Chapter 20
The Chemistry of Carboxylic Acids

Eric J. Kantorowski
California Polytechnic State University
San Luis Obispo, CA
Chapter 20 Overview

• 20.1 Nomenclature of Carboxylic Acids
• 20.2 Structure and Physical Properties of Carboxylic Acids
• 20.3 Spectroscopy of Carboxylic Acids
• 20.4 Acid-Base Properties of Carboxylic Acids
• 20.5 Fatty Acids, Soaps, and Detergents
• 20.6 Synthesis of Carboxylic Acids
• 20.7 Introduction to Carboxylic Acids Reactions
• 20.8 Conversion of Carboxylic Acids into Esters
• 20.9 Conversion of Carboxylic Acids into Acid Chlorides and Anhydrides
• 20.10 Reduction of Carboxylic Acids to Primary Alcohols
• 20.11 Decarboxylation of Carboxylic Acids
Carboxylic Acids

• The characteristic functional group in carboxylic acids is the **carboxy group**

\[
\begin{align*}
\text{H}_3\text{C} & \equiv \text{C} \equiv \text{OH} \quad \text{acetic acid} \\
\text{H}_3\text{C} & \equiv \text{CO}_2\text{H} \quad \text{condensed structure}
\end{align*}
\]

• This chapter will also survey the chemistry of sulfonic acids

\[
\begin{align*}
\text{H}_3\text{C} & \equiv \text{S} \equiv \text{OH} \quad \text{methanesulfonic acid} \\
\text{H}_3\text{C} & \equiv \text{SO}_3\text{H} \quad \text{condensed structure}
\end{align*}
\]

20.1 Nomenclature of Carboxylic Acids
Common Nomenclature

- Dicarboxylic acids

\[
\begin{align*}
\text{H}_3\text{C} & \xrightarrow{\text{O}} \text{C} \xrightarrow{\text{OH}} \text{acet} + \text{i}c\ \text{acid} = \text{acetic acid} \\
\text{benzo} + \text{i}c\ \text{acid} & = \text{benzoic acid} \\
\text{H}_3\text{C} & \xrightarrow{\text{C}} \text{CH}_2 \xrightarrow{\text{CH}} \text{CH} \xrightarrow{\text{C}} \text{OH} \quad \gamma \xrightarrow{\beta} \alpha \xrightarrow{\text{O}} \text{Br} \\
& = \alpha\text{-bromobutyric acid}
\end{align*}
\]

- succinic acid
- methylmalonic acid
- \(\beta,\beta\)-dimethylglutaric acid
- phthalic acid

20.1 *Nomenclature of Carboxylic Acids*
# Common Nomenclature

<table>
<thead>
<tr>
<th>Systematic name</th>
<th>Common name</th>
<th>Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>methanoic* acid</td>
<td>formic acid</td>
<td>HCO₂H</td>
</tr>
<tr>
<td>ethanoic* acid</td>
<td>acetic acid</td>
<td>CH₃CO₂H</td>
</tr>
<tr>
<td>propanoic acid</td>
<td>propionic acid</td>
<td>CH₃CH₂CO₂H</td>
</tr>
<tr>
<td>butanoic acid</td>
<td>butyric acid</td>
<td>CH₃CH₂CH₂CO₂H</td>
</tr>
<tr>
<td>2-methylpropanoic acid</td>
<td>isobutyric acid</td>
<td>(CH₃)₂CHCO₂H</td>
</tr>
<tr>
<td>pentanoic acid</td>
<td>valeric acid</td>
<td>CH₂(CH₂)₂CO₂H</td>
</tr>
<tr>
<td>3-methylbutanoic acid</td>
<td>isovaleric acid</td>
<td>(CH₃)₂CHCH₂CO₂H</td>
</tr>
<tr>
<td>2,2-dimethylpropanoic acid</td>
<td>pivalic acid</td>
<td>(CH₃)₂CCO₂H</td>
</tr>
<tr>
<td>hexanoic acid</td>
<td>caproic acid</td>
<td>CH₂(CH₂)₄CO₂H</td>
</tr>
<tr>
<td>octanoic acid</td>
<td>caprylic acid</td>
<td>CH₂(CH₂)₆CO₂H</td>
</tr>
<tr>
<td>decanoic acid</td>
<td>capric acid</td>
<td>CH₂(CH₂)₈CO₂H</td>
</tr>
<tr>
<td>dodecanoic acid</td>
<td>lauric acid</td>
<td>CH₂(CH₂)₁₀CO₂H</td>
</tr>
<tr>
<td>tetradecanoic acid</td>
<td>myristic acid</td>
<td>CH₂(CH₂)₁₂CO₂H</td>
</tr>
<tr>
<td>hexadecanoic acid</td>
<td>palmitic acid</td>
<td>CH₂(CH₂)₁₄CO₂H</td>
</tr>
<tr>
<td>octadecanoic acid</td>
<td>stearic acid</td>
<td>CH₂(CH₂)₁₆CO₂H</td>
</tr>
<tr>
<td>2-propenoic* acid</td>
<td>acrylic acid</td>
<td>H₂C==CHCO₂H</td>
</tr>
<tr>
<td>2-butoenoic* acid</td>
<td>crotonic acid</td>
<td>CH₃CH==CHCO₂H</td>
</tr>
<tr>
<td>benzoic acid</td>
<td>benzoic acid</td>
<td>PhCO₂H</td>
</tr>
</tbody>
</table>

