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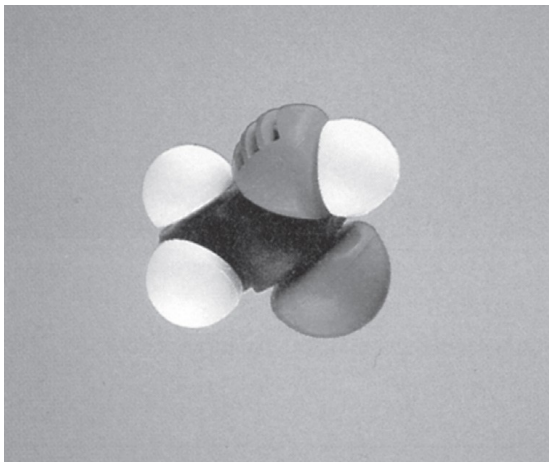
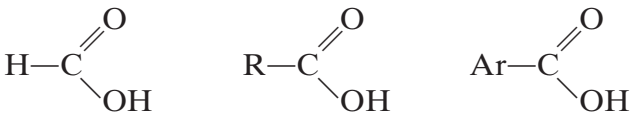


Carboxylic Acids

13.1 Structure

Of the organic compounds that show appreciable acidity, by far the most important are the carboxylic acids. These compounds contain the **carboxyl group**

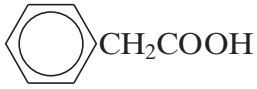


attached to hydrogen (HCOOH), an alkyl group (RCOOH), or an aryl group (ArCOOH) (see Fig. 13.1). For example:

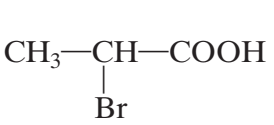
$HCOOH$	CH_3COOH	$CH_3(CH_2)_{10}COOH$	$CH_3(CH_2)_7CH{=}CH(CH_2)_7COOH$
Formic acid	Acetic acid	Lauric acid	Oleic acid
Methanoic acid	Ethanoic acid	Dodecanoic acid	*cis*-9-Octadecenoic acid

Benzoic acid

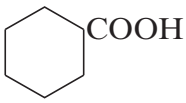
p-Nitrobenzoic acid



Phenylacetic acid



α-Bromopropionic acid
2-Bromopropanoic acid



Cyclohexanecarboxylic acid

Acrylic acid
Propenoic acid

Whether the group is aliphatic or aromatic, saturated or unsaturated, substituted or unsubstituted, the properties of the carboxyl group are essentially the same.

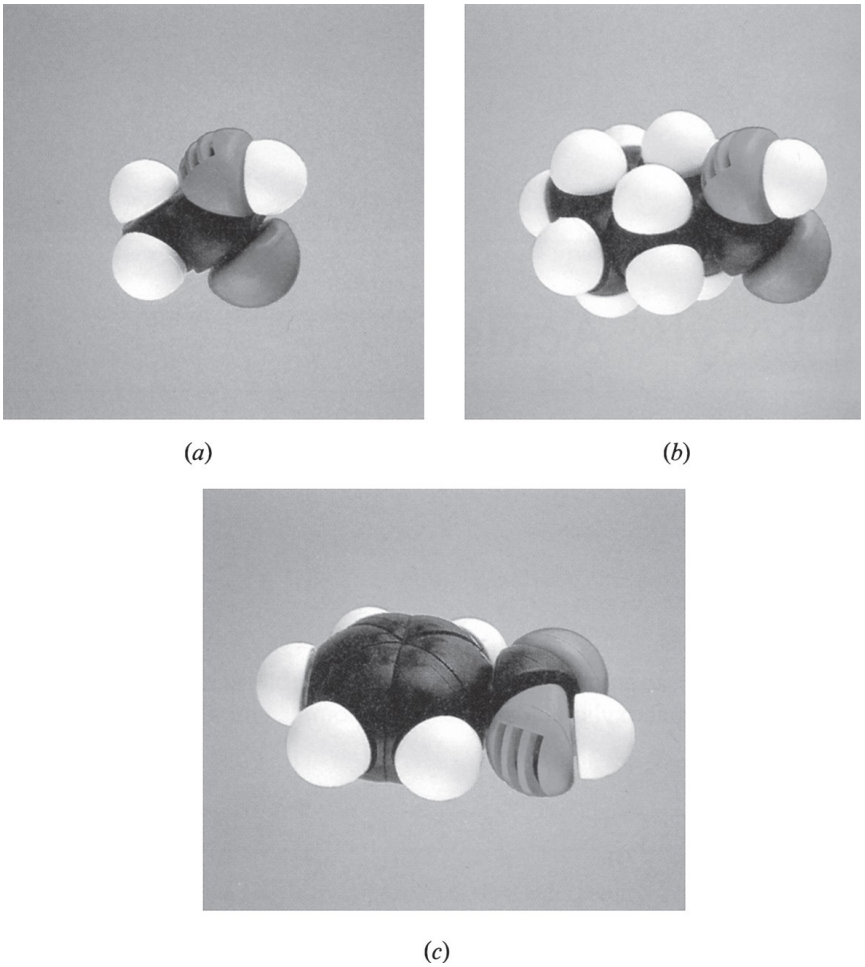
13.2 Nomenclature

The aliphatic carboxylic acids have been known for a long time, and as a result have common names that refer to their sources rather than to their chemical structures. The **common names** of the more important acids are shown in Table 13.1. *Formic acid*, for example, adds the sting to the bite of an ant (Latin: *formica*, ant); *butyric acid* gives rancid butter its typical smell (Latin: *butyrum*, butter); and *caproic*, *caprylic*, and *capric acids* are all found in goat fat (Latin: *caper*, goat).

Table 13.1 CARBOXYLIC ACIDS

Name	Formula	M.p., °C	B.p., °C	Solubility g/100 g H_2O
Formic	HCOOH	8	100.5	∞
Acetic	CH_3COOH	16.6	118	∞
Propionic	CH_3CH_2COOH	–22	141	∞
Butyric	$CH_3(CH_2)_2COOH$	–6	164	∞
Valeric	$CH_3(CH_2)_3COOH$	–34	187	3.7
Caproic	$CH_3(CH_2)_4COOH$	–3	205	1.0
Caprylic	$CH_3(CH_2)_6COOH$	16	239	0.7
Capric	$CH_3(CH_2)_8COOH$	31	269	0.2
Lauric	$CH_3(CH_2)_{10}COOH$	44	225^{100}	i.
Myristic	$CH_3(CH_2)_{12}COOH$	54	251^{100}	i.
Palmitic	$CH_3(CH_2)_{14}COOH$	63	269^{100}	i.
Stearic	$CH_3(CH_2)_{16}COOH$	70	287^{100}	i.
Oleic	*cis*-9-Octadecenoic	16	223^{10}	i.
Linoleic	*cis*,*cis*-9,12-Octadecadienoic	–5	230^{16}	i.
Linolenic	*cis*,*cis*,*cis*-9,12,15-Octadecatrienoic	–11	232^{17}	i.
Cyclohexanecarboxylic	*cyclo*-$C_6H_{11}COOH$	31	233	0.20
Phenylacetic	$C_6H_5CH_2COOH$	77	266	1.66
Benzoic	C_6H_5COOH	122	250	0.34
o-Toluic	*o*-$CH_3C_6H_4COOH$	106	259	0.12
m-Toluic	*m*-$CH_3C_6H_4COOH$	112	263	0.10
p-Toluic	*p*-$CH_3C_6H_4COOH$	180	275	0.03
o-Chlorobenzoic	*o*-ClC_6H_4COOH	141		0.22
m-Chlorobenzoic	*m*-ClC_6H_4COOH	154		0.04
p-Chlorobenzoic	*p*-ClC_6H_4COOH	242		0.009
o-Bromobenzoic	*o*-BrC_6H_4COOH	148		0.18
m-Bromobenzoic	*m*-BrC_6H_4COOH	156		0.04
p-Bromobenzoic	*p*-BrC_6H_4COOH	254		0.006
o-Nitrobenzoic	*o*-$O_2NC_6H_4COOH$	147		0.75
m-Nitrobenzoic	*m*-$O_2NC_6H_4COOH$	141		0.34

p-Nitrobenzoic	*p*-$O_2NC_6H_4COOH$	242	0.03
Phthalic	*o*-$C_6H_4(COOH)_2$	231	0.70
Isophthalic	*m*-$C_6H_4(COOH)_2$	348	0.01
Terephthalic	*p*-$C_6H_4(COOH)_2$	300 *subl.*	0.002
Salicylic	*o*-HOC_6H_4COOH	159	0.22
p-Hydroxybenzoic	*p*-HOC_6H_4COOH	213	0.65
Anthranilic	*o*-$H_2NC_6H_4COOH$	146	0.52
m-Aminobenzoic	*m*-$H_2NC_6H_4COOH$	179	0.77
p-Aminobenzoic	*p*-$H_2NC_6H_4COOH$	187	0.3
o-Methoxybenzoic	*o*-$CH_3OC_6H_4COOH$	101	0.5
m-Methoxybenzoic	*m*-$CH_3OC_6H_4COOH$	110	s. hot
p-Methoxybenzoic (Anisic)	*p*-$CH_3OC_6H_4COOH$	184	0.04



(*a*) (*b*) (*c*)

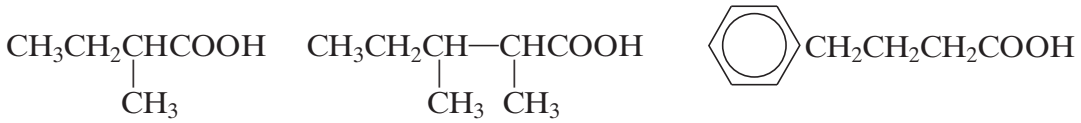
Figure 13.1 Models of some carboxylic acids: (*a*) acetic acid, CH_3COOH; (*b*) cyclohexanecarboxylic acid, *cyclo*-$C_6H_{11}COOH$; (*c*) benzoic acid, C_6H_5COOH.

Branched-chain acids and substituted acids are named as derivatives of the straight-chain acids. To indicate the position of attachment, the Greek letters, α-, β-, γ-, δ-, etc., are used; the α-carbon is the one bearing the carboxyl group.

$$\overset{\delta}{\text{C}}\text{—}\overset{\gamma}{\text{C}}\text{—}\overset{\beta}{\text{C}}\text{—}\overset{\alpha}{\text{C}}\text{—COOH}$$

Used in common names

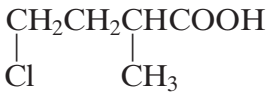
For example:



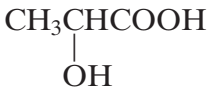
α-Methylbutyric acid

α,β-Dimethylvaleric acid

γ-Phenylbutyric acid



γ-Chloro-α-methylbutyric acid

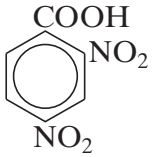


α-Hydroxypropionic acid
Lactic acid

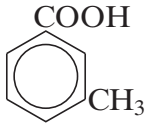
Generally the parent acid is taken as the one of longest carbon chain, although some compounds are named as derivatives of acetic acid.

Aromatic acids, ArCOOH, are usually named as derivatives of the parent acid, **benzoic acid**, C_6H_5COOH. The methylbenzoic acids are given the special name of *toluic acids*.

p-Bromobenzoic acid



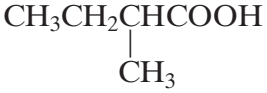
2,4-Dinitrobenzoic acid



m-Toluic acid

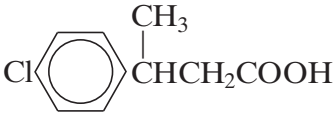
The **IUPAC names** follow the usual pattern. The longest chain carrying the carboxyl group is considered the parent structure, and is named by replacing the *-e* of the corresponding alkane with **-oic acid**. For example:

Pentanoic acid



2-Methylbutanoic acid

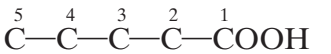
3-Phenylpropanoic acid



3-(*p*-Chlorophenyl)butanoic acid

2-Butenoic acid

The position of a substituent is indicated as usual by a number. We should notice



Used in IUPAC names

that the carboxyl carbon is always considered as C–1, and hence C–2 corresponds to α of the common names, C–3 to β, and so on. (*Caution*: Do not mix Greek letters with IUPAC names, or Arabic numerals with common names.)

The name of a **salt** of a carboxylic acid consists of the name of the cation (*sodium*, *potassium*, *ammonium*, etc.) followed by the name of the acid with the ending *-ic acid* changed to **-ate**. For example:

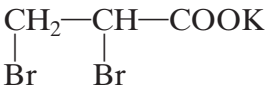
Sodium benzoate

$(CH_3COO)_2Ca$

Calcium acetate

$HCOONH_4$

Ammonium formate



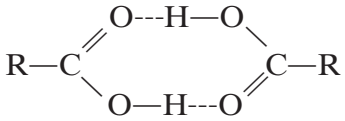
Potassium α,β-dibromopropionate
Potassium 2, 3-dibromopropionate

13.3 Physical properties

As we would expect from their structure, carboxylic acid molecules are polar, and like alcohol molecules can form hydrogen bonds with each other and with other kinds of molecules. The aliphatic acids therefore show very much the same solubility behavior as the alcohols: the first four are miscible with water, the five-carbon acid is partly soluble, and the higher acids are virtually insoluble. Water solubility undoubtedly arises from hydrogen bonding between the carboxylic acid and water. The simplest aromatic acid, benzoic acid, contains too many carbon atoms to show appreciable solubility in water.

Carboxylic acids are soluble in less polar solvents like ether, alcohol, benzene, etc.

We can see from Table 13.1 that as a class the carboxylic acids are even higher boiling than alcohols. For example, propionic acid (b.p. 141°C) boils more than 20°C higher than the alcohol of comparable molecular weight, *n*-butyl alcohol (b.p. 118 °C). These very high boiling points are due to the fact that a pair of carboxylic acid molecules are held together not by one but by two hydrogen bonds:

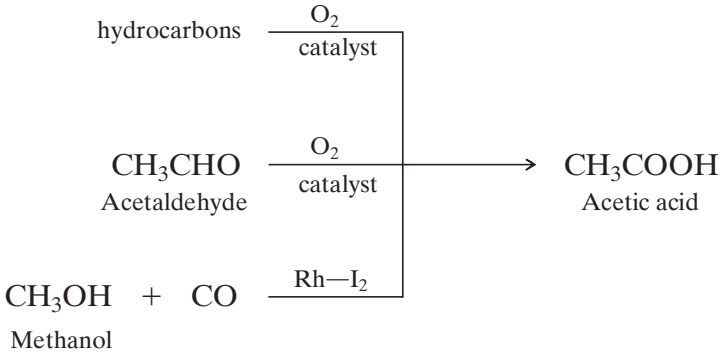


Problem 13.1 At 110 °C and 454 mm pressure, 0.11 g acetic acid vapor occupies 63.7 mL; at 156 °C and 458 mm, 0.081 g occupies 66.4 mL. Calculate the molecular weight of acetic acid in the vapor phase at each temperature. How do you interpret these results?

The odors of the lower aliphatic acids progress from the sharp, irritating odors of formic and acetic acids to the distinctly unpleasant odors of butyric, valeric, and caproic acids; the higher acids have little odor because of their low volatility.

13.4 Industrial source

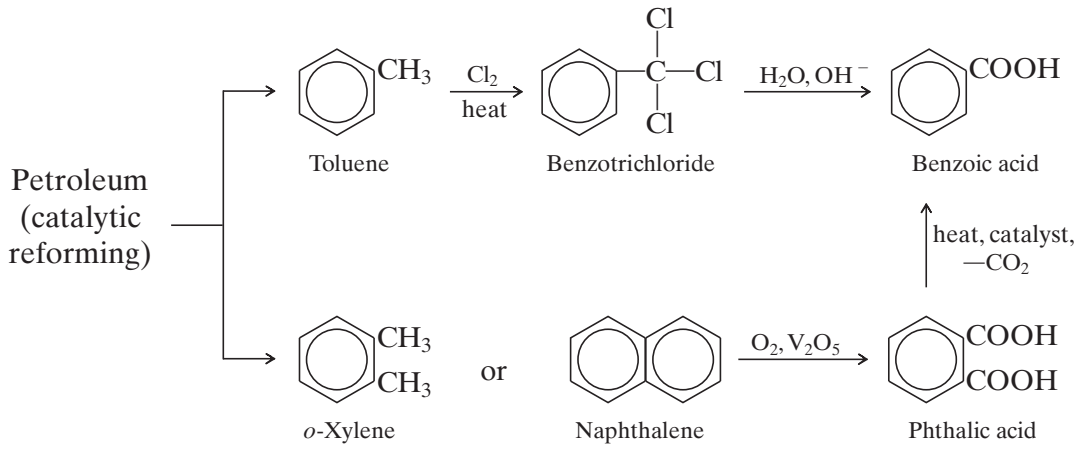
Acetic acid, by far the most important of all carboxylic acids, has been prepared chiefly by catalytic air oxidation of various hydrocarbons or of acetaldehyde. A newer method involves reaction between methanol and carbon monoxide in the presence of an iodine–rhodium catalyst.



Large amounts of acetic acid are also produced as the dilute aqueous solution known as *vinegar*. Here, too, the acetic acid is prepared by air oxidation; the compound that is oxidized is ethyl alcohol, and the catalysts are bacterial (*Acetobacter*) enzymes.

The most important sources of aliphatic carboxylic acids are the animal and vegetable **fats**. From fats there can be obtained, in purity of over 90%, straight-chain carboxylic acids of even carbon number ranging from six to eighteen carbon atoms. These acids can be converted into the corresponding alcohols that can then be used to make a great number of other compounds containing long, straight-chain units.

The most important of the aromatic carboxylic acids, **benzoic acid** and the **phthalic acids**, are prepared on an industrial scale by a reaction we have already encountered: oxidation of alkylbenzenes. The toluene and xylenes required are readily obtained from petroleum by catalytic reforming of aliphatic hydrocarbons; much smaller amounts of these arenes are isolated directly from coal tar. Another precursor of phthalic acid (the *ortho* isomer) is the aromatic hydrocarbon *naphthalene*, also found in coal tar. Cheap oxidizing agents like chlorine or even air (in the presence of catalysts) are used.



Problem 13.2 In the presence of peroxides, carboxylic acids (or esters) react with 1-alkenes to yield more complicated acids. For example:

$$\underset{\text{1-Hexene}}{n\text{-}C_4H_9CH{=}CH_2} + \underset{n\text{-Butyric acid}}{CH_3CH_2CH_2COOH} \xrightarrow{\text{peroxides}} \underset{\text{2-Ethyloctanoic acid (70\% yield)}}{n\text{-}C_4H_9CH_2CH_2\underset{\displaystyle C_2H_5}{\underset{|}{C}}HCOOH}$$

(a) Outline all steps in a likely mechanism for this reaction. Predict the products of similar reactions between: (b) 1-octene and propionic acid; (c) 1-decene and isobutyric acid; (d) 1-octene and ethyl malonate, $CH_2(COOC_2H_5)_2$.

Problem 13.3 (a) Carbon monoxide converts a sulfuric acid solution of each of the following into 2,2-dimethylbutanoic acid: 2-methyl-2-butene, *tert*-pentyl alcohol, neopentyl alcohol. Suggest a likely mechanism for this method of synthesizing carboxylic acids, (b) *n*-Butyl alcohol and *sec*-butyl alcohol give the same product. What would you expect it to be?

13.5 Preparation

The straight-chain aliphatic acids up to C_6 and those of even carbon number up to C_{18} are commercially available, as are the simple aromatic acids. Other carboxylic acids can be prepared by the methods outlined below.

PREPARATION OF CARBOXYLIC ACIDS

1. Oxidation of primary alcohols.

$$R{-}CH_2OH \xrightarrow{KMnO_4} R{-}COOH$$

Examples:

$$R{-}CH_2OH \xrightarrow{KMnO_4} R{-}COOH$$

$$\underset{\text{2-Methyl-1-butanol}}{CH_3CH_2\underset{\displaystyle CH_3}{\underset{|}{C}}HCH_2OH} \xrightarrow{KMnO_4} \underset{\text{2-Methylbutanoic acid}}{CH_3CH_2\underset{\displaystyle CH_3}{\underset{|}{C}}HCOOH}$$

$$\underset{\text{Isobutyl alcohol}}{CH_3\underset{\displaystyle CH_3}{\underset{|}{C}}HCH_2OH} \xrightarrow{KMnO_4} \underset{\text{Isobutyric acid}}{CH_3\underset{\displaystyle CH_3}{\underset{|}{C}}HCOOH}$$

2. Oxidation of alkylbenzenes.

$$Ar{-}R \xrightarrow{KMnO_4 \text{ or } K_2Cr_2O_7} Ar{-}COOH$$

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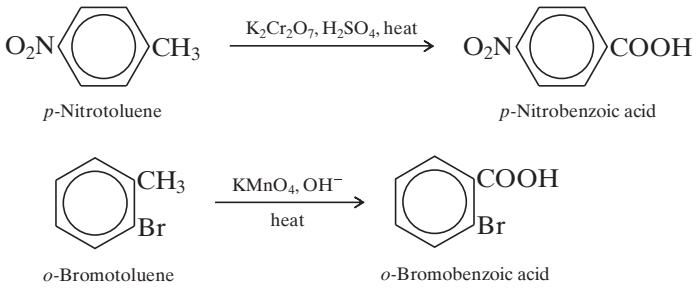
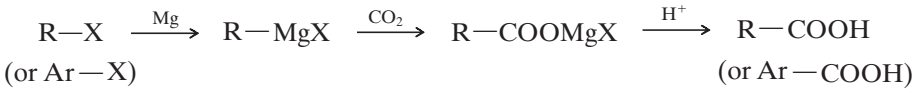
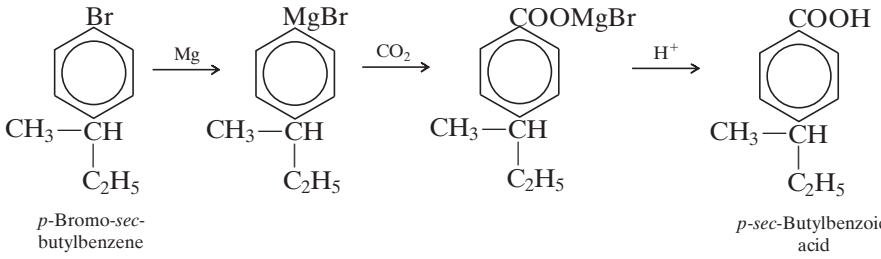
Examples:

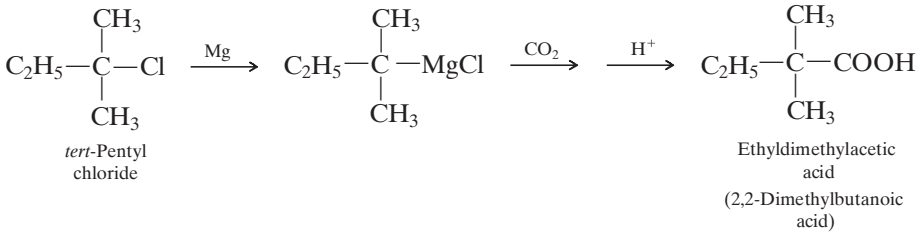


3. Carbonation of Grignard reagents.

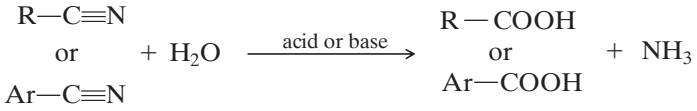


Examples:





4. Hydrolysis of nitriles.



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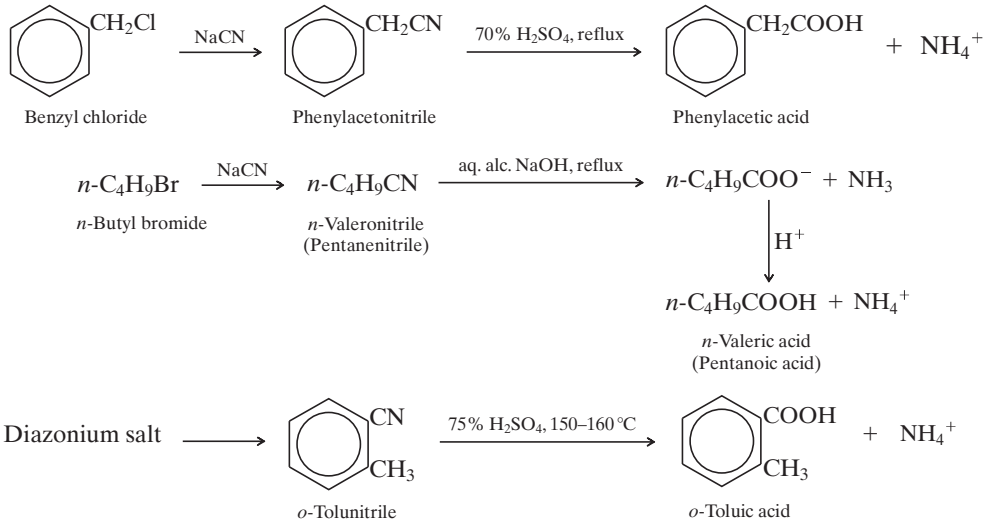
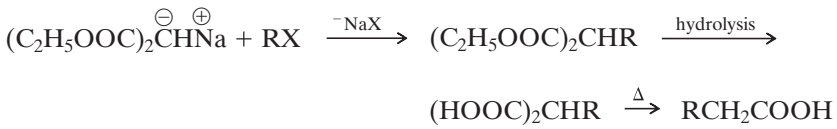
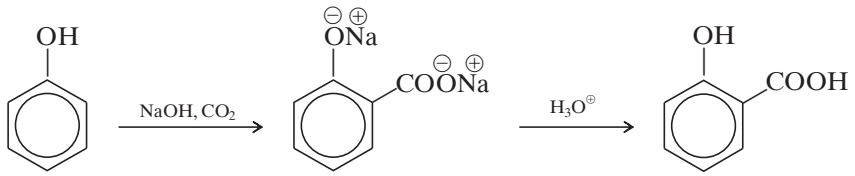
Examples:



5. Malonic ester synthesis. (See active methylene compounds)



6. Special methods for phenolic acids.



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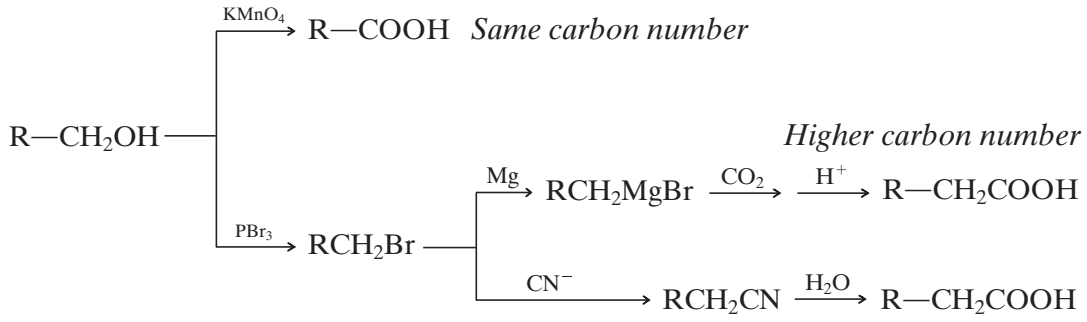
All the methods listed are important; our choice is governed by the availability of starting materials.

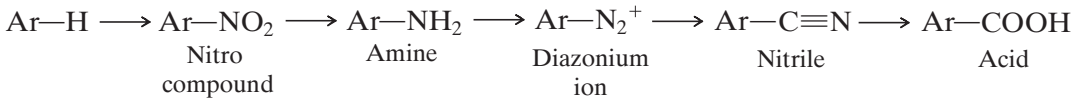
Oxidation is the most direct and is generally used when possible, some lower aliphatic acids being made from the available alcohols, and substituted aromatic acids from substituted toluenes.

The **Grignard synthesis** and the **nitrile synthesis** have the special advantage of increasing the length of a carbon chain, and thus extending the range of available materials. In the aliphatic series both Grignard reagents and nitriles are prepared from halides, which in turn are usually prepared from alcohols. The syntheses thus amount to the preparation of acids from alcohols containing one less carbon atom.



Problem 13.4 Which carboxylic acid can be prepared from *p*-bromotoluene: (a) by direct oxidation? (b) by free-radical chlorination followed by the nitrile synthesis?

Aromatic nitriles generally cannot be prepared from the unreactive aryl halides. Instead they are made from diazonium salts. Diazonium salts are prepared from aromatic amines, which in turn are prepared from nitro compounds. Thus the carboxyl group eventually occupies the position on the ring where a nitro group was originally introduced by direct nitration.

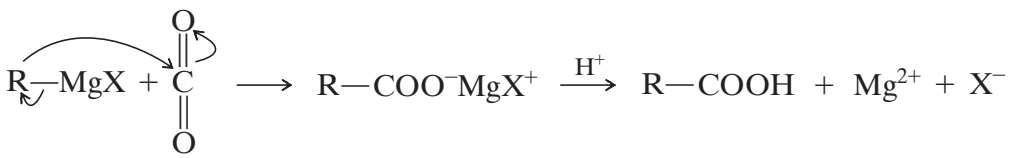


For the preparation of quite complicated acids, the most versatile method of all is used, the *malonic ester synthesis*.

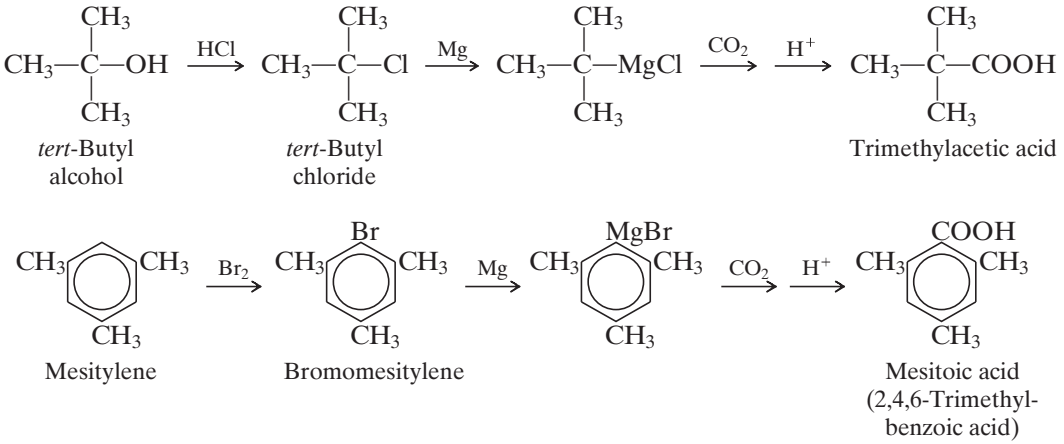
13.6 Grignard synthesis

The Grignard synthesis of a carboxylic acid is carried out by bubbling gaseous CO_2 into the ether solution of the Grignard reagent, or by pouring the Grignard reagent on crushed Dry Ice (solid CO_2); in the latter method Dry Ice serves not only as reagent but also as cooling agent.

The Grignard reagent adds to the carbon–oxygen double bond just as in the reaction with aldehydes and ketones. The product is the magnesium salt of the carboxylic acid, from which the free acid is liberated by treatment with mineral acid.



The Grignard reagent can be prepared from primary, secondary, tertiary, or aromatic halides; the method is limited only by the presence of other reactive groups in the molecule. The following syntheses illustrate the application of this method:



13.7 Nitrile synthesis

Aliphatic nitriles are prepared by treatment of alkyl halides with sodium cyanide in a solvent that will dissolve both reactants; in dimethyl sulfoxide, reaction occurs rapidly and exothermically at room temperature. The resulting nitrile is then hydrolysed to the acid by boiling aqueous alkali or acid.

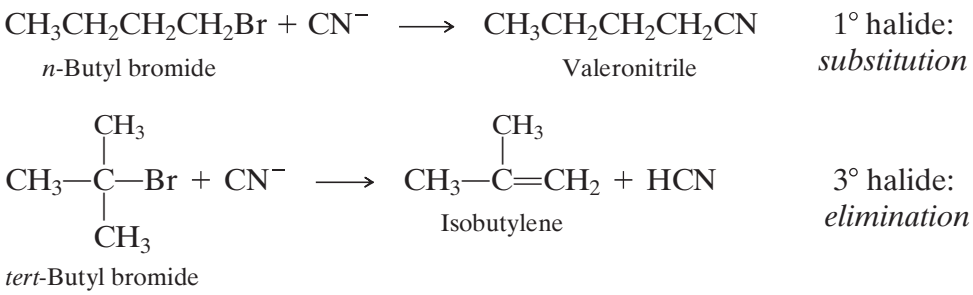
$$R{-}X + CN^- \longrightarrow R{-}C{\equiv}N + X^-$$

$$R{-}C{\equiv}N + H_2O \xrightarrow{H^+} R{-}COOH + NH_4^+$$

$$R{-}C{\equiv}N + H_2O \xrightarrow{OH^-} R{-}COO^- + NH_3$$

The reaction of an alkyl halide with cyanide ion involves nucleophilic substitution. The fact that HCN is a very weak acid tells us that cyanide ion is a strong base; as we might expect, this strongly basic ion can abstract hydrogen ion and thus cause elimination as well as substitution. Indeed, with tertiary halides elimination is the principal reaction; even with secondary halides the yield of substitution product is poor. Here again we find a nucleophilic substitution reaction that is of synthetic importance *only when primary halides are used.*

As already mentioned, aromatic nitriles are made, not from the unreactive aryl halides, but from diazonium salts.



Although nitriles are sometimes named as *cyanides* or as *cyano* compounds, they generally take their names from the acids they yield upon hydrolysis. They are named by dropping *-ic acid* from the common name of the acid and adding **-nitrile**; usually for euphony an "o" is inserted between the root and the ending (e.g., *acetonitrile*). In the IUPAC system they are named by adding *-nitrile* to the name of the parent hydrocarbon (e.g., *ethanenitrile*). For example:

Acetonitrile (Ethanenitrile) — *n*-Valeronitrile (Pentanenitrile) — Benzonitrile — *p*-Tolunitrile

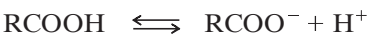
13.8 Reactions

The characteristic chemical behavior of carboxylic acids is, of course, determined by their functional group, **carboxyl**, —COOH. This group is made up of a carbonyl group (C═O) and a hydroxyl group (—OH). As we shall see, it is the —OH that actually undergoes nearly every reaction—loss of H^+, or replacement by another group— but *it does so in a way that is possible only because of the effect of the* C═O.

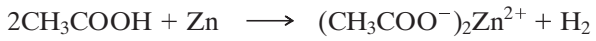
The rest of the molecule undergoes reactions characteristic of its structure; it may be aliphatic or aromatic, saturated or unsaturated, and may contain a variety of other functional groups.

REACTIONS OF CARBOXYLIC ACIDS

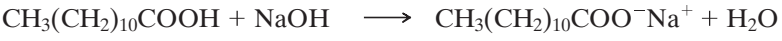
1. Acidity. Salt formation and decarboxylation reaction.



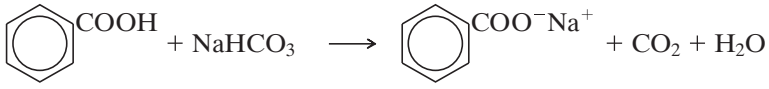
Examples:



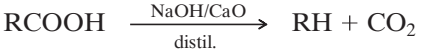
Acetic acid — Zinc acetate



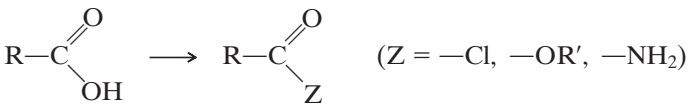
Lauric acid — Sodium laurate



Benzoic acid — Sodium benzoate



2. Conversion into functional derivatives.



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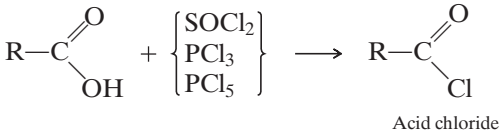
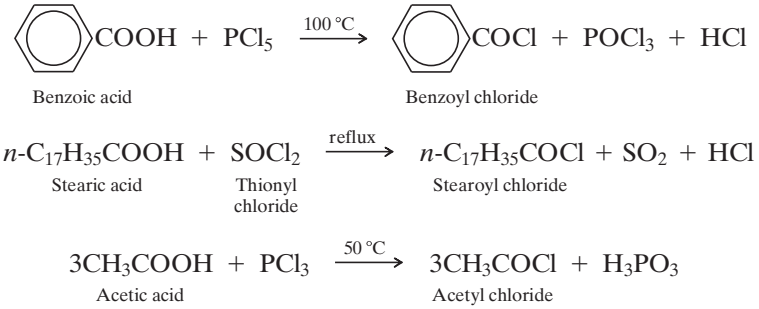
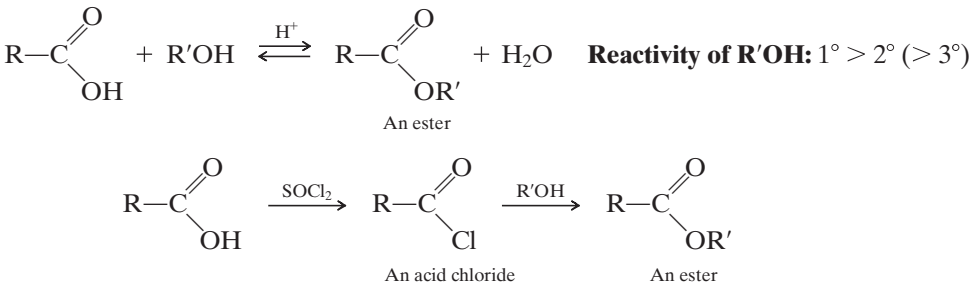
(a) Conversion into acid chlorides.



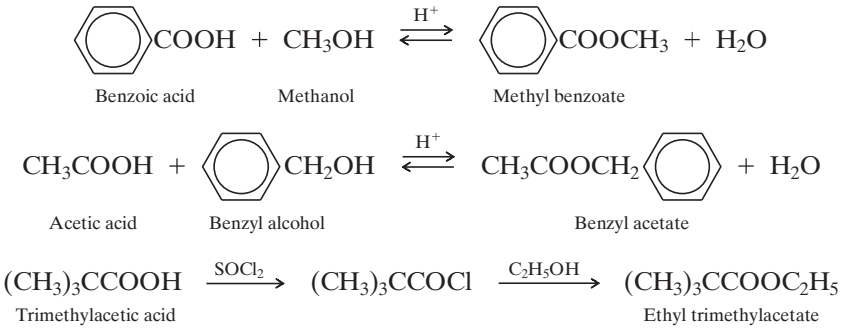
Examples:



(b) Conversion into esters.



Examples:



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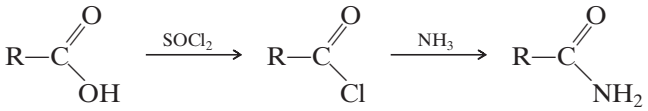
(c) Conversion into amides.



An acid chloride — An amide

Example:

$$C_6H_5CH_2COOH \xrightarrow{SOCl_2} C_6H_5CH_2COCl \xrightarrow{NH_3} C_6H_5CH_2CONH_2$$

Phenylacetic acid — Phenylacetyl chloride — Phenylacetamide

3. Reduction.

$$R{-}COOH \xrightarrow{LiAlH_4} R{-}CH_2OH$$

1° alcohol

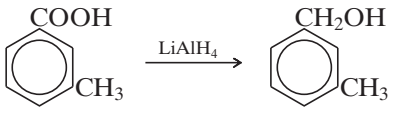
Also reduced via esters

$$R{-}COOH \xrightarrow{\text{diborane}} RCH_2OH$$

Examples:

$$4(CH_3)_3CCOOH + 3LiAlH_4 \xrightarrow{\text{ether}} [(CH_3)_3CCH_2O]_4AlLi + 2LiAlO_2 + 4H_2 \xrightarrow{H^+} (CH_3)_3CCH_2OH$$

Trimethylacetic acid — Neopentyl alcohol (2,2-Dimethyl-1-propanol)



m-Toluic acid — *m*-Methylbenzyl alcohol

4. Substitution in alkyl or aryl group.

(a) Alpha-halogenation of aliphatic acids. Hell–Volhard–Zelinsky reaction.

$$RCH_2COOH + X_2 \xrightarrow{P} \underset{\displaystyle X}{RCHCOOH} + HX \qquad X_2 = Cl_2, Br_2$$

An α-halo acid

Examples:

$$CH_3COOH \xrightarrow{Cl_2, P} ClCH_2COOH \xrightarrow{Cl_2, P} Cl_2CHCOOH \xrightarrow{Cl_2, P} Cl_3CCOOH$$

Acetic acid — Chloroacetic acid — Dichloroacetic acid — Trichloroacetic acid

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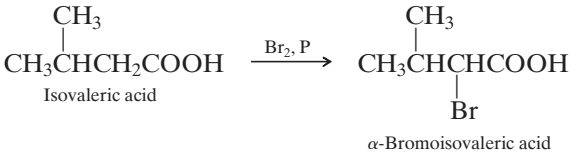
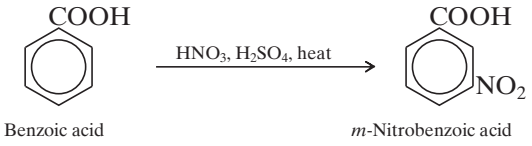


(b) Ring substitution in aromatic acids.

—COOH : deactivates, and directs *meta* in electrophilic substitution.

Example:



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The most characteristic property of the carboxylic acids is the one that gives them their name: **acidity**. Their tendency to give up a hydrogen ion is such that in aqueous solution a measurable equilibrium exists between acid and ions; they are thus much more acidic than any other class of organic compounds we have studied so far.

$$RCOOH + H_2O \rightleftharpoons RCOO^- + H_3O^+$$

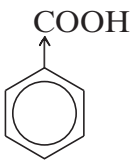
The OH of an acid can be replaced by a Cl, OR′, or NH_2 group to yield an *acid chloride*, an *ester*, or an *amide*. These compounds are called **functional derivatives** of acids; they all contain the **acyl group:** R–Co—

The functional derivatives are all readily reconverted into the acid by simple hydrolysis, and are often converted one into another.

One of the few reducing agents capable of reducing an acid directly to an alcohol is *lithium aluminum hydride*, $LiAlH_4$. The best reagent to reduce an acid to corresponding alcohol is borane.

The hydrocarbon portion of an aliphatic acid can undergo the free-radical halogenation characteristic of alkanes, but because of the random nature of the substitution it is seldom used. The presence of a small amount of phosphorus, however, causes halogenation (by a heterolytic mechanism) to take place *exclusively at the alpha position*. This reaction is known as the **Hell–Volhard–Zelinsky reaction**, and it is of great value in synthesis.

An aromatic ring bearing a carboxyl group undergoes the aromatic electrophilic substitution reactions expected of a ring carrying a deactivating, *meta*-directing group. Deactivation is so strong that the Friedel–Crafts reaction does not take place. We have already accounted for this effect of the —COOH group on the basis of its strong electron-withdrawing tendencies.



—COOH withdraws electrons: deactivates, directs meta in electrophilic substitution

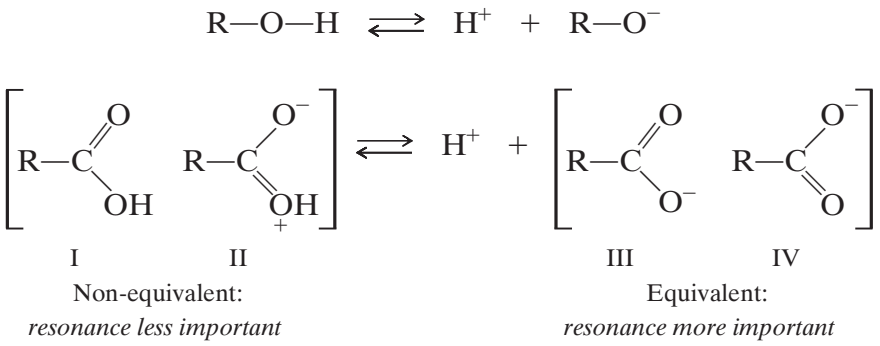
Decarboxylation reaction, that is, elimination of the COOH group as CO_2, is of limited importance in aromatic acids and highly important for some aliphatic acids like malonic acid, acetoacetic acid etc. It is worthless for most simple aliphatic acids, yielding a complicated mixture of hydrocarbons.

13.9 Acidity of carboxylic acids

Let us see how the acidity of carboxylic acids is related to structure. In doing this we shall assume that acidity is determined chiefly by the difference in stability between the acid and its anion.

First, and most important, there is the fact that carboxylic acids are acids at all. How can we account for the fact that the —OH of a carboxylic acid tends to release a hydrogen ion so much more readily than the —OH of, say, an alcohol? Let us examine the structures of the reactants and products in these two cases.

We see that the alcohol and alkoxide ion are each represented satisfactorily by a single structure. However, we can draw two reasonable structures (I and II) for the carboxylic acid and two reasonable structures (III and IV) for the carboxylate anion. Both acid and anion are resonance hybrids. But is resonance equally important in



the two cases? On principle we know that resonance is much more important between the exactly equivalent structures III and IV than between the non-equivalent structures I and II. As a result, although both acid and anion are stabilized by resonance, stabilization is far greater for the anion than for the acid (Fig. 13.2). Equilibrium is shifted in the direction of increased ionization, and K_a is increased.

Strictly speaking, resonance is less important for the acid because the contributing structures are of *different stability*, whereas the equivalent structures for the ion must necessarily be of *equal stability*. In structure II two atoms of similar electronegativity carry opposite charges; since energy must be supplied to separate opposite charges, II should contain more energy and hence be less stable than I. Consideration of *separation of charge* is one of the rules of thumb that can be used to estimate relative stability and hence relative importance of a contributing structure.

The acidity of a carboxylic acid is thus due to the powerful resonance stabilization of its anion. *This stabilization and the resulting acidity are possible only because of the presence of the carbonyl group.*

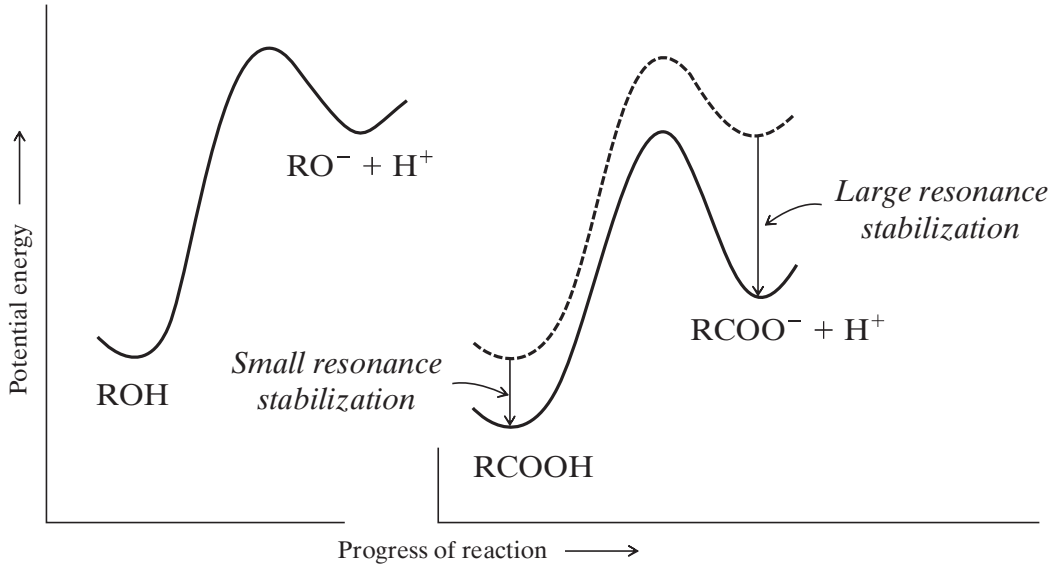
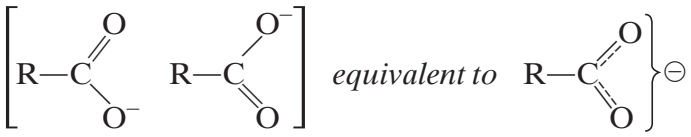


Figure 13.2 Molecular structure and position of equilibrium. A carboxylic acid yields a resonance-stabilized anion; it is a stronger acid than an alcohol. (The plots are aligned with each other for easy comparison.)

13.10 Structure of carboxylate ions

According to the resonance theory, then, a carboxylate ion is a hybrid of two structures which, being of equal stability, contribute equally. Carbon is joined to each oxygen by a "one-and-a-half" bond. The negative charge is evenly distributed over both oxygen atoms.



That the anion is indeed a resonance hybrid is supported by the evidence of bond length. Formic acid, for example, contains a carbon–oxygen double bond and a carbon–oxygen single bond; we would expect these bonds to have different lengths. Sodium formate, on the other hand, if it is a resonance hybrid, ought to contain two equivalent carbon–oxygen bonds; we would expect these to have the same length, intermediate between double and single bonds. X-ray and electron diffraction show that these expectations are correct. Formic acid contains one carbon–oxygen bond of 1.36 Å (single bond) and another of 1.23 Å (double bond); sodium formate contains two equal carbon–oxygen bonds, each 1.27 Å long.

Formic acid Sodium formate

Problem 13.5 How do you account for the fact that the three carbon–oxygen bonds in $CaCCO_3$ have the same length, and that this length (1.31 Å) is greater than that found in sodium formate?

What does this resonance mean in terms of orbitals? Carboxyl carbon is joined to the three other atoms by σ bonds (Fig. 13.3), since these bonds utilize sp^2 orbitals, they lie in a plane and are 120° apart. The remaining p orbital of the carbon overlaps equally well p orbitals from *both* of the oxygens, to form hybrid bonds. In this way the electrons are bound not just to one or two nuclei but to *three* nuclei (one carbon

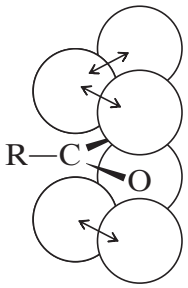


Figure 13.3 Carboxylate ion. Overlap of p orbitals in both directions: delocalization of π electrons, and dispersal of charge.

and two oxygens); they are therefore held more tightly, the bonds are stronger, and the anion is more stable. This participation of electrons in more than one bond, this smearing-out or derealization of the electron cloud, is what is meant by representing the anion as a resonance hybrid of two structures.

Problem 13.6 How do you account for the fact that the α-hydrogens of an aldehyde (say, *n*-butyraldehyde) are much more acidic than any other hydrogens in the molecule?

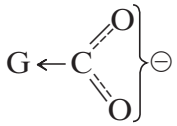
$$\overset{\gamma}{C}H_3\overset{\beta}{C}H_2\overset{\alpha}{C}H_2\overset{H}{C}{=}O$$

n-Butyraldehyde

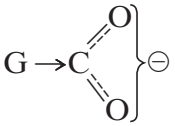
13.11 Effect of substituents on acidity

Next, let us see how changes in the structure of the group bearing the —COOH affect the acidity. Any factor that stabilizes the anion more than it stabilizes the acid should increase the acidity; any factor that makes the anion less stable should decrease acidity. From what we have learned about carbocations, we know what we might reasonably expect. Electron-withdrawing substituents should disperse the negative charge, stabilize the anion, and thus increase acidity. Electron-releasing substituents should intensify the negative charge, destabilize the anion, and thus decrease acidity.

Acid strength



G withdraws electrons: *stabilizes anion, strengthens acid*



G releases electrons: *destabilizes anion, weakens acid*

The K_a values listed in Table 13.2 are in agreement with this prediction.

Table 13.2 ACIDITY CONSTANTS OF CARBOXYLIC ACIDS

	K_a		K_a
HCOOH	17.7×10^{-5}	$CH_3CHClCH_2COOH$	8.9×10^{-5}
CH_3COOH	1.75×10^{-5}	$ClCH_2CH_2CH_2COOH$	2.96×10^{-5}
$ClCH_2COOH$	136×10^{-5}	FCH_2COOH	260×10^{-5}
$Cl_2CHCOOH$	5530×10^{-5}	$BrCH_2COOH$	125×10^{-5}
Cl_3CCOOH	23200×10^{-5}	ICH_2COOH	67×10^{-5}
$CH_3CH_2CH_2COOH$	1.52×10^{-5}	$C_6H_5CH_2COOH$	4.9×10^{-5}
$CH_3CH_2CHClCOOH$	139×10^{-5}	p-$O_2NC_6H_4CH_2COOH$	14.1×10^{-5}

Table 13.3 ACIDITY CONSTANTS OF SUBSTITUTED BENZOIC ACIDS

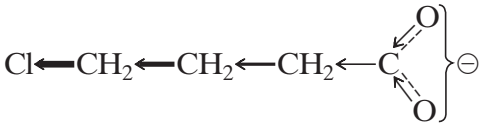
K_a of benzoic acid $= 6.3 \times 10^{-5}$

	K_a		K_a		K_a
p-NO_2	30×10^{-5}	m-NO_2	32×10^{-5}	o-NO_2	670×10^{-5}
p-Cl	10.3×10^{-5}	m-Cl	15.1×10^{-5}	o-Cl	120×10^{-5}
p-CH_3	4.2×10^{-5}	m-CH_3	5.4×10^{-5}	o-CH_3	12.4×10^{-5}
p-OCH_3	3.3×10^{-5}	m-OCH_3	8.2×10^{-5}	o-OCH_3	8.2×10^{-5}
p-OH	2.6×10^{-5}	m-OH	8.3×10^{-5}	o-OH	105×10^{-5}
P-NH_2	1.4×10^{-5}	m-NH_2	1.9×10^{-5}	o-NH_2	1.6×10^{-5}

Looking first at the aliphatic acids, we see that the electron-withdrawing halogens strengthen acids: chloroacetic acid is 100 times as strong as acetic acid, dichloroacetic acid is still stronger, and trichloroacetic acid is more than 10,000 times as strong as the unsubstituted acid. The other halogens exert similar effects.

Problem 13.7 (a) What do the K_a values of the monohaloacetic acids tell us about the relative strengths of the inductive effects of the different halogens? (b) On the basis of Table 13.2, what kind of inductive effect does the phenyl group, $—C_6H_5$, appear to have?

α-Chlorobutyric acid is about as strong as chloroacetic acid. As the chlorine is moved away from the —COOH, however, its effect rapidly dwindles: β-chlorobutyric acid is only six times as strong as butyric acid, and γ-chlorobutyric acid is only twice as strong. It is typical of inductive effects that they decrease rapidly with distance, and are seldom important when acting through more than four atoms.



Inductive effect: *decreases with distance*

The aromatic acids (Table 13.3) are similarly affected by substituents: —CH_3, —OH, and —NH_2 make benzoic acid weaker, and —Cl and —NO_2 make benzoic acid stronger. We recognize the acid-weakening groups as the ones that activate the ring toward electrophilic substitution (and deactivate toward nucleophilic substitution). The acid-strengthening groups are the ones that deactivate toward electrophilic substitution (and activate toward nucleophilic substitution). Furthermore, the groups that have the largest effects on reactivity—whether activating or deactivating—have the largest effects on acidity.

The —OH and —OCH_3 groups display both kinds of effect we have attributed to them: from the *meta* position, an electron-withdrawing acid-strengthening inductive effect; and from the *para* position, an electron-releasing acid-weakening resonance effect (which at this position outweighs the inductive effect). Compare the two effects exerted by halogen on electrophilic aromatic substitution.

ortho-Substituted acids do not fit into the pattern set by their *meta* and *para* isomers, and by aliphatic acids. Nearly all *ortho* substituents exert an effect of the same kind—acid-strengthening—whether they are electron-withdrawing or electron-releasing, and the effect is unusually large. (Compare, for example, the effects of *o*-NO_2 and *o*-CH_3, of *o*-NO_2 and *m*- or *p*-NO_2.) This *ortho* effect undoubtedly has to do with the *nearness* of the groups involved, but is more than just steric hindrance arising from their bulk.

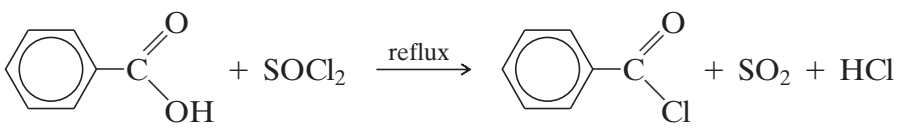
Thus we see that the same concepts—inductive effect and resonance—that we found so useful in dealing with rates of reaction are also useful in dealing with equilibria. By using these concepts to estimate the stabilities of anions, we are able to predict the relative strengths of acids; in this way we can account not only for the effect of substituents on the acid strength of carboxylic acids but also for the very fact that the compounds are acids.

Problem 13.8 There is evidence that certain groups like *p*-methoxy weaken the acidity of benzoic acids not so much by destabilizing the anion as by stabilizing the acid. Draw structures to show the kind of resonance that might be involved. Why would you expect such resonance to be more important for the acid than for the anion?

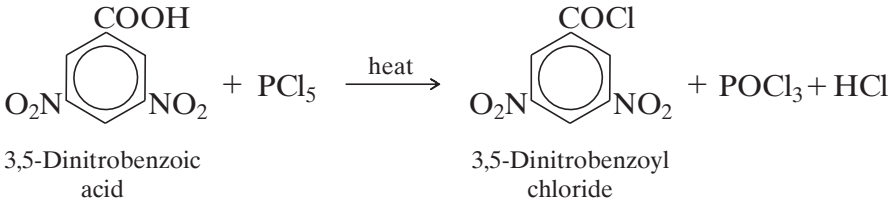
13.12 Conversion into acid chlorides

A carboxylic acid is perhaps more often converted into the acid chloride than into any other of its functional derivatives. From the highly reactive acid chloride there can then be obtained many other kinds of compounds, including esters and amides.

An acid chloride is prepared by substitution of —Cl for the —OH of a carboxylic acid. Three reagents are commonly used for this purpose: *thionyl chloride*, $SOCl_2$; *phosphorus trichloride*, PCl_3; and *phosphorus pentachloride*, PCl_5. (Of what inorganic acids might we consider these reagents to be the acid chlorides?) For example:



Benzoic acid Benzoyl chloride



3,5-Dinitrobenzoic acid

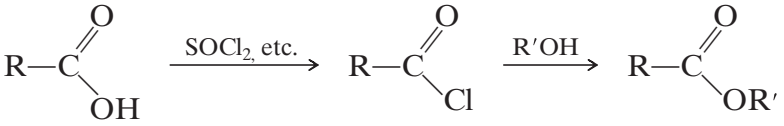
3,5-Dinitrobenzoyl chloride

$$3RCOOH + PCl_3 \longrightarrow 3RCOCl + H_3PO_3$$

Thionyl chloride is particularly convenient, since the products formed besides the acid chloride are gases and thus easily separated from the acid chloride; any excess of the low-boiling thionyl chloride (79 °C) is easily removed by distillation.

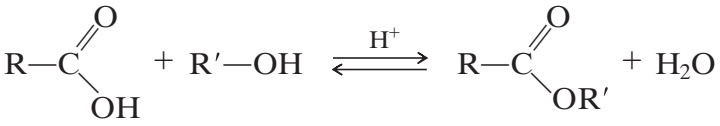
13.13 Conversion into esters

Acids are frequently converted into their esters via the acid chlorides:



Acid Acid chloride Ester

A carboxylic acid is converted directly into an ester when heated with an alcohol in the presence of a little mineral acid, usually concentrated sulfuric acid or dry hydrogen chloride. This reaction is reversible, and generally reaches equilibrium when there are appreciable quantities of both reactants and products present.



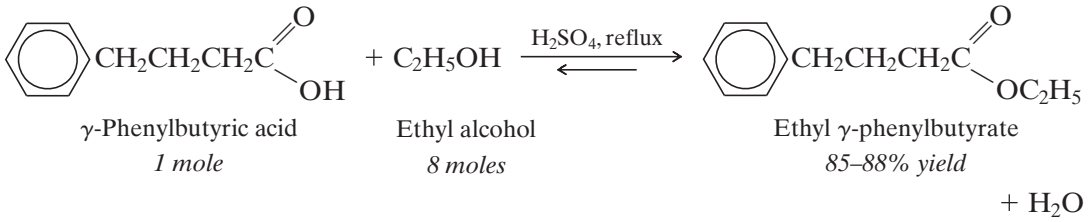
Acid Alcohol Ester

For example, when we allow one mole of acetic acid and one mole of ethyl alcohol to react in the presence of a little sulfuric acid until equilibrium is reached (after several hours), we obtain a mixture of about two-thirds mole each of ester and water, and one-third mole each of acid and alcohol. We obtain this same equilibrium mixture, of course, if we start with one mole of ester and one mole of water, again in the presence of sulfuric acid. *The same catalyst, hydrogen ion, that catalyses the forward reaction, esterification, necessarily catalyses the reverse reaction, hydrolysis.*

This reversibility is a disadvantage in the preparation of an ester directly from an acid; the preference for the acid chloride route is due to the fact that both

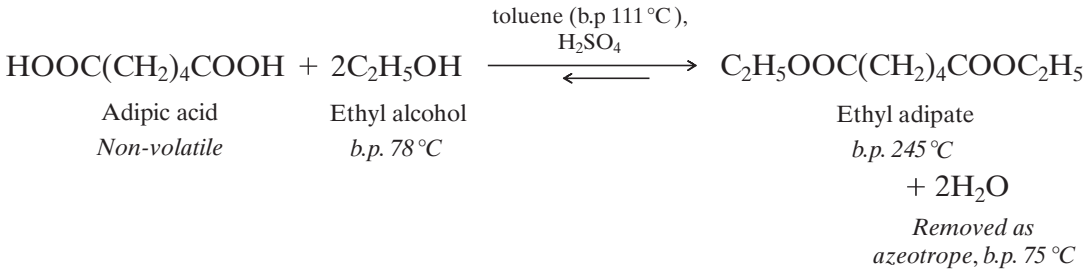
steps—preparation of acid chloride from acid, and preparation of ester from acid chloride—are essentially irreversible and go to completion.

Direct esterification, however, has the advantage of being a single-step synthesis; it can often be made useful by application of our knowledge of equilibria. If either the acid or the alcohol is cheap and readily available, it can be used in large excess to shift the equilibrium toward the products and thus to increase the yield of ester. For example, it is worthwhile to use eight moles of cheap ethyl alcohol to convert one mole of valuable γ-phenylbutyric acid more completely into the ester:



γ-Phenylbutyric acid *1 mole* | Ethyl alcohol *8 moles* | Ethyl γ-phenylbutyrate *85–88% yield*

Sometimes the equilibrium is shifted by removing one of the products. An elegant way of doing this is illustrated by the preparation of ethyl adipate. The dicarboxylic acid adipic acid, an excess of ethyl alcohol, and toluene are heated with a little sulfuric acid under a distillation column. The lowest boiling component (b.p. 75 °C) of the reaction mixture is an azeotrope of water, ethyl alcohol, and toluene; consequently, as fast as water is formed it is removed as the azeotrope by distillation. In this way a 95–97% yield of ester is obtained:



Adipic acid *Non-volatile* | Ethyl alcohol *b.p. 78 °C* | Ethyl adipate *b.p. 245 °C* | *Removed as azeotrope, b.p. 75 °C*

The equilibrium is particularly unfavorable when phenols (ArOH) are used instead of alcohols; yet, if water is removed during the reaction, phenolic esters (RCOOAr) are obtained in high yield.

The presence of bulky groups near the site of reaction, whether in the alcohol or in the acid, slows down esterification (as well as its reverse, hydrolysis).

Reactivity in esterification

$CH_3OH > 1° > 2° (> 3°)$

$HCOOH > CH_3COOH > RCH_2COOH > R_2CHCOOH > R_3CCOOH$

This *steric hindrance* can be so marked that special methods are required to prepare esters of tertiary alcohols or esters of acids like 2,4,6-trimethylbenzoic acid (mesitoic acid). (See Fig. 13.4).

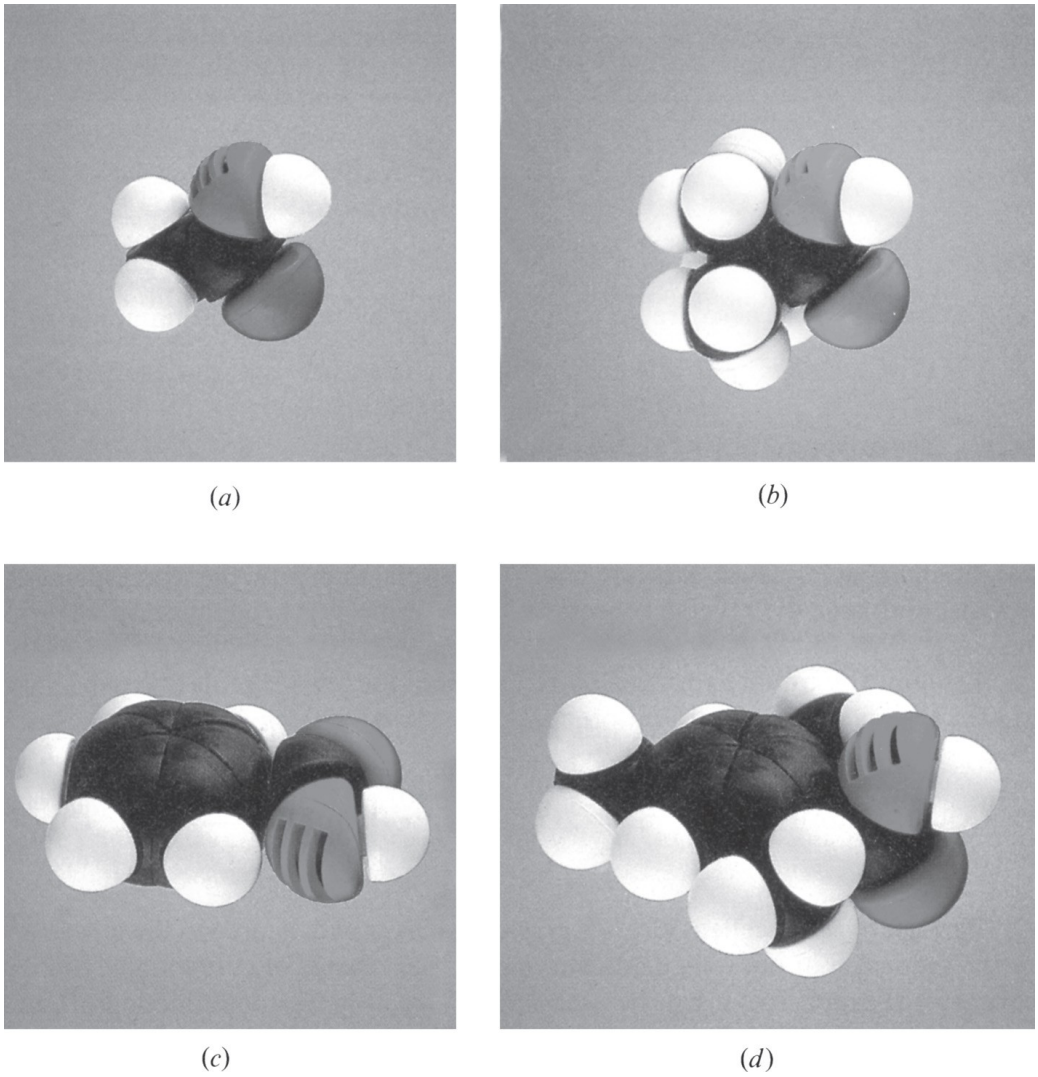


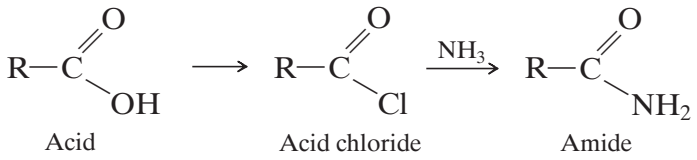
Figure 13.4 Molecular structure and reactivity: the steric factor in esterification. Crowding about the carboxyl group. Compare (*a*) acetic acid with (*b*) trimethylacetic acid, and (*c*) benzoic acid with (*d*) 2,4,6-trimethylbenzoic acid.

The mechanism of esterification is necessarily the exact reverse of the mechanism of hydrolysis of esters.

Problem 13.9 (a) In the formation of an acid chloride, which bond of a carboxylic acid is broken, C—OH or CO—H? (b) When labeled methanol, $CH_3{}^{18}OH$, was allowed to react with ordinary benzoic acid, the methyl benzoate produced was found to be enriched in ^{18}O, whereas the water formed contained only ordinary oxygen. In this esterification, which bond of the carboxylic acid is broken, C—OH or CO—H? Which bond of the alcohol?

13.14 Conversion into amides

Amides are compounds in which the —OH of the carboxylic acid has been replaced by $—NH_2$. These are generally prepared by reaction of ammonia with acid chlorides.



13.15 Reduction of acids to alcohols

Conversion of alcohols into acids is important because, in general, alcohols are more available than acids. This is not always true, however; long straight-chain acids from fats are more available than are the corresponding alcohols, and here the reverse process becomes important: reduction of acids to alcohols.

Lithium aluminum hydride, $LiAlH_4$, is one of the few reagents that can reduce an acid to an alcohol; the initial product is an alkoxide from which the alcohol is liberated by hydrolysis:

$$4R\text{—}COOH + 3LiAlH_4 \longrightarrow 4H_2 + 2LiAlO_2 + (RCH_2O)_4AlLi \xrightarrow{H_2O} \underset{1^\circ \text{ alcohol}}{4R\text{—}CH_2OH}$$

Because of the excellent yields it gives, $LiAlH_4$ is widely used in the laboratory for the reduction of not only acids but many other classes of compounds. Since it is somewhat expensive, it can be used in industry only for the reduction of small amounts of valuable raw materials, as in the synthesis of certain drugs and hormones.

As an alternative to direct reduction, acids are often converted into alcohols by a two-step process: esterification, and reduction of the ester. Esters can be reduced in a number of ways that are adaptable to both laboratory and industry. RCOOH can be best reduced to RCH_2OH with borane (i.e, diborane).

$$RCOOH \xrightarrow{B_2H_6} RCH_2OH + B(OH)_3$$

We have seen that in the carboxylic acids obtained from fats we have available long straight-chain units for use in organic synthesis. Reduction of these acids to alcohols (either directly or as esters) is a fundamental step in the utilization of these raw materials, since from the alcohols, as we know, a host of other compounds can be prepared. Although only acids of even carbon number are available, it is possible, of course, to increase the chain length and thus prepare compounds of odd carbon number.

Problem 13.10 Outline the synthesis from lauric acid (n-$C_{11}H_{23}COOH$, dodecanoic acid) of the following compounds:

(a) 1-bromododecane
(b) tridecanoic acid (C_{13} acid)
(c) 1-tetradecanol
(d) 1-dodecene
(e) dodecane
(f) 1-dodecyne
(g) n-decyl methyl ketone
(h) 2-dodecanol
(i) undecanoic acid
(j) 2-tetradecanol
(k) 2-methyl-2-tetradecanol

13.16 Halogenation of aliphatic acids. Substituted acids (HVZ reaction)

In the presence of a small amount of phosphorus, aliphatic carboxylic acids react smoothly with chlorine or bromine to yield a compound in which α-hydrogen has been replaced by halogen. This is the **Hell–Volhard–Zelinsky reaction**. Because of its regioselectivity—*only alpha halogenation*—and the readiness with which it takes place, it is of considerable importance in synthesis.

$$CH_3COOH \xrightarrow{Cl_2, P} ClCH_2COOH \xrightarrow{Cl_2, P} Cl_2CHCOOH \xrightarrow{Cl_2, P} Cl_3CCOOH$$

$$CH_3CH_2COOH \xrightarrow{Br_2, P} CH_3CHBrCOOH \xrightarrow{Br_2, P} CH_3CBr_2COOH$$

$$\downarrow Br_2, P$$

no further substitution

The function of the phosphorus is ultimately to convert a little of the acid into acid halide.

$$P + X_2 \longrightarrow PX_3$$

$$RCH_2COOH + PX_3 \longrightarrow RCH_2COX$$

$$RCH_2COX + X_2 \longrightarrow \underset{\displaystyle X}{\underset{|}{RCH}}COX + HX$$

$$\underset{\displaystyle X}{\underset{|}{RCH}}COX + RCH_2COOH \rightleftharpoons \underset{\displaystyle X}{\underset{|}{RCH}}COOH + RCH_2COX$$

α-Halo acid

The halogen of these halogenated acids undergoes *nucleophilic displacement* and *elimination* much as it does in the simpler alkyl halides. Halogenation is therefore the first step in the conversion of a carboxylic acid into many important substituted carboxylic acids:

$$\underset{\displaystyle Br}{\underset{|}{RCH}}COOH + \text{large excess of } NH_3 \longrightarrow \underset{\displaystyle NH_2}{\underset{|}{RCH}}COOH$$

An α-halogenated acid — An α-amino acid

$$\underset{\displaystyle Br}{\underset{|}{RCH}}COOH + NaOH \longrightarrow \underset{\displaystyle OH}{\underset{|}{RCH}}COONa \xrightarrow{H^+} \underset{\displaystyle OH}{\underset{|}{RCH}}COOH$$

An α-hydroxy aci

$$\underset{\displaystyle Br}{\underset{|}{RCH_2CH}}COOH + KOH\ (alc) \longrightarrow RCH{=}CHCOO^- \xrightarrow{H^+} RCH{=}CHCOOH$$

An α,β-unsaturated acid

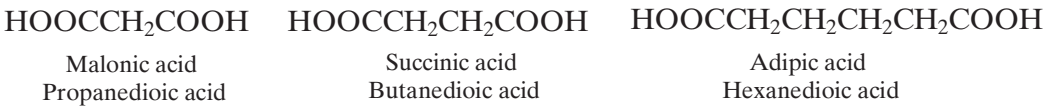
These new substituents can, in turn, undergo *their* characteristic reactions.

Problem 13.11 Predict the product of each of the following reactions:

(a) $CH_2{=}CHCOOH + H_2/Ni$
(b) *trans*-$CH_3CH{=}CHCOOH + Br_2/CCl_4$
(c) $C_6H_5CH(OH)CH_2COOH + H^+, \text{heat} \longrightarrow C_9H_8O_2$
(d) *o*-$HOOCC_6H_4CH_2OH + H^+, \text{heat} \longrightarrow C_8H_6O_2$

13.17 Dicarboxylic acids

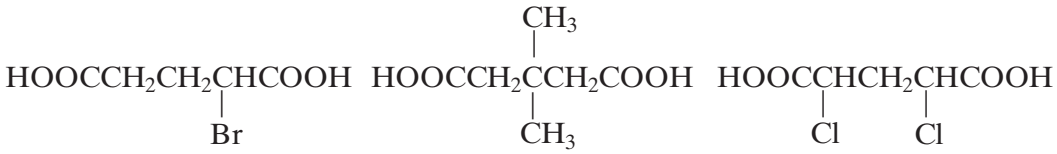
If the substituent is a second carboxyl group, we have a *dicarboxylic acid*. For example:



Malonic acid
Propanedioic acid

Succinic acid
Butanedioic acid

Adipic acid
Hexanedioic acid



α- Bromoglutaric acid
2-Bromopentanedioic acid

β,β-Dimethylglutaric acid
3,3-Dimethylpentanedioic acid

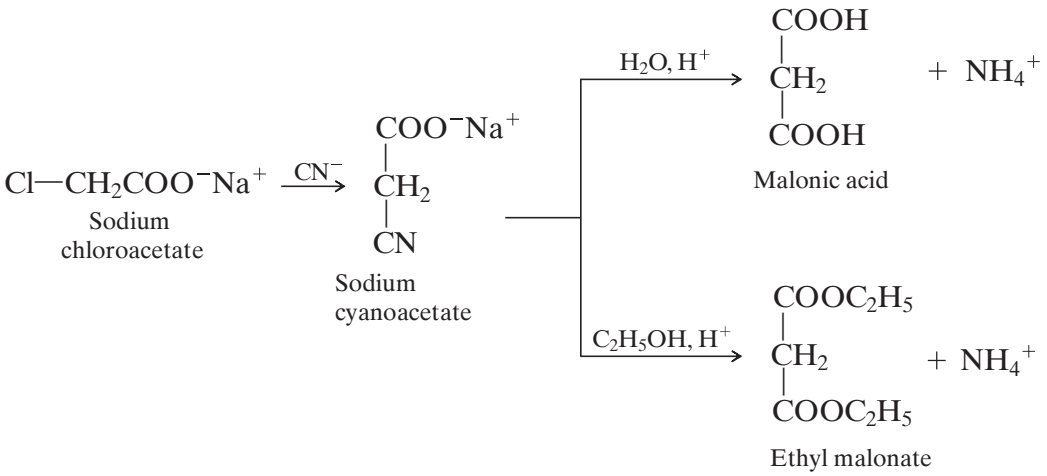
α,α-Dichloroglutaric acid
2,4-Dichloropentanedioic acid

Table 13.4 DICARBOXYLIC ACIDS

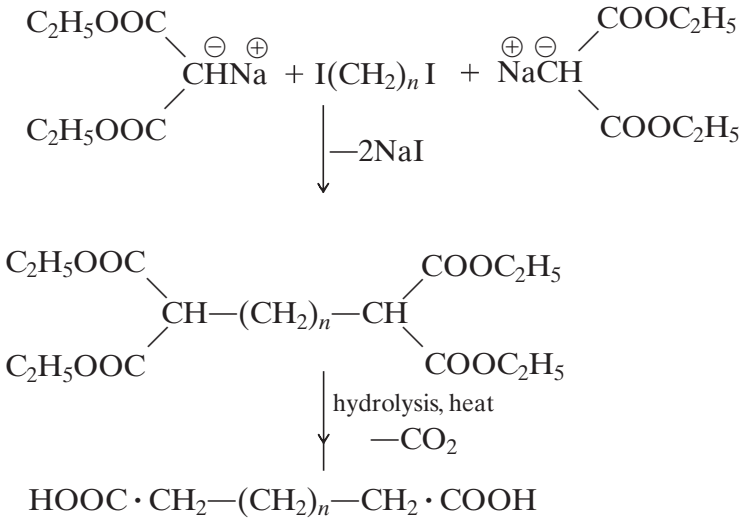
Name	Formula	M.p., °C	Solubility g/100g H_2O at 20 °C	K_1	K_2
Oxalic	HOOC—COOH	189	9	5400×10^{-5}	5.2×10^{-5}
Malonic	$HOOCCH_2COOH$	136	74	140×10^{-5}	0.20×10^{-5}
Succinic	$HOOC(CH_2)_2COOH$	185	6	6.4×10^{-5}	0.23×10^{-5}
Glutaric	$HOOC(CH_2)_3COOH$	98	64	4.5×10^{-5}	0.38×10^{-5}
Adipic	$HOOC(CH_2)_4COOH$	151	2	3.7×10^{-5}	0.39×10^{-5}
Maleic	*cis*-HOOCCH=CHCOOH	130.5	79	1000×10^{-5}	0.055×10^{-5}
Fumaric	*trans*-HOOCCH=CHCOOH	302	0.7	96×10^{-5}	4.1×10^{-5}
Phthalic	1,2-$C_6H_4(COOH)_2$	231	0.7	110×10^{-5}	0.4×10^{-5}
Isophthalic	1,3-$C_6H_4(COOH)_2$	348.5	0.01	24×10^{-5}	2.5×10^{-5}
Terephthalic	1,4-$C_6H_4(COOH)_2$	300 *subl.*	0.002	29×10^{-5}	3.5×10^{-5}

Most dicarboxylic acids are prepared by adaptation of methods used to prepare monocarboxylic acids. Where hydrolysis of a nitrile yields a monocarboxylic acid,

hydrolysis of a dinitrile or a cyanocarboxylic acid yields a dicarboxylic acid; where oxidation of a methylbenzene yields a benzoic acid, oxidation of a dimethylbenzene yields a phthalic acid. For example:



The dicarboxylic acids where the two COOH groups are separated by more than one carbon atom, can be prepared from sodio diethylmalonate. For example:



where, $n = 0, 1, 2 \ldots$

Problem 13.12 Why is chloroacetic acid converted into its salt before treatment with cyanide in the above preparation?

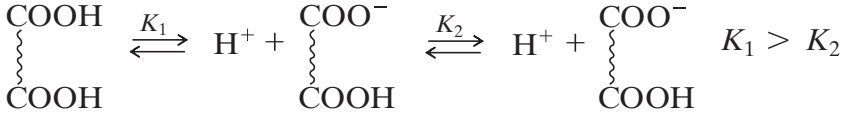
Problem 13.13 Outline a synthesis of: (a) pentanedioic acid from 1,3-propanediol (available from a fermentation of glycerol); (b) nonanedioic acid from *cis* -9-octa-decenoic acid (oleic acid, obtained from fats); (c) succinic acid from 1,4-butynediol (available from acetylene and formaldehyde).

In general, dicarboxylic acids show the same chemical behavior as monocarboxylic acids. It is possible to prepare compounds in which only one of the carboxyl groups has been converted into a derivative; it is possible to prepare compounds in which the two carboxyl groups have been converted into different derivatives.

Problem 13.14 Predict the products of the following reactions:

(a) adipic acid (146 g) + 95% ethanol (146 g) + benzene + conc. H_2SO_4, 100 °C
(b) adipic acid (146 g) + 95% ethanol (50 g) + benzene + conc. H_2SO_4, 100 °C
(c) succinic acid + $LiAlH_4$
(d) pentanedioic acid + 1 mol Br_2, P
(e) terephthalic acid + excess $SOCl_2$
(f) maleic acid (*cis*-butenedioic acid) + Br_2CCl_4

As with other acids containing more than one ionizable hydrogen (H_2SO_4, H_2CO_3, H_3PO_4, etc.), ionization of the second carboxyl group occurs less readily than ionization of the first (compare K_1 values with K_2 values in Table 13.4. More energy is required to separate a positive hydrogen ion from the doubly charged anion than from the singly charged anion.



Problem 13.15 Compare the acidity (first ionization) of oxalic acid with that of formic acid; of malonic acid with that of acetic acid. How do you account for these differences?

Problem 13.16 Arrange oxalic, malonic, succinic, and glutaric acids in order of acidity (first ionization). How do you account for this order?

Certain reactions of dicarboxylic acids, while fundamentally the same as those undergone by any carboxylic acid, lead to unusual results simply because there *are* two carboxyl groups in each molecule. In addition, some dicarboxylic acids undergo certain special reactions that are possible only because the two carboxyl groups are located in a particular way with respect to each other.

Problem 13.17 Give a likely structure for the product of each of the following reactions:

(a) oxalic acid + 1,2-ethanediol $\longrightarrow$ $C_4H_4O_4$
(b) succinic acid + heat $\longrightarrow$ $C_4H_4O_3$
(c) terephthalic acid + 1,2-ethanediol $\longrightarrow$ $(C_{10}H_8O_4)_n$, the polymer Dacron

13.18 Spectroscopic analysis of carboxylic acids

Infrared The carboxyl group is made up of a carbonyl group (C═O) and a hydroxyl group (OH), and the infrared spectrum of carboxylic acids reflects both these structural units. For hydrogen-bonded (dimeric) acids, O—H stretching gives a strong, broad band in the 2500–3000 cm^{-1} range (see Fig. 13.5)

O—H stretching, *strong*, *broad*

—COOH and enols	2500–3000 cm^{-1}
ROH and ArOH	3200–3600 cm^{-1}

With acids we encounter again absorption due to stretching of the carbonyl group. As we saw for aldehydes and ketones, this strong band appