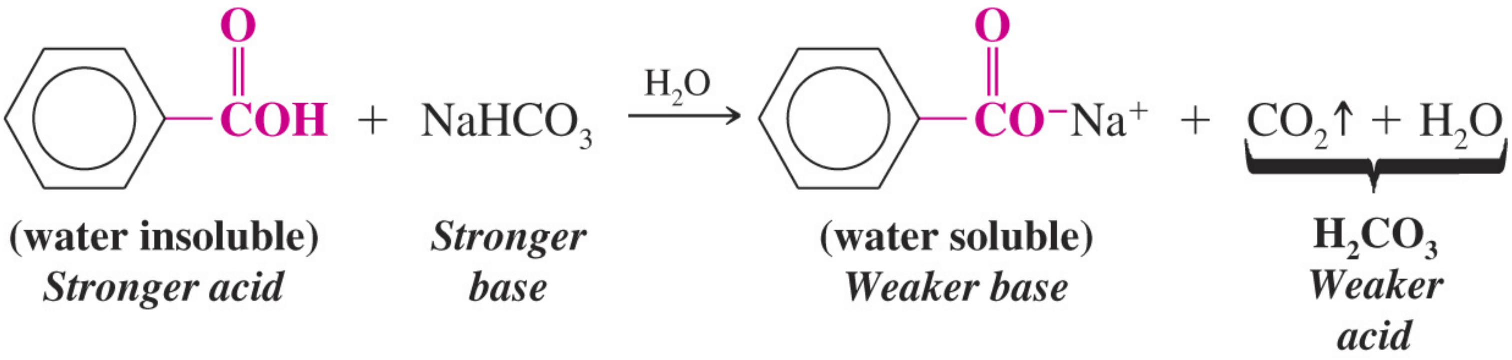
Benzoic Acid: pK_a = 4.19

Reactions of Carboxylic Acids

1. With Bases

Carboxylic acids are readily deprotonated by sodium hydroxide or sodium bicarbonate to form carboxylate salts





- The carboxylate anion is named by changing **–ic acid** to **–ate**

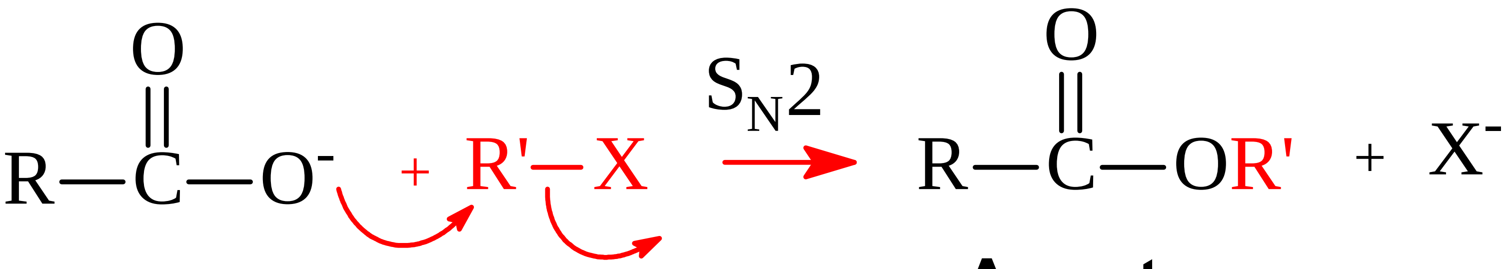
CH_3CO_2H

Acetic acid

$CH_3CO_2^- Na^+$

Sodium acetate

- The carboxylate ion is good nucleophile.

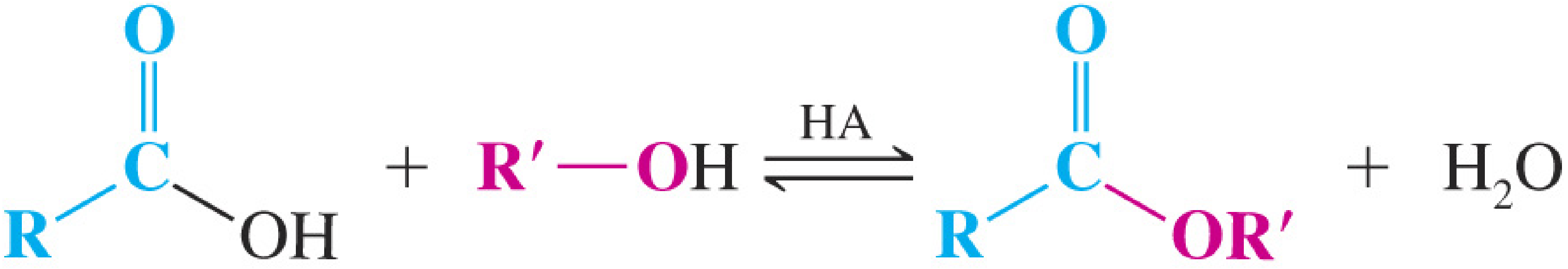


$$R-\overset{\overset{\displaystyle O}{\|}}{C}-O^- + R'-X \xrightarrow{S_N2} R-\overset{\overset{\displaystyle O}{\|}}{C}-OR' + X^-$$

