Carboxylic acids, esters, and other acid derivatives

Chapter 16
Structure of carboxylic acids and their derivatives

- The functional group present in a carboxylic acid is a combination of a carbonyl group and a hydroxyl group; however, the resulting **carboxyl group** (-COOH) possesses properties that are unlike those present in aldehydes/ketones and alcohols.

![Diagram showing the structure of a carboxylic acid with labels for carbonyl group, hydroxyl group, and carboxyl group.]
Structure of carboxylic acids and their derivatives

- Carboxylic acids have the following general formula:

- Some simple carboxylic acids:
  - Formic acid
    - IUPAC: Methanoic acid
  - Acetic acid
    - IUPAC: Ethanoic acid
  - Benzoic acid
    - IUPAC: Benzoic acid

- Since carbon can have only four bonds, there are no cyclic carboxylic acids (i.e. the carboxyl group cannot form part of a carbon ring)
Structure of carboxylic acids and their derivatives

• The following molecules have a similar structure to carboxylic acids, and will be encountered in this chapter and the next.

- Carboxylic acid
- Ester
- Acid chloride
- Acid anhydride
- Amide
IUPAC nomenclature for carboxylic acids

- For **naming** carboxylic acids:
  - Select the longest, continuous carbon chain that involves the carboxyl group. This is the parent chain and the \(-\text{COOH}\) carbon is designated as C #1.
  - Name the parent chain by dropping the “e” from the corresponding alkane name and changing to “oic acid”
  - Indicate the identity and location of substituents on the parent chain at the front of the carboxylic acid’s name

- **Butanoic acid**
- **3,3-Dibromobutanoic acid**
- **2-Methylpropanoic acid**
- **3,5-Dichlorobenzoic acid**

![Chemical structures of various carboxylic acids](image-url)
### Common names for carboxylic acids

<table>
<thead>
<tr>
<th>Length of Carbon Chain</th>
<th>Structural Formula</th>
<th>Common Name(^a)</th>
<th>IUPAC Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{C}_1) monoacid</td>
<td>(\text{H—COOH})</td>
<td>formic acid</td>
<td>methanoic acid</td>
</tr>
<tr>
<td>(\text{C}_2) monoacid</td>
<td>(\text{CH}_3—\text{COOH})</td>
<td>acetic acid</td>
<td>ethanoic acid</td>
</tr>
<tr>
<td>(\text{C}_3) monoacid</td>
<td>(\text{CH}_3—\text{CH}_2—\text{COOH})</td>
<td>propionic acid</td>
<td>propanoic acid</td>
</tr>
<tr>
<td>(\text{C}_4) monoacid</td>
<td>(\text{CH}_3—(\text{CH}_2)_2—\text{COOH})</td>
<td>butyric acid</td>
<td>butanoic acid</td>
</tr>
<tr>
<td>(\text{C}_5) monoacid</td>
<td>(\text{CH}_3—(\text{CH}_2)_3—\text{COOH})</td>
<td>valeric acid</td>
<td>pentanoic acid</td>
</tr>
<tr>
<td>(\text{C}_6) monoacid</td>
<td>(\text{CH}_3—(\text{CH}_2)_4—\text{COOH})</td>
<td>caproic acid</td>
<td>hexanoic acid</td>
</tr>
</tbody>
</table>

\(^a\) The mnemonic “Frogs are polite, being very courteous” is helpful in remembering, in order, the first letters of the common names of these six simple saturated monocarboxylic acids.
Polyfunctional carboxylic acids

- Carboxylic acids that contain other functional groups besides the –COOH group are called polyfunctional carboxylic acids. Some examples are shown below:

- an unsaturated acid
- a hydroxy acid
- a keto acid
- an aldo acid
- an amino acid

![Chemical structures](image-url)
Polyfunctional carboxylic acids

Unsaturated acids

• Unsaturated acids possess a unit of unsaturation (double/triple C-C bond) in the structure. Three common unsaturated acids are shown:

maleic acid
IUPAC: cis-Butenedioic acid

Ibuprofen

Naproxen
Polyfunctional carboxylic acids

Hydroxy acids

• Four of the simplest hydroxy acids:

![Structural formulas of hydroxy acids]

* don’t memorize these names
Polyfunctional carboxylic acids

Keto acids

• For keto acids, a carbonyl group is present as part of a carbon chain that involves a carboxylic acid group:

For IUPAC naming of this structure, the O-atom of the carbonyl group is treated as an “oxo” substituent and the molecule is called 2-oxopropanoic acid

* don’t memorize these names
Physical properties of carboxylic acids

- Carboxylic acids are the most polar functional group we have seen so far. The presence of the carbonyl group next to the OH causes the O-H bond to be even more polar. This is why -COOH groups are considered to be acidic, while -OH groups are not.

\[
\begin{align*}
\text{alcohols} & \quad \text{carboxylic acids} \\
pK_a & \approx 16-19 \quad pK_a \approx 4-10
\end{align*}
\]
Acidity of carboxylic acids

<table>
<thead>
<tr>
<th>Acid</th>
<th>$K_a$</th>
<th>Percent Ionization (0.100 M Solution)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formic</td>
<td>$1.8 \times 10^{-4}$</td>
<td>4.2%</td>
</tr>
<tr>
<td>Acetic</td>
<td>$1.8 \times 10^{-5}$</td>
<td>1.3%</td>
</tr>
<tr>
<td>Propionic</td>
<td>$1.3 \times 10^{-5}$</td>
<td>1.2%</td>
</tr>
<tr>
<td>Butyric</td>
<td>$1.5 \times 10^{-5}$</td>
<td>1.2%</td>
</tr>
<tr>
<td>Valeric</td>
<td>$1.5 \times 10^{-5}$</td>
<td>1.2%</td>
</tr>
<tr>
<td>Caproic</td>
<td>$1.4 \times 10^{-5}$</td>
<td>1.2%</td>
</tr>
</tbody>
</table>
Acidity of carboxylic acids

- When carboxylic acids are placed in water, they undergo deprotonation as discussed in Ch-10:

\[
HA + H_2O \rightarrow A^- + H_3O^+ 
\]

\[
\text{carboxylic acid} \quad \text{H}_2\text{O} \quad \text{carboxylate ion} \quad \text{hydronium} 
\]

Remember from Ch-10:

\[
HA + H_2O \Leftrightarrow A^- + H_3O^+ 
\]
Acidity of carboxylic acids

\[
\text{H}_3\text{C} = \text{C} - \text{CO}_{\text{OH}} + \text{H}_2\text{O} \rightleftharpoons \text{H}_3\text{C} = \text{C} - \text{O}^- + \text{H}_3\text{O}^+ \\
\text{acetic acid} \quad \text{IUPAC: Ethanoic acid}
\]

\[
\text{H}_2\text{O}_{\text{2}} \quad \text{acetate ion} \quad \text{IUPAC: Ethanoate ion}
\]

\[
\text{HO} = \text{C} = \text{C} - \text{OH} + 2\text{H}_2\text{O} \rightleftharpoons \text{O}^\cdot = \text{C} - \text{C} - \text{O}^- \quad + \quad 2\text{H}_3\text{O}^+ \\
\text{oxalic acid} \quad \text{IUPAC: Ethanedioic acid}
\]

\[
\text{O}^\cdot = \text{C} - \text{C} - \text{O}^- \quad \text{oxalate ion} \quad \text{IUPAC: Ethanedioate ion}
\]
Conjugate bases of carboxylic acid

- The name of the de-protonated carboxylic acid (i.e. the conjugate base) is obtained from the name of the carboxylic acid.
- Remove the “-ic acid” part of the acid’s name and replace with “-ate”

<table>
<thead>
<tr>
<th>Acid</th>
<th>Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>propanoic acid</td>
<td>propanoate ion</td>
</tr>
<tr>
<td>2-methylpropanoic</td>
<td>2-methylpropanoate</td>
</tr>
<tr>
<td>benzoic acid</td>
<td>benzoate ion</td>
</tr>
</tbody>
</table>
Carboxylic acid salts

When carboxylic acids are reacted with strong bases, they are converted to salts as follows:

\[
\text{Acid} + \text{Base} \rightarrow \text{Salt} + \text{H}_2\text{O}
\]

**Example:**

- Carboxylic acid + NaOH → Salt (sodium acetate) + Water

**Chemical Structure:**

\[
\text{R—C—O—H} + \text{NaOH} \rightarrow \text{R—C—O}^- \text{Na}^+ + \text{H}_2\text{O}
\]

**IUPAC:** Sodium ethanoate

**Chemical Formula:**

- Carboxylic acid: R—C—O—H (acetic acid: H$_3$C—C—O—H)
- Base: NaOH
- Salt: R—C—O$^-$ Na$^+$
- Water: H$_2$O

**IUPAC Names:**

- Carboxylic acid: Ethanoic acid
- Sodium acetate: Sodium ethanoate
Carboxylic acid salts

- Salts of carboxylic acids are much more water-soluble than the acids themselves.
- Also, they can be converted back to the acid form by reacting them with a strong acid:

\[
\text{H}_3\text{C} - \text{C} - \text{O}^- \quad \text{Na}^+ + \text{HCl} \quad \rightarrow \quad \text{H}_3\text{C} - \text{C} - \text{OH} + \text{NaCl}
\]

Handy rule: things that are charged tend to be more water-soluble than things that aren’t (when comparing two similar structures)
Uses of carboxylic acid salts

- Because of their enhanced solubility in water compared to the acid form, many drugs and medicines that possess acid groups are marketed as carboxylic acid salts (sodium or potassium salts).

- Benzoic acid
- Potassium benzoate
- Sorbic acid
- Sodium sorbate
A brief review of boiling point trends

- Boiling points are determined by attractions between molecules; the stronger the attractions are, the higher the boiling point for the substance.

Weakest intermolecular attraction (lowest b.p.)

\[ \text{CH}_3\cdot\text{CH}_2\cdot\text{CH}_2\cdot\text{CH}_3 \]

London forces

\[ \text{CH}_3\cdot\text{CH}_2\cdot\text{CH}_2\cdot\text{CH}_3 \]

In simple hydrocarbons (alkanes, alkenes, etc.) there are only non-polar bonds. No dipole-dipole or H-bonding possible. Only London forces.

Mid-range b.p.

\[
\begin{align*}
\text{O} & \quad \text{\Large \varepsilon^-} \\
\text{CH}_3\cdot\text{C} & \quad \text{\Large \varepsilon^+} \\
\text{\Large \varepsilon^-} & \quad \text{\Large \varepsilon^+} \\
\text{CH}_3\cdot\text{C} & \quad \text{\Large \varepsilon^-} \\
\text{\Large \varepsilon^+} & \quad \text{CH}_3
\end{align*}
\]

Dipole-dipole forces

Alkanes, alkenes, alkynes, aromatics

Strongest intermolecular attraction (highest b.p.)

\[ \text{CH}_3\cdot\text{CH}_2\cdot\text{CH}_2\cdot\text{O} \rightarrow \text{H} \]

H-bonding

In certain molecules, a H-atom may be involved in a bond to an O, N, or F-atom. This kind of H can bond to O, N, or F-atoms of other molecules.

Polar molecules have dipole-dipole attractive forces, in addition to London forces.

Aldehydes, ketones, esters

Alcohols, carboxylic acids, amines, amides
Physical properties of carboxylic acids

- Because of the **very polar** –COOH group, carboxylic acids exhibit strong intermolecular attractions.
- As expected, carboxylic acids of a given number of carbon atoms have higher **boiling points** than alcohols.

<table>
<thead>
<tr>
<th>Name</th>
<th>Functional-Group Class</th>
<th>Molecular Mass</th>
<th>Boiling Point (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>diethyl ether</td>
<td>ether</td>
<td>74</td>
<td>34</td>
</tr>
<tr>
<td>ethyl formate</td>
<td>ester</td>
<td>74</td>
<td>54</td>
</tr>
<tr>
<td>methyl acetate</td>
<td>ester</td>
<td>74</td>
<td>57</td>
</tr>
<tr>
<td>butanal</td>
<td>aldehyde</td>
<td>72</td>
<td>76</td>
</tr>
<tr>
<td>1-butanol</td>
<td>alcohol</td>
<td>74</td>
<td>118</td>
</tr>
<tr>
<td>propionic acid</td>
<td>acid</td>
<td>74</td>
<td>141</td>
</tr>
</tbody>
</table>
Boiling point trends

Stronger H-bond than between alcohols

Carboxylic acids

Alcohols

Boiling point (°C)

Carbon number

R-COOH

R-OH

R-CHO

C_nH_{2n+2}
Physical properties of carboxylic acids

- In terms of water-solubility, because of H-bonding, carboxylic acids dissolve well in water (up to 4-carbon chains).
- Beyond 4 carbons, water-solubility drops off rapidly.

Water-solubility:
- Is the molecule polar? What about chain length?
- Can it H-bond with water? Can water H-bond to it?
Preparation of carboxylic acids

- We saw in Ch-15 that carboxylic acids can be prepared from aldehydes (which can be prepared from primary alcohols):

1° alcohol $\xrightarrow{[O]}$ aldehyde $\xrightarrow{[O]}$ carboxylic acid

- Oxidation of an alcohol:
  - Remove two H-atoms, one from OH, other from the adjacent C-atom

- Oxidation of an aldehyde:
  - Insert an O-atom between the adjacent C and the H-atom it is bound to
• Reduction will accomplish the reverse of these reactions

If you can remember that $1^\circ$ alcohols can be oxidized to aldehydes, and then to ketones, the reduction reactions are much easier to do (just reverse of the oxidation reactions)
Structure of esters

- Esters are carboxylic acid derivatives having an alkoxy group instead of a hydroxyl group.

\[
\begin{align*}
\text{carboxylic acid} & : R-C=O-H \\
\text{ester} & : R-C=O-R'
\end{align*}
\]
Preparation of esters

• Esters are prepared by condensation reactions (called an esterification reaction in this case):

\[
\text{carboxylic acid} + \text{alcohol} \rightarrow \text{ester} + \text{H}_2\text{O}
\]

An alcohol and a carboxylic acid both have an -OH group.

In this reaction, a larger molecule (the ester) is made when the carboxylic acid and the alcohol react together to release a water molecule.

The C and the O that were bound to the OH and H become bonded together in the process.
Summary of most important reactions seen so far

- **Addition:**

  \[
  \begin{align*}
  &\text{C} = \text{C} + \text{A-B} \rightarrow \text{C} - \text{C} \\
  \end{align*}
  \]

- **Elimination:**

  \[
  \begin{align*}
  &\text{C} - \text{C} \rightarrow \text{C} = \text{C} + \text{A-B} \\
  \end{align*}
  \]

- **Oxidation:**

  \[
  \begin{align*}
  &\text{CH}_3\cdot\text{CH}_2\cdot\text{C} - \text{OH} \rightarrow [\text{O}] \rightarrow \text{CH}_3\cdot\text{CH}_2\cdot\text{C} - \text{H} \\
  \end{align*}
  \]

- **Reduction:**

  \[
  \begin{align*}
  &\text{CH}_3\cdot\text{CH}_2\cdot\text{C} - \text{H} \rightarrow [\text{R}] \rightarrow \text{CH}_3\cdot\text{CH}_2\cdot\text{C} - \text{OH} \\
  \end{align*}
  \]

- **Condensation:**

  \[
  \begin{align*}
  &\text{R} - \text{OH} + \text{HO} - \text{C} - \text{R'} \rightarrow \text{R} - \text{O} - \text{C} - \text{R'} + \text{H}_2\text{O} \\
  \end{align*}
  \]
Preparation of esters

• Esters are prepared by **condensation reactions** involving carboxylic acids and alcohols. Such reactions are called **esterification reactions**:

  ![Reaction diagram](image)

  Reaction is encouraged by the presence of excess alcohol (Le Chatelier’s Principle)

• Thus, an ester consists of an acid portion and an alcohol portion:

  ![Ester structure](image)
Preparation of esters

• Complete the following reactions:

\[
\text{carboxylic acid} + \text{alcohol} \xrightarrow{H^+} \text{ester} + \text{H}_2\text{O}
\]
Preparation of esters

- **Cyclic esters** (lactones) are created from hydroxy acids (bear both a hydroxyl group and a carboxyl group) in an *intra*molecular esterification reaction:

\[
\text{OH} \quad \text{CH}_2-\text{CH}_2-\text{CH}_2-C-\text{OH} \quad \rightarrow \quad \text{O} \quad \text{C}_5\text{H}_{10}\text{O}_2 \quad + \quad \text{H}_2\text{O}
\]

- Lactones (like cyclic ethers) are examples of *heterocyclic compounds* (meaning it’s a cyclic compounds in which at least one member of the ring is not a carbon atom).
Nomenclature for esters

• Thinking of an ester in terms of an “alcohol portion” and a “carboxylic acid portion” is important for naming esters using the IUPAC system:
  1. The name for the alcohol portion comes first: name the alkyl part of the alcohol (e.g., for the ester shown below, the first part of the ester’s name is methyl (alcohol part comes from methanol). Present the alkyl name separate from the remainder of the ester name.
  2. The carboxylic acid portion is named as if it were deprotonated (i.e. the conjugate base of the carboxylic acid), changing the “-ic acid” part of that name to “-ate”

Methyl propanoate
Nomenclature for esters

- Some other examples:
  - Ethyl butanoate
    - Ethyl 2-methylbutanoate
  - 2-Methylpropyl butanoate
  - Isobutyl butanoate
  - 2-Butyl butanoate
  - Sec-Butyl butanoate

The “alcohol part” of the ester is bonded to the -O- part of the ester.
# Selected common esters

**Flavor/fragrance agents**

<table>
<thead>
<tr>
<th>IUPAC Name</th>
<th>Structural Formula</th>
<th>Characteristic Flavor and Odor</th>
</tr>
</thead>
<tbody>
<tr>
<td>(methylpropyl) isobutyl methanoate</td>
<td><img src="formula1.png" alt="Formula" /></td>
<td>raspberry</td>
</tr>
<tr>
<td>propyl ethanoate</td>
<td><img src="formula2.png" alt="Formula" /></td>
<td>pear</td>
</tr>
<tr>
<td>pentyl ethanoate</td>
<td><img src="formula3.png" alt="Formula" /></td>
<td>banana</td>
</tr>
<tr>
<td>octyl ethanoate</td>
<td><img src="formula4.png" alt="Formula" /></td>
<td>orange</td>
</tr>
<tr>
<td>pentyl propanoate</td>
<td><img src="formula5.png" alt="Formula" /></td>
<td>apricot</td>
</tr>
<tr>
<td>methyl butanoate</td>
<td><img src="formula6.png" alt="Formula" /></td>
<td>apple</td>
</tr>
<tr>
<td>ethyl butanoate</td>
<td><img src="formula7.png" alt="Formula" /></td>
<td>pineapple</td>
</tr>
</tbody>
</table>
Selected common esters

• Pheromones:

- Alarm pheromone for honeybee
- Sexual attractant for canines

• Medications:

- Benzocaine
- Aspirin
Selected common esters

- **Synthesis of Aspirin**

  
  
  \[
  \text{Salicylic acid} + \text{Acetic acid} \xrightarrow{\text{H}^+ \text{ heat}} \text{Aspirin} + \text{H}_2\text{O}
  \]

  (better yield if acetic anhydride is used instead of acetic acid)

- **Synthesis of oil of wintergreen:**

  
  
  \[
  \text{Salicylic acid} + \text{Methanol} \xrightarrow{\text{H}^+ \text{ heat}} \text{Oil of wintergreen} + \text{H}_2\text{O}
  \]
Isomerism in carboxylic acids and esters

• Recall that constitutional isomers are molecules that share the same formula but differ in their atom-to-atom connectivities.

• Three kinds of constitutional isomers (in the order we encountered them):
  – positional isomers (position of the functional group differs, C-chain is same)
  – skeletal isomers (have different C-chains)
  – functional group isomers (have different functional groups)

• Carboxylic acids and esters that have a given number of carbon atoms form another example of functional group isomers:
Isomerism in carboxylic acids and esters

• For both carboxylic acids and esters, skeletal isomers are possible:

(carboxylic acids)

Butanoic acid

2-Methylpropanoic acid

(esters)

Methyl butanoate

Methyl 2-methylpropanoate
Isomerism in carboxylic acids and esters

• Positional isomers are possible for esters, but not carboxylic acids.

![Diagram showing positional isomers of methyl butanoate and butyl methanoate.](image)

For esters, this “R” group can be H (looks almost like an aldehyde).
Physical properties of esters

- Because they don’t possess OH groups, esters cannot form H-bonds with other ester molecules. As a result, esters have lower boiling points than carboxylic acids and alcohols that have approximately the same molar mass.
- They do have a C=O bond (polar) so their boiling points are between alcohols and alkanes.
- Water molecules can H-bond to esters, at the oxygen atoms. This makes low molecular weight esters water-soluble.
Chemical reactions of esters

- **Ester hydrolysis**: the hydrolysis of an ester is accomplished by reacting water with the ester in the presence of an acid catalyst (ester hydrolysis is the reverse reaction of esterification).

\[
\text{ester} + \text{H}_2\text{O} \xrightarrow{\text{H}^+} \text{alcohol} + \text{carboxylic acid}
\]

- An example:

\[
\text{Methyl propanoate} + \text{H}_2\text{O} \xrightarrow{\text{H}^+} \text{Methanol} + \text{Propanoic acid}
\]
Some things that sound the same but mean different things

- **Hydrolysis**: reverse of condensation → water is reacted with a large molecule to break it into two smaller molecules.

  \[
  \text{CH}_3\cdot\text{O}=-\text{C}=-\text{CH}_2\cdot\text{CH}_3 + \text{H}^+ + \text{H}_2\text{O} \rightarrow \text{CH}_3\cdot\text{OH} + \text{HO}=-\text{C}=-\text{CH}_2\cdot\text{CH}_3
  \]

  one organic molecule becomes two

- **Hydration**: water is added across a multiple bond, breaking a \(\pi\)-bond and producing new C-H and C-OH bonds. Example:

  \[
  \text{CH}_3\cdot\text{C}=-\text{CH}-\text{CH}_3 + \text{HO}-\text{H} \rightarrow \text{CH}_3\cdot\text{C}=-\text{CH}=-\text{CH}_3
  \]

  one organic molecule on reactant and product sides
Chemical reactions of esters

Hydrolysis in basic conditions = saponification

- **Ester saponification**: another hydrolysis reaction, but this time, under basic conditions. Rather than a carboxylic acid, the acid salt is produced here. Because the carboxylic acid that *would* form during hydrolysis can’t exist in basic conditions.

\[
\text{Ester} \quad \xrightarrow{\text{NaOH, } \text{H}_2\text{O}} \quad \text{Alcohol} + \text{Carboxylic acid salt}
\]

**Example:**

\[
\begin{align*}
\text{2-Propyl propanoate} & \quad \text{NaOH, } \text{H}_2\text{O} \quad \text{2-Propanol} + \text{Sodium propanoate} \\
\text{CH}_3 & \quad \text{CH} \quad \text{O} \quad \text{C} \quad \text{CH}_2 - \text{CH}_3 \\
\text{CH}_3 & \quad \text{CH} \quad \text{O} \quad \text{C} \quad \text{CH}_2 - \text{CH}_3
\end{align*}
\]
An example of ester saponification

- **Triglycerides** (Ch-19, example shown below) or fats, are structures that permit the body to store energy in a water-insoluble form. They are tri-esters, made by a reaction between glycerol and three fatty acid molecules:

\[
\text{glycerol} + 3\text{fatty acids} \rightarrow \text{triglycerides} + 3\text{H}_2\text{O}
\]
Saponification of a triglyceride

\[ \text{fatty acids} \quad \xrightarrow{\text{long carbon chain}} \quad \xrightarrow{\text{C}} \quad \xrightarrow{\text{OH}} \quad \text{not very water-soluble} \]

fatty acid salts

interacts with oil

interacts with water

Soap!

Grease

Fatty acid micelle
Polyesters

- **Condensation polymerization** creates polymers through the loss of water molecules:

  "poly" means *many*
  "polyester" means many esters linked together in one big molecule

  "Difunctional" reactants

  HO--CH$_2$·CH$_2$·OH + O--CH$_2$·CH$_2$·OH
ethylene glycol
  terephthalic acid
  -2n H$_2$O

  A polyester

  PET: Polyethylene terephthalate

H$^+$ (cat)
Acid chlorides and acid anhydrides

• Acid chlorides and anhydrides have structures that are quite similar to carboxylic acids and esters.
• Both are able to be hydrolized* to produce carboxylic acids.

* Hydrolysis reaction
Esters and anhydrides of inorganic acids

- **Phosphate esters** are the most important class of inorganic esters.
- Because phosphoric acid has three OH groups, it can form mono-, di- and tri-esters:

```
H₂O  trimethyl ester of phosphoric acid

H₂O  dimethyl ester of phosphoric acid

H₂O  methyl ester of phosphoric acid

R-OH = CH₃OH here
```

*notice: octet rule not followed for P*
Esters and anhydrides of inorganic acids

- Phosphoric acid anhydrides are also made via condensation reactions:

\[ \text{phosphoric acid} + \text{phosphoric acid} \rightarrow \text{diphosphoric acid} \]

\[ \text{diphosphoric acid} + \text{phosphoric acid} \rightarrow \text{triphosphoric acid} \]

- These systems are important components of cellular processes for biochemical energy production.
ATP

phosphoanhydride component