*The common name is almost always used instead.

## 20.1 Nomenclature of Carboxylic Acids
## Common Nomenclature

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Dicarboxylic acids</th>
<th>Molecular Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>ethanedioic* acid</td>
<td>oxalic acid</td>
<td>HO₂C—CO₂H</td>
</tr>
<tr>
<td>propanedioic* acid</td>
<td>malonic acid</td>
<td>HO₂C(CH₃)CO₂H</td>
</tr>
<tr>
<td>butanedioic* acid</td>
<td>succinic acid</td>
<td>HO₂C(CH₂)₂CO₂H</td>
</tr>
<tr>
<td>pentanedioic* acid</td>
<td>glutaric acid</td>
<td>HO₂C(CH₂)₃CO₂H</td>
</tr>
<tr>
<td>hexanedioic* acid</td>
<td>adipic acid</td>
<td>HO₂C(CH₂)₄CO₂H</td>
</tr>
<tr>
<td>heptanedioic* acid</td>
<td>pimelic acid</td>
<td>HO₂C(CH₂)₅CO₂H</td>
</tr>
<tr>
<td>1,2-benzenedicarboxylic*</td>
<td>phththalic acid</td>
<td><img src="image" alt="Phthalic Acid" /></td>
</tr>
<tr>
<td>acid</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Z)-2-butenedioic* acid</td>
<td>maleic acid</td>
<td><img src="image" alt="Maleic Acid" /></td>
</tr>
<tr>
<td>(E)-2-butenedioic* acid</td>
<td>fumaric acid</td>
<td><img src="image" alt="Fumaric Acid" /></td>
</tr>
</tbody>
</table>

*The common name is almost always used instead.

## 20.1 Nomenclature of Carboxylic Acids
Substitutive Nomenclature

propane + oic acid = propanoic acid

octanedioic acid

3-methylpentanoic acid
cyclohexanecarboxylic acid

1,2,4-benzenetricarboxylic acid

Priority for citation as principal group:

\[ \text{O} > \text{C—OH} > \text{C—H} > \text{C—} > \text{—OH} > \text{—SH} \]

20.1 Nomenclature of Carboxylic Acids
• The **carbonyl oxygen** is the oxygen involved with the C=O double bond

• The **carboxylate oxygen** is the oxygen involved with the C-O single bond
• Many aromatic and dicarboxylic acids are solids

• Simple carboxylic acids and dicarboxylic acids are soluble in water (H-bonding)
IR Spectroscopy

- C=O stretch: 1710 cm\(^{-1}\) (as the dimer)
- O-H stretch: 2400-3600 cm\(^{-1}\) (very broad)

![IR Spectroscopy of Carboxylic Acids](image)
NMR Spectroscopy

- O-H: δ 9-13 (broad; exchanges with D$_2$O)
Acidity of Carboxylic Acids

- Acidity is one of the most important properties of carboxylic acids

\[ R-C=O + H_2O \rightleftharpoons R-C=O^- + H_3O^+ \]

carboxylic acid  \hspace{5em}  carboxylate ion

- Conjugate bases of carboxylic acids are called carboxylate ions

\[ \text{sodium acetate} \]
}\hspace{5em} \text{potassium benzoate}\\
\text{(aceté + ate = acetate)}
Acidity of Carboxylic Acids

Increasing acidity

C₂H₅—O—H  O
ₚKₐ  15.9

O

O

H₃C—C—O—H

ₚKₐ  9.95  4.76

resonance structures of acetate ion

H₃C—CO₂H  FCH₂—CO₂H  F₂CH—CO₂H  F₃C—CO₂H

acetic acid  fluoroacetic acid  difluoroacetic acid  trifluoroacetic acid

ₚKₐ  4.76  2.66  1.24  0.23

20.4 Acid-Base Properties of Carboxylic Acids
# pK_a Values of Some Carboxylic Acids

<table>
<thead>
<tr>
<th>Acid*</th>
<th>pK_a</th>
</tr>
</thead>
<tbody>
<tr>
<td>formic</td>
<td>3.75</td>
</tr>
<tr>
<td>acetic</td>
<td>4.76</td>
</tr>
<tr>
<td>propionic</td>
<td>4.87</td>
</tr>
<tr>
<td>2,2-dimethylpropanoic (pivalic)</td>
<td>5.05</td>
</tr>
<tr>
<td>acrylic</td>
<td>4.26</td>
</tr>
<tr>
<td>chloroacetic</td>
<td>2.85</td>
</tr>
<tr>
<td>phenylacetic</td>
<td>4.31</td>
</tr>
<tr>
<td>benzoic</td>
<td>4.18</td>
</tr>
<tr>
<td>p-methylbenzoic (p-toluic)</td>
<td>4.37</td>
</tr>
<tr>
<td>p-nitrobenzoic</td>
<td>3.43</td>
</tr>
<tr>
<td>p-chlorobenzoic</td>
<td>3.98</td>
</tr>
<tr>
<td>p-methoxybenzoic (p-anisic)</td>
<td>4.47</td>
</tr>
<tr>
<td>2,4,6-trinitrobenzoic</td>
<td>0.65</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Acid*</th>
<th>First pK_a</th>
<th>Second pK_a</th>
</tr>
</thead>
<tbody>
<tr>
<td>carbonic</td>
<td>3.77*</td>
<td>10.33</td>
</tr>
<tr>
<td>oxalic</td>
<td>1.27</td>
<td>4.27</td>
</tr>
<tr>
<td>malonic</td>
<td>2.86</td>
<td>5.70</td>
</tr>
<tr>
<td>succinic</td>
<td>4.21</td>
<td>5.64</td>
</tr>
<tr>
<td>glutaric</td>
<td>4.34</td>
<td>5.27</td>
</tr>
<tr>
<td>adipic</td>
<td>4.41</td>
<td>5.28</td>
</tr>
<tr>
<td>phthalic</td>
<td>2.95</td>
<td>5.41</td>
</tr>
</tbody>
</table>

*See Table 20.1 for structures.

\*This value, which corrects for the amount of H_2CO_3 in aqueous CO_2, is the actual pK_a of carbonic acid. An often-cited value of 6.4 treats all dissolved CO_2 as H_2CO_3.
Acidity of Sulfonic Acids

- Sulfonic acids are useful as acid catalysts in organic solvents because they are more soluble than most inorganic acids

\[ \text{\textit{p-toluenesulfonic acid}} \]

(TsOH, or tosic acid)

a strong acid; \( pK_a \approx -1 \)

\[ \text{\textit{sulfonate anion}} \]

\[ \text{\textit{octet structure}} \]

20.4 Acid-Base Properties of Carboxylic Acids
Acidity of Carboxylic Acids

• The alkali metal salts of carboxylic acids are soluble in water

\[
\begin{align*}
R-C-\overset{\cdot}{O}H + Na^+ - OH \xrightarrow{H_2O} R-C-\overset{\cdot}{O}^- Na^+ + H_2O
\end{align*}
\]

more soluble than the carboxylic acid in water

• Even a 5% NaHCO\textsubscript{3} solution is basic enough (pH ≈ 8.5) to dissolve a carboxylic acid
Basicity of Carboxylic Acids

• The carbonyl oxygen is weakly basic

\[
\begin{align*}
R-C-\ddot{O}H + H_3O^+ & \rightleftharpoons [ \overset{\ddot{O}H}{\overset{\ddot{O}H}{\overset{\ddot{O}H}{\overset{\ddot{O}H}}}} R-C-\ddot{O}H \rightleftharpoons R-C-\ddot{O}H] + H_2O \\
\text{protonated carboxylic acid} & \text{pK}_a \approx -6
\end{align*}
\]

• Note that the carboxylate oxygen is \textit{not} protonated

\[
\begin{align*}
+\ddot{O}H & R-C-\ddot{O}H \\
\text{resonance-stabilized} & \text{(Eq. 20.8)}
\end{align*}
\]

\[
\begin{align*}
:O: & R-C-\overset{+}{O}-H \\
\text{not resonance-stabilized;} & \text{does not form}
\end{align*}
\]

• The basicity of carboxylic acids plays an important role in many of their reactions
Fatty Acids

• Carboxylic acids with long, unbranched carbon chains

\[ \text{CH}_3(\text{CH}_2)_{14}\text{CO}_2\text{H} \] or \[ \text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CO}_2\text{H} \]

- Palmitic acid
  (from palm oil)

- Stearic acid
  (Greek *stear*, meaning “tallow,” or “beef fat”)

\[ \text{CH}_3(\text{CH}_2)_{16}\text{CO}_2\text{H} \]

- Oleic acid

• Many are isolated from fats and oils by the hydrolytic process of *saponification*
Soaps and Detergents

• Na$^+$ and K$^+$ salts of fatty acids are **soaps**

\[
\text{CH}_3(\text{CH}_2)_{16}-\text{C}--\text{O}^- \quad \text{Na}^+
\]

**sodium stearate**
(a soap)

• Soaps are part of a larger class of compounds called **detergents**

\[
\text{Na}^+ \quad \text{O}--\text{S}--\text{(CH}_2\text{)}_{11}\text{CH}_3
\]

**sodium 4-dodecyl-1-benzenesulfonate**
(a synthetic detergent)
Surfactants

• Soaps and detergents are part of an even broader class of compounds called surfactants.

• Surfactants contain a polar head group and a hydrocarbon tail.

\[
\text{PhCH}_2\text{--N}^+\text{--(CH}_2\text{)}_{15}\text{CH}_3\text{--Cl}^- \\
\text{CH}_3
\]

benzylcetyldimethylammonium chloride (benzalkonium chloride) a cationic surfactant and germicide

• Phospholipids are also surfactants.
Micelles

- Micelles form when the surfactant concentration is raised above the **critical micelle concentration**
- Micelles are spherical aggregates of 50-150 surfactant molecules
Synthesis of Carboxylic Acids

- Oxidation of primary alcohols
- Side-chain oxidation of alkylbenzenes
- Grignard or organolithium with carbon dioxide
Carboxylic Acid Reactions

• There are four main types of reactions:
  1. Reactions at the carbonyl group
  2. Reactions at the carboxylate oxygen
  3. Loss of the carboxy group as CO$_2$ (decarboxylation)
  4. Reactions involving the $\alpha$-carbon (Ch 22)
Carboxylic Acid Reactions

- Reactions at the carbonyl group

\[
\begin{align*}
\text{R–C–OH} + \text{E–Y} & \rightleftharpoons \text{R–C–Y} + \text{HO–E} \\
\text{R–C–OH} & \rightleftharpoons \text{R–C═O} + \text{Y}^{-}
\end{align*}
\]
Carboxylic Acid Reactions

• Reactions at the carboxyl group

\[
\begin{align*}
&\text{R} - \text{C} - \ddot{\text{O}} - \text{H} + \text{H}_2\text{O}^\ddagger \quad \text{\rightarrow} \quad \text{R} - \text{C} - \ddot{\text{O}}^- \quad \text{\rightarrow} \quad \text{R} - \text{C} = \ddot{\text{O}}^- + \text{H}_3\text{O}^+ \\
&\text{R} - \text{C} - \ddot{\text{O}}^- + \text{E} - \dddot{\text{Y}} \quad \text{\rightarrow} \quad \text{R} - \text{C} - \dddot{\text{O}} - \text{E} + \dddot{\text{Y}}^- \end{align*}
\]
Carboxylic Acid Reactions

• Loss of the carboxy group as CO$_2$ (decarboxylation)
Acid-Catalyzed Esterification

• Esters are carboxylic acid derivatives

\[
\begin{align*}
\text{R—C—O—R'} & \quad (R = \text{H, alkyl, or aryl; } R' = \text{alkyl or aryl}) \\
\text{general structure} & \quad \text{of an ester}
\end{align*}
\]

\[
\text{C—OH} + \text{CH}_3\text{OH} \xrightarrow{\text{H}_2\text{SO}_4} \text{C—OCH}_3 + \text{H}_2\text{O}
\]

• Also referred to as the Fischer esterification
• The equilibrium is favorable, but not large
• The alcohol needs to be present in large excess (commonly as the solvent)

20.8 Conversion of Carboxylic Acids into Esters
Acid-Catalyzed Esterification

• Isotopic labeling with $^{18}$O determined that the carboxyl oxygen in the ester is from the alcohol

$$\text{Ph} - \text{C} - \text{OH} + \text{H}_3\text{C} - \text{OH} \rightarrow \text{Ph} - \text{C} - \text{OCH}_3 + \text{H}_2\text{O}$$

or

$$\text{Ph} - \text{C} - \text{OCH}_3 + \text{H}_2\text{O}$$

20.8 Conversion of Carboxylic Acids into Esters
Acid-Catalyzed Esterification

$\text{20.8 Conversion of Carboxylic Acids into Esters}$
Acid-Catalyzed Esterification

20.8 Conversion of Carboxylic Acids into Esters
Acid-Catalyzed Esterification

- Esterification illustrates a very general mechanistic pattern

\[
\begin{align*}
\text{O} & \quad \text{R} \quad \text{C} \quad \text{X} + \text{Y} \quad \text{H} & \quad \text{R} \quad \text{C} \quad \text{X} & \quad \text{R} \quad \text{C} \quad \text{Y} + \text{X} \quad \text{H} \\
\text{can act as a leaving group} & \quad \text{tetrahedral} & \quad \text{addition intermediate}
\end{align*}
\]

- Compare with aldehydes and ketones

\[
\begin{align*}
\text{O} & \quad \text{R} \quad \text{C} \quad \text{R} + \text{Y} \quad \text{H} & \quad \text{R} \quad \text{C} \quad \text{R} & \quad \text{R} \quad \text{C} \quad \text{R} \quad \text{Y} \\
\text{cannot act as leaving groups}
\end{align*}
\]

20.8 Conversion of Carboxylic Acids into Esters
Esterification by Alkylation

- The carboxylate oxygen acts as a nucleophile

\[
\begin{align*}
\text{CH}_3(\text{CH}_2)_3\text{CH}_2 & \quad \text{H} \\
\text{C} & \quad \text{C} \\
\text{C} & \quad \text{C} \\
\text{O} & \quad \text{H} \\
\end{align*}
\]

\((E)-2\text{-octenoic acid}\)

\[
\begin{align*}
\text{CH}_3(\text{CH}_2)_3\text{CH}_2 & \quad \text{H} \\
\text{C} & \quad \text{C} \\
\text{C} & \quad \text{C} \\
\text{O} & \quad \text{OCH}_3 \\
\end{align*}
\]

\((E)-2\text{-octenoic acid \ (91\% \ yield)}\)

\[
\begin{align*}
\text{R} & \quad \text{C} \\
\text{O} & \quad \text{H} \\
\end{align*}
\]

\(\text{R-C-O^- + H}_2\text{C-N}=\text{N}: \rightarrow \text{R-C-O^-} + \text{H}_3\text{C-N}=\text{N}:\)

\(\text{methyl diazonium ion}\)

\[
\begin{align*}
\text{R} & \quad \text{C} \\
\text{O} & \quad \text{CH}_3 \\
\end{align*}
\]

\(\text{R-C-O^-} + \text{H}_3\text{C-N}=\text{N}: \rightarrow \text{R-C-O^-CH}_3 + \text{N}=\text{N}:\)

20.8 Conversion of Carboxylic Acids into Esters
Esterification by Alkylation

- Carboxylate ions are less basic, and therefore less nucleophilic, than alkoxides

\[
\text{K}_2\text{CO}_3 + \text{C} \quad \text{H}_3\text{C} - \text{I} \rightarrow \text{acetone} \rightarrow \text{C} \quad \text{OCH}_3
\]

2-acetylbenzoic acid

- This is an $S_N2$ reaction and works best with especially reactive alkylation agents

20.8 Conversion of Carboxylic Acids into Esters
Synthesis of Acid Chlorides

\[ R - C - Cl \quad (R = H, \text{ alkyl, or aryl}) \]

General structure of an acid chloride

\[
\begin{align*}
\text{CH}_3\text{CH}_2\text{CH}_2\text{C} - \text{OH} + \text{SOCl}_2 & \rightarrow \text{CH}_3\text{CH}_2\text{CH}_2\text{C} - \text{Cl} + \text{HCl} + \text{SO}_2 \\
\text{butyric acid} & \quad \text{thionyl chloride} \\
\text{butyryl chloride} \quad & \quad \text{(an acid chloride; 85% yield)}
\end{align*}
\]

\[
\begin{align*}
\text{O}_2\text{N-} - \text{C} - \text{OH} + \text{PCl}_3 & \rightarrow \text{O}_2\text{N-} - \text{C} - \text{Cl} + \text{POCl}_3 + \text{HCl} \\
p\text{-nitrobenzoic acid} & \quad \text{phosphorus pentachloride} \\
p\text{-nitrobenzoyl chloride} \quad & \quad \text{(90–96% yield)}
\end{align*}
\]

\[
\begin{align*}
\text{O} & \quad \text{Cl is substituted for } \text{OH} \\
\text{R} - \text{C} - \text{OH} & \rightarrow \text{R} - \text{C} - \text{Cl}
\end{align*}
\]

20.9 Conversion of Carboxylic Acids into Acid Chlorides and Anhydrides
Synthesis of Sulfonyl Chlorides

- Sulfonyl chlorides are the acid chlorides of sulfonic acids
- Typically their sodium salts are treated with PCl$_5$

$$\text{H}_3\text{C} - \text{SO}^-\text{Na}^+ + \text{PCl}_5 \rightarrow \text{H}_3\text{C} - \text{SO}^\text{Cl} + \text{POCl}_3 + \text{NaCl}$$

20.9 Conversion of Carboxylic Acids into Acid Chlorides and Anhydrides
Synthesis of Sulfonyl Chlorides

- Aromatic sulfonyl chlorides may also be prepared

\[
\text{benzene} + 2\text{ClSO}_2\text{H} \xrightarrow{20-25 \, ^\circ\text{C}} \text{benzenesulfonyl chloride} (73-77\% \text{ yield})
\]

\[
\text{benzene} + \text{ClSO}_3\text{H} \rightarrow \text{benzenesulfonic acid} + \text{HCl}
\]

\[
\text{benzenesulfonic acid} + \text{ClSO}_3\text{H} \xrightarrow{(\text{excess})} \text{benzenesulfonyl chloride} + \text{H}_2\text{SO}_4 + \text{HCl}
\]

20.9 Conversion of Carboxylic Acids into Acid Chlorides and Anhydrides
Synthesis of Anhydrides

\[ R-C-O-C-R \quad (R = H, \text{ alkyl, or aryl}) \]

general structure of an anhydride

• *Anhydride* = “without water”

\[ R-C-O-C-R + H_2O \rightarrow R-C-OH + HO-C-R \]

an anhydride

\[ 2F_3C-C-OH + P_2O_5 \rightarrow F_3C-O-C-O-CF_3 + \text{complex phosphates} \]

trifluoroacetic acid
phosphorus pentoxide

trifluoroacetic anhydride
(74% yield)

20.9 Conversion of Carboxylic Acids into Acid Chlorides and Anhydrides
Synthesis of Anhydrides

- Most anhydrides may themselves be used to form other anhydrides

\[ \text{H}_3\text{C}-\text{CH} \qquad + \qquad \text{H}_3\text{C}-\text{C} \qquad \rightarrow \qquad \text{H}_3\text{C}-\text{CH} \]

\[ \text{CH}_2\text{C} \qquad \text{OH} \qquad \text{O} \quad \text{acetic anhydride} \]

\[ \text{CH}_2\text{C} \qquad \text{O} \quad + \quad 2\text{H}_3\text{C} \qquad \text{C} \qquad \text{OH} \]

\[ \beta\text{-methylglutaric acid} \quad \text{\textbeta\text{-methylglutaric anhydride}} \]

(\text{>90% yield; a cyclic anhydride})
Synthesis of Anhydrides

- 5- and 6-membered ring anhydrides can commonly be formed simply by heating.
Reduction of Carboxylic Acids

- The powerful reducing agent LiAlH$_4$ is required

2. Reduction of Carboxylic Acids to Primary Alcohols

20.10 Reduction of Carboxylic Acids to Primary Alcohols
Reduction of Carboxylic Acids

• The overall sequence for reduction is summarized as:

\[
\text{R—C—OH} \xrightarrow{\text{substitution}} \text{R—C—H} \xrightarrow{\text{addition}} \text{R—C—H
}\]

20.10 Reduction of Carboxylic Acids to Primary Alcohols
Decarboxylation of Carboxylic Acids

- **Decarboxylation**: The loss of CO$_2$ from RCO$_2$H

\[
\begin{align*}
\text{R} &\text{C} &\text{O} &\text{H} &\longrightarrow &\text{R} &\text{H} &\text{O} &\text{O} \\
& & & & & & & &
\end{align*}
\]

- Most ordinary carboxylic acids do not participate, but the following types do:
  1. $\beta$-keto acids
  2. Malonic acid derivatives
  3. Carbonic acid derivatives
Decarboxylation of Carboxylic Acids

• Decarboxylation from β-keto acids

\[
\begin{align*}
\text{H}_3\text{C} & \quad \text{CH}_2 & \quad \text{OH} & \quad \xrightarrow{\text{H}_3\text{O}^+} & \quad \text{H}_3\text{C} & \quad \text{CH}_2 \\
\text{O} & \quad \text{C} & \quad \text{O} & \quad \text{C} & \quad \text{C} & \quad \text{H}_2 \\
\beta & \quad \alpha & \quad \beta & \quad \text{CH}_3 & \quad \text{C} & \quad \text{H}_3
\end{align*}
\]

acetoacetic acid (a β-ketoacid) \quad \xrightarrow{25^\circ C} \quad \text{acetone} + \text{CO}_2

• Decarboxylation of the β-keto acid occurs more readily than its conjugate base form

20.11 Decarboxylation of Carboxylic Acids
Decarboxylation of Carboxylic Acids

- Decarboxylation from malonic acid derivatives

\[
\text{HO}_2\text{C} - \text{CH} - \text{CO}_2\text{H} \xrightarrow{\text{H}_3\text{O}^+ \atop 135^\circ\text{C}} \text{HO}_2\text{C} - \text{CH}_2 + \text{CO}_2
\]

- methylmalonic acid
- propionic acid

- This reaction also does not occur in base
- Note the similarity to the $\beta$-keto acid

\[
\text{O} \quad \begin{array}{c} \beta \\ \alpha \end{array} \quad \text{HO} - \text{C} - \text{CH}_2 - \text{CO}_2\text{H} \quad \text{R} - \text{C} - \text{CH}_2 - \text{CO}_2\text{H}
\]

- malonic acid
- a $\beta$-keto acid
Decarboxylation of Carboxylic Acids

- Decarboxylation from carbonic acid derivatives

\[
\begin{align*}
\text{carbonic acid} & \quad \overset{\text{H}_3\text{O}^+}{\rightleftharpoons} \quad \text{CO}_2 + \text{H}_2\text{O} \\
\text{methyl carbonate} & \quad \overset{\text{H}_3\text{O}^+}{\rightleftharpoons} \quad \text{CH}_3\text{OH} + \text{CO}_2 \\
\text{carbamic acid} & \quad \overset{\text{H}_3\text{O}^+}{\rightleftharpoons} \quad \text{CO}_2 + \text{NH}_3 \quad \overset{\text{H}_2\text{O}^+}{\rightleftharpoons} \quad \text{NH}_4^+
\end{align*}
\]