An ester

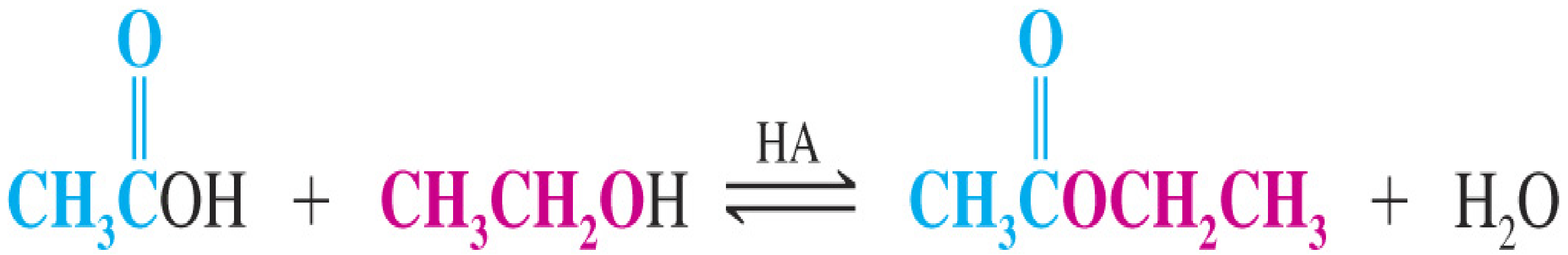
2. Esterfication of Carboxylic Acids

- Ester formation is acid catalyzed reaction of alcohols and carboxylic acids.



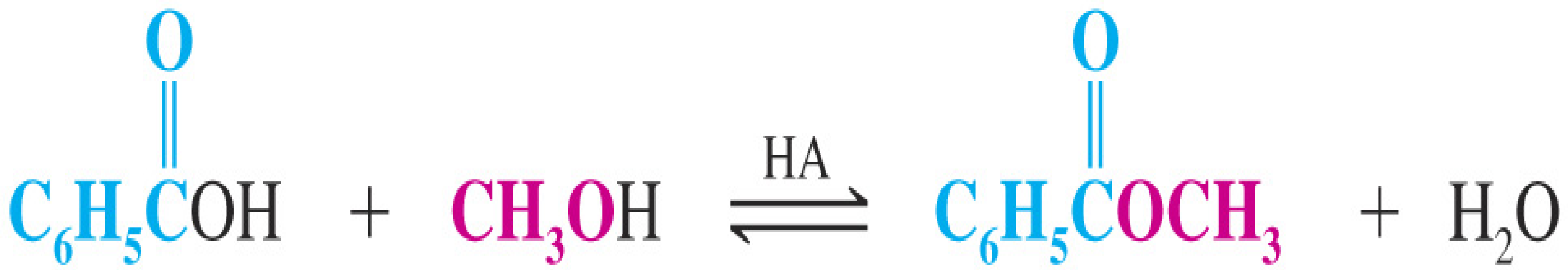
An ester

Examples



$$CH_3\overset{O}{\overset{\|}{C}}OH + CH_3CH_2OH \overset{HA}{\rightleftharpoons} CH_3\overset{O}{\overset{\|}{C}}OCH_2CH_3 + H_2O$$

Acetic acid Ethanol Ethyl acetate



$$C_6H_5\overset{O}{\overset{\|}{C}}OH + CH_3OH \overset{HA}{\rightleftharpoons} C_6H_5\overset{O}{\overset{\|}{C}}OCH_3 + H_2O$$

Benzoic acid Methanol Methyl benzoate

- Reactivity of alcohols toward esterfication

3° ROH 2° ROH 1°ROH CH_3OH

Increasing reactivity

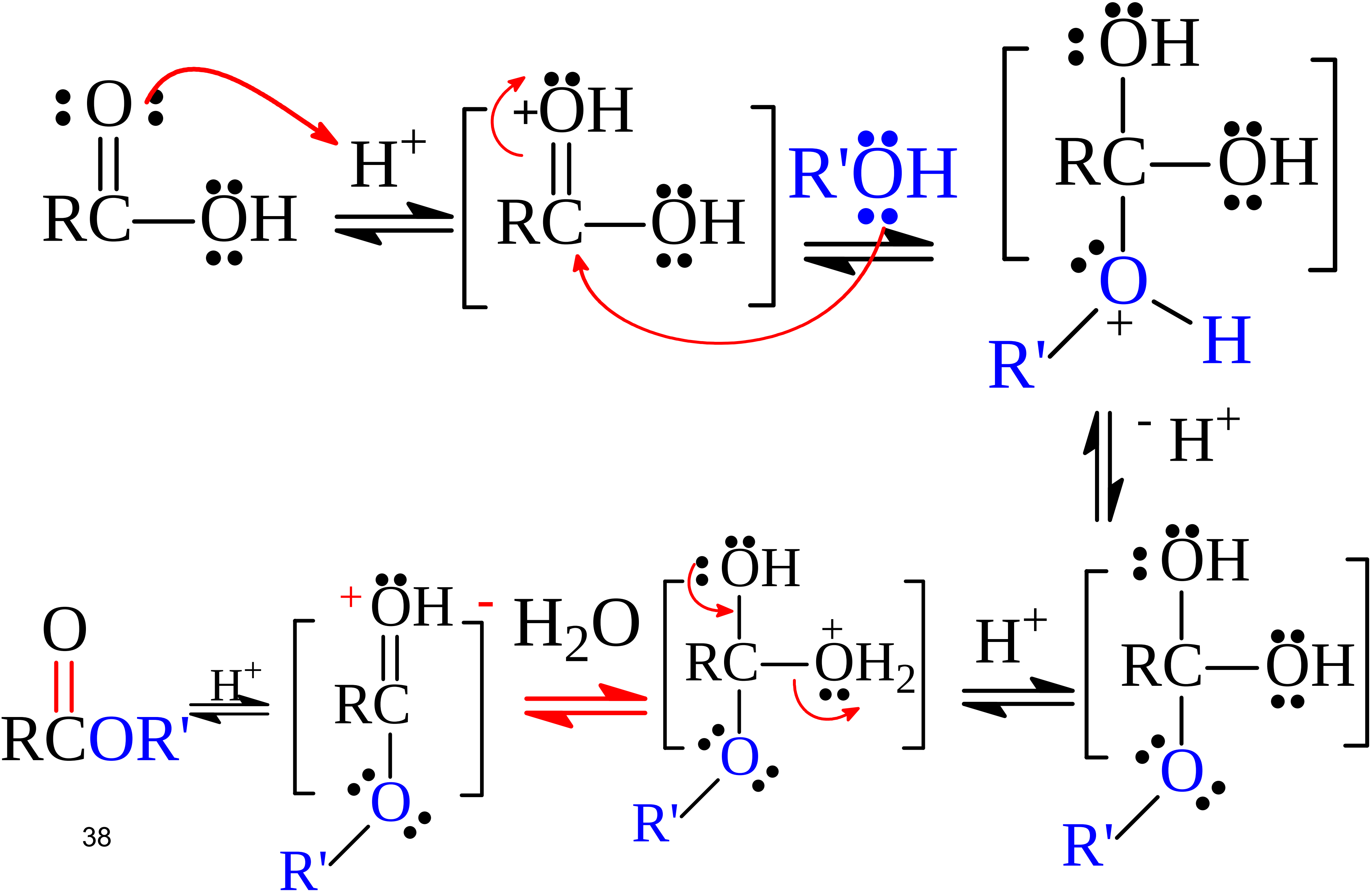
- **Reactivity of carboxylic acids toward esterfication**

R_3CCO_2H R_2CHCO_2H RCH_2CO_2H CH_3CO_2H HCO_2H

Increasing reactivity

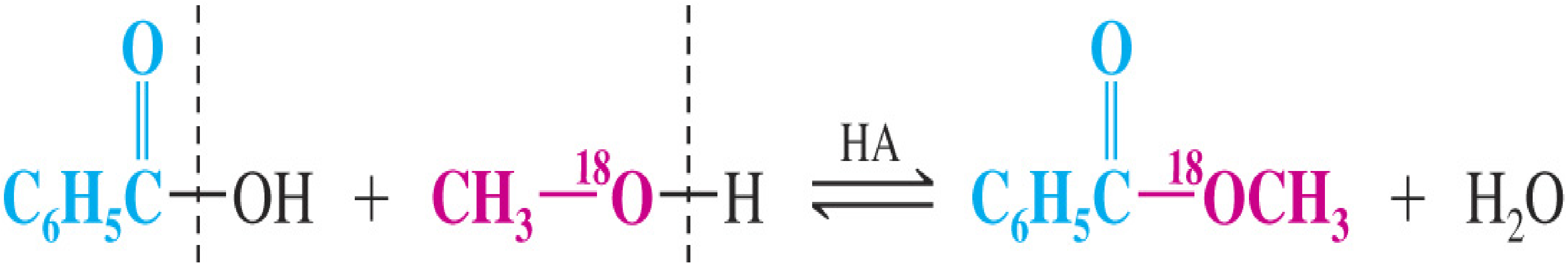
DUE TO STERIC HINDERANCE

Mechanism of Esterfication



- Esterification with labeled methanol gives a product labeled only at the oxygen atom bonded to the methyl group ➔ C-O bond of the carboxylic acid that is broken.

- **The O-H bond of the acid and the C-O bond of the alcohol are not broken.**



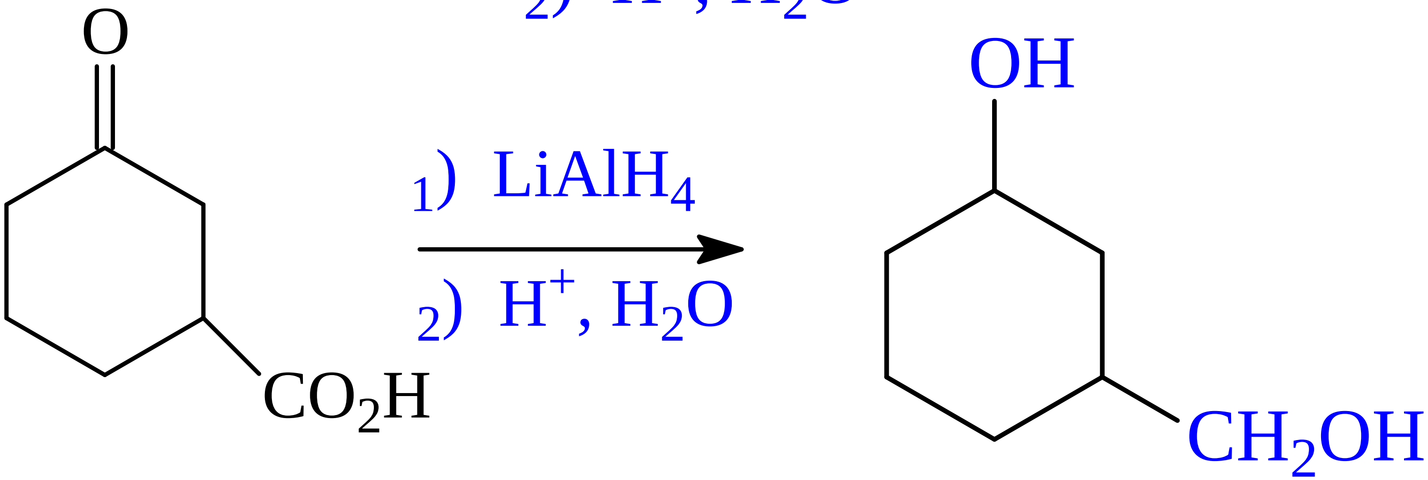
$$C_6H_5\overset{\overset{O}{\|}}{C}-OH + CH_3-{}^{18}O-H \overset{HA}{\rightleftharpoons} C_6H_5\overset{\overset{O}{\|}}{C}-{}^{18}OCH_3 + H_2O$$

4. Reduction of carboxylic acid

- $LiAlH_4$ reduces acid to primary alcohol

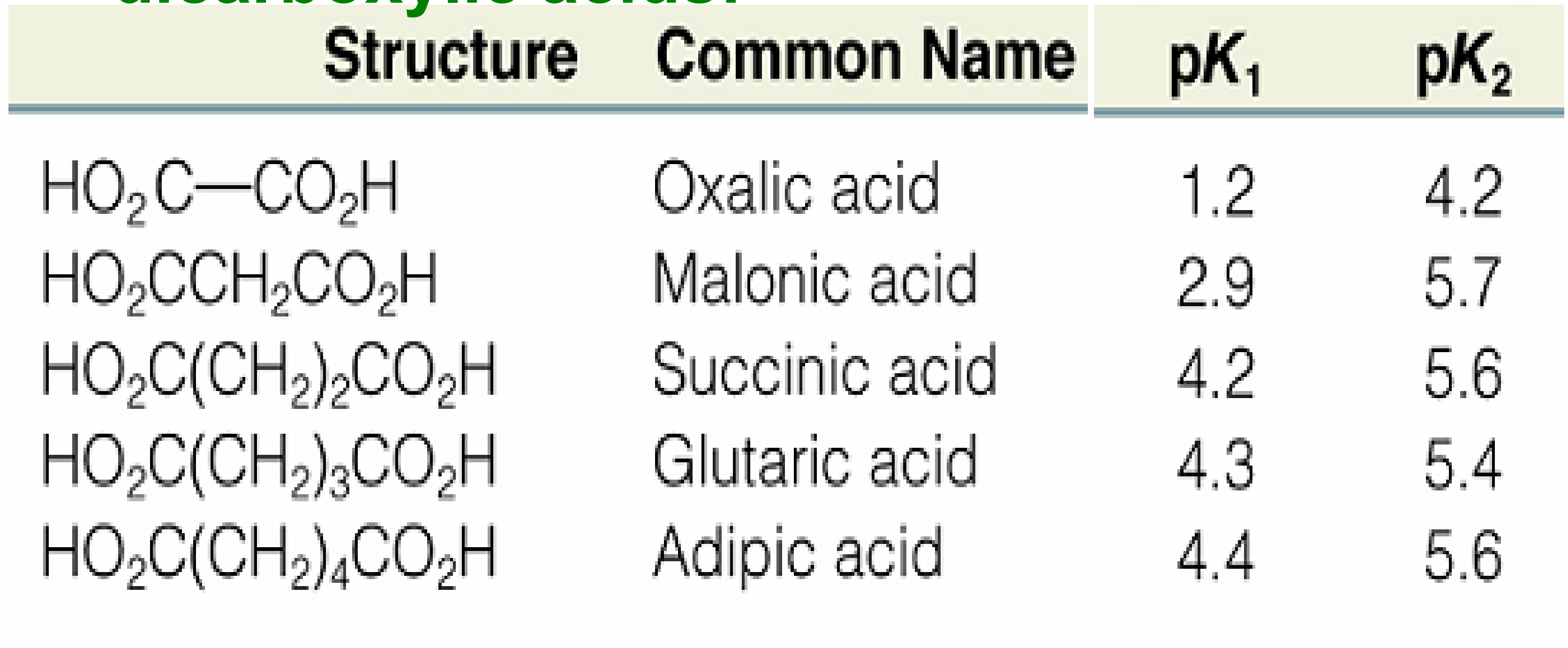
$$RCO_2H \xrightarrow[2)\ H^+,\ H_2O]{1)\ LiAlH_4} RCH_2OH$$

$$CH_3CH{=}CHCO_2H \xrightarrow[2)\ H^+,\ H_2O]{1)\ LiAlH_4} CH_3CH{=}CHCH_2OH$$



Dicarboxylic Acids

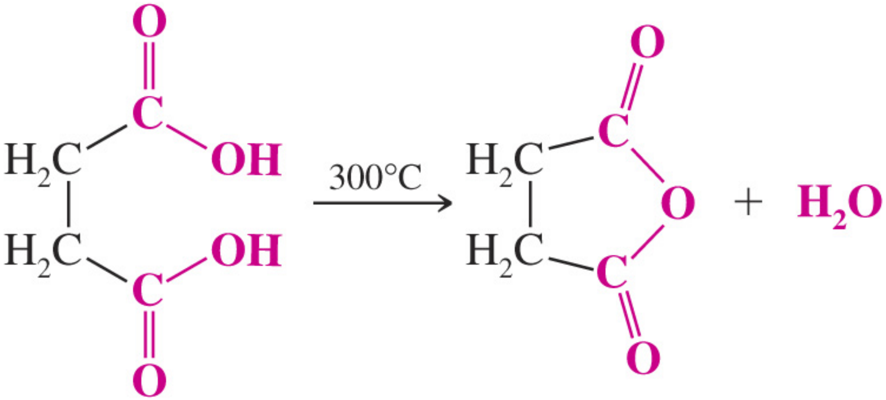
- Dicarboxylic acids are named as alkanedioic acids in the IUPAC system.
- **Common names are often used for simple dicarboxylic acids:**



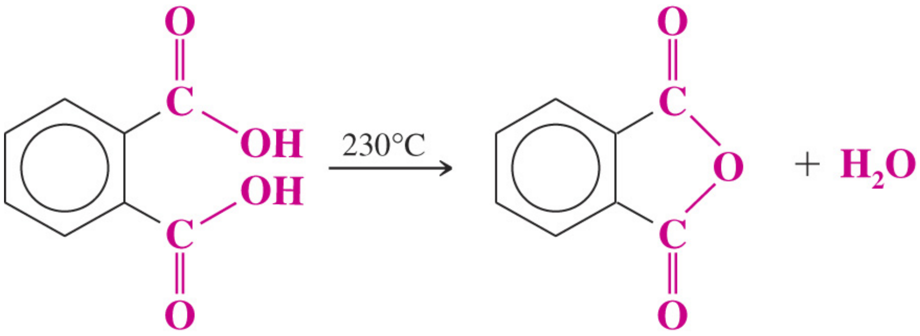
Structure	Common Name	pK_1	pK_2
$HO_2C—CO_2H$	Oxalic acid	1.2	4.2
$HO_2CCH_2CO_2H$	Malonic acid	2.9	5.7
$HO_2C(CH_2)_2CO_2H$	Succinic acid	4.2	5.6
$HO_2C(CH_2)_3CO_2H$	Glutaric acid	4.3	5.4
$HO_2C(CH_2)_4CO_2H$	Adipic acid	4.4	5.6

Anhydride Formation by Dibasic Acids

- Cyclic anhydrides with 5- and 6-membered rings can be synthesized by heating the appropriate diacid

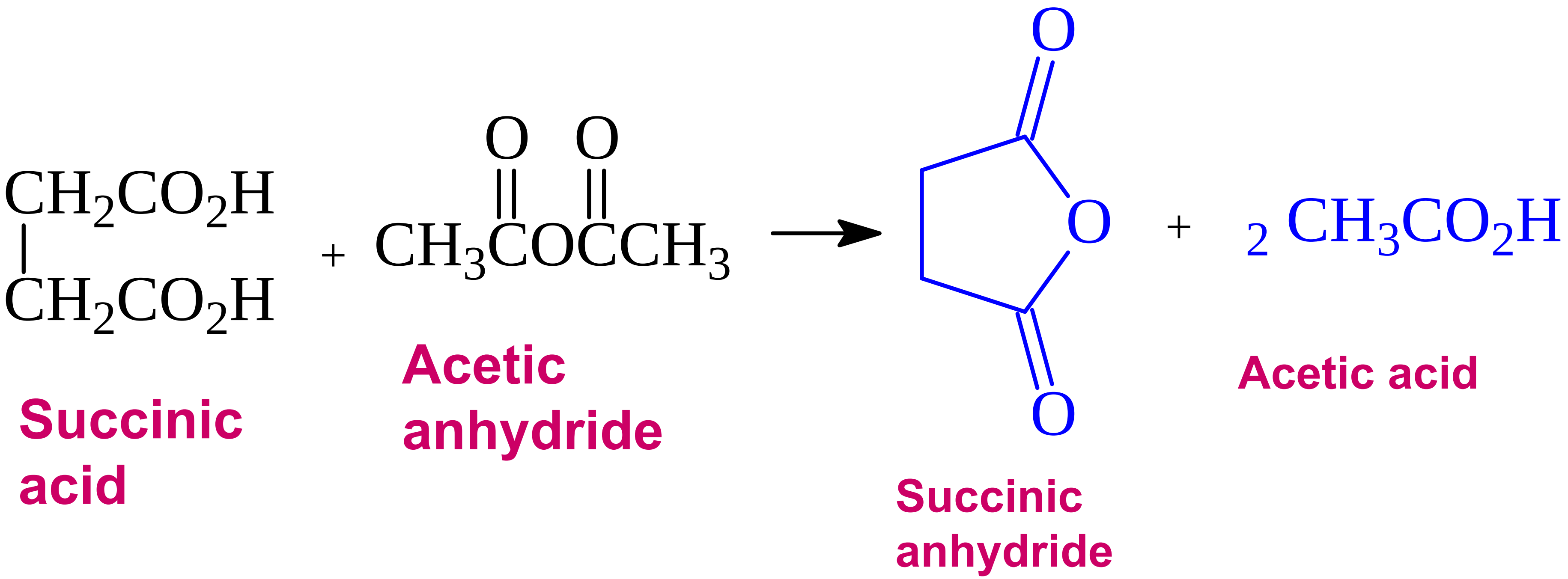


Succinic acid **Succinic anhydride**



Phthalic acid **Phthalic anhydride**
(~100%)

Anhydrides can be formed by heating with acetic anhydride

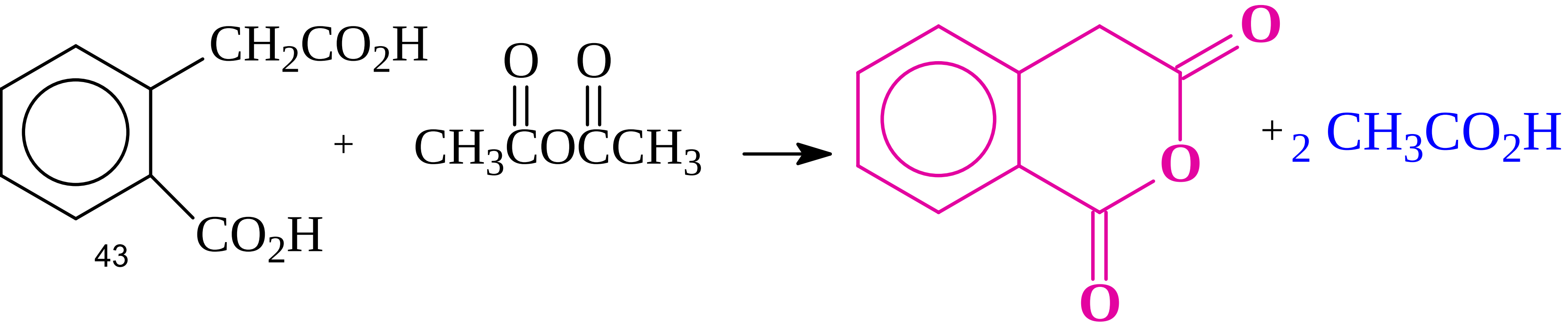


Succinic acid

Acetic anhydride

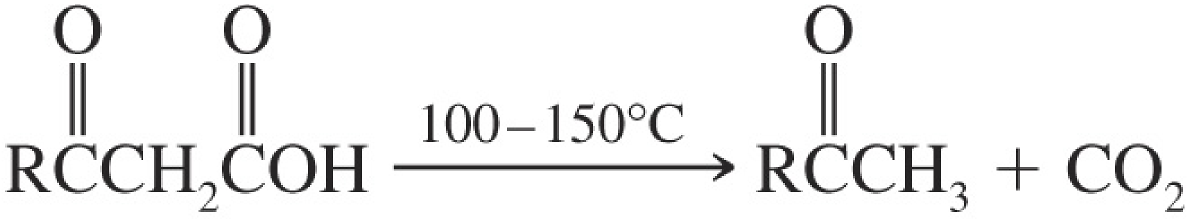
Succinic anhydride

Acetic acid



Decarboxylation of Carboxylic Acids

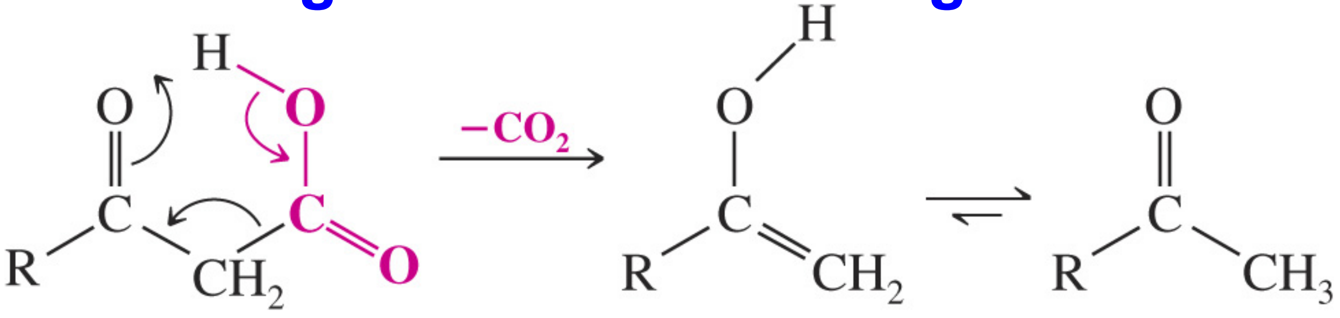
1. β-Keto carboxylic acids decarboxylate readily when heated



$$R\overset{\overset{O}{\|}}{C}CH_2\overset{\overset{O}{\|}}{C}OH \xrightarrow{100-150^\circ C} R\overset{\overset{O}{\|}}{C}CH_3 + CO_2$$

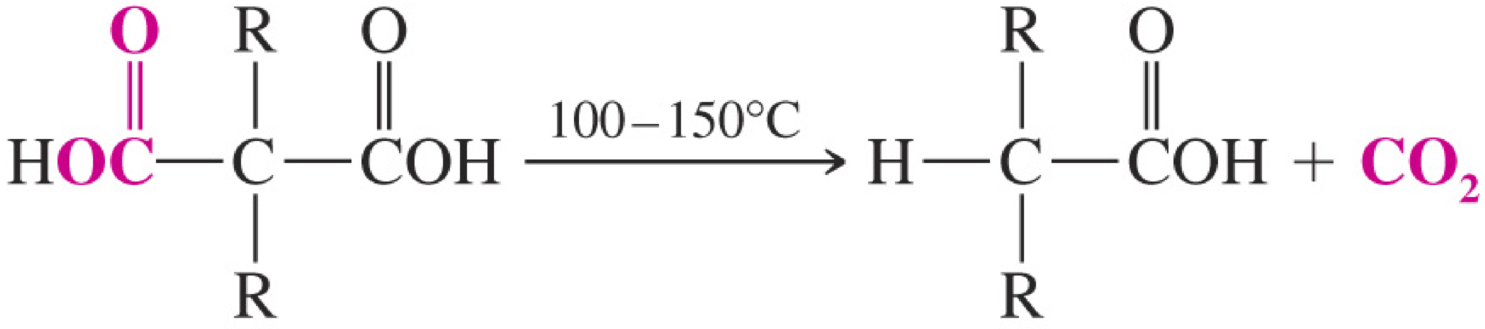
A *β*-keto acid

The mechanism of β-keto acid decarboxylation proceeds through a 6-membered ring transition state



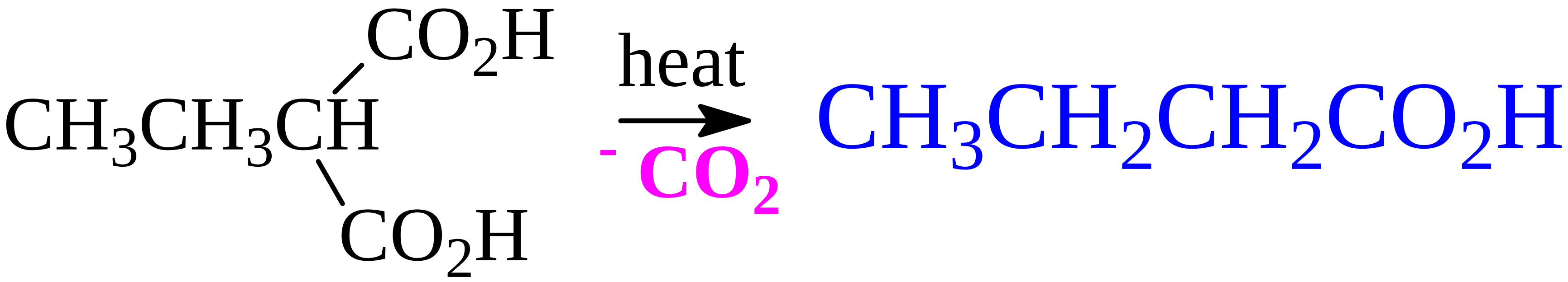
***β*-Keto acid** **Enol** **Ketone**

2. A β-diacid also decarboxylate when heated.



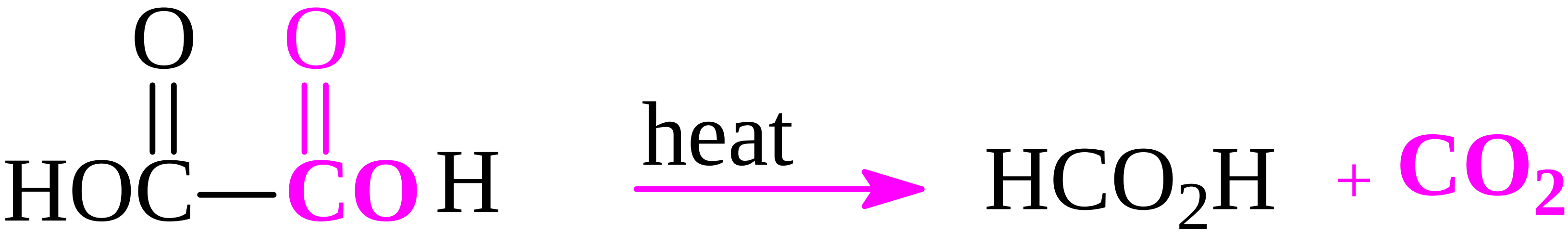
$$\mathrm{HO\overset{O}{\overset{\|}{C}}-\overset{R}{\overset{|}{\underset{R}{\underset{|}{C}}}}-\overset{O}{\overset{\|}{C}}OH \xrightarrow{100-150^\circ C} H-\overset{R}{\overset{|}{\underset{R}{\underset{|}{C}}}}-\overset{O}{\overset{\|}{C}}OH + CO_2}$$

A malonic acid



$$\mathrm{CH_3CH_3CH(CO_2H)_2 \xrightarrow[-\,CO_2]{heat} CH_3CH_2CH_2CO_2H}$$

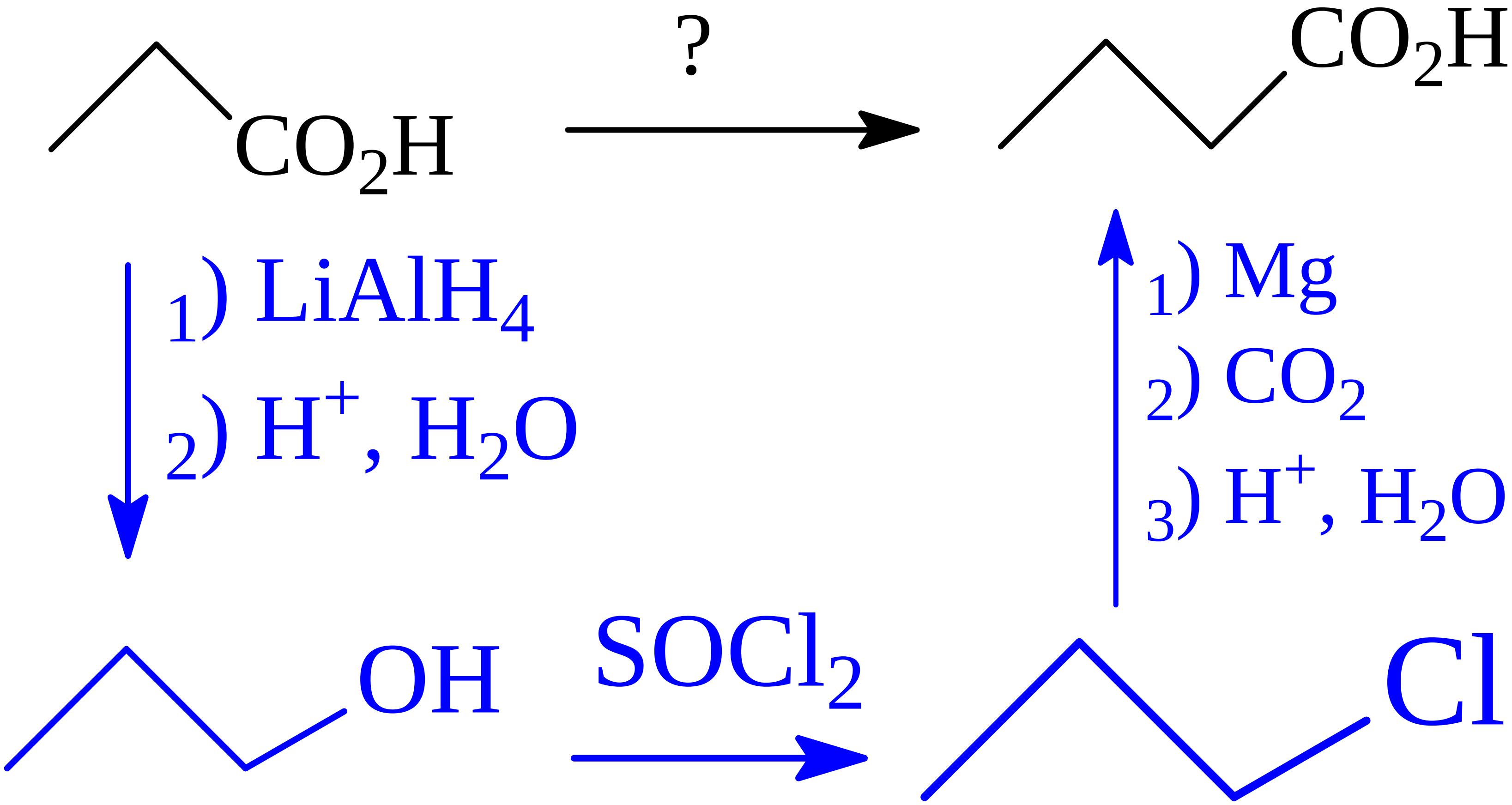
3. A few α-carbonyl acids can undergo decarboxylation



$$\mathrm{HO}\overset{\mathrm{O}}{\overset{\|}{\mathrm{C}}}-\overset{\mathrm{O}}{\overset{\|}{\mathrm{C}}}\mathrm{OH} \xrightarrow{\text{heat}} \mathrm{HCO_2H} + \mathrm{CO_2}$$

$$\mathrm{CH_3}\overset{\mathrm{O}}{\overset{\|}{\mathrm{C}}}-\overset{\mathrm{O}}{\overset{\|}{\mathrm{C}}}\mathrm{OH} \xrightarrow{\text{heat}} \mathrm{CH_3}\overset{\mathrm{O}}{\overset{\|}{\mathrm{C}}}-\mathrm{H} + \mathrm{CO_2}$$

Synthesis



1) $LiAlH_4$
2) H^+, H_2O

$SOCl_2$

1) Mg
2) CO_2
3) H^+, H_2O

Another synthetic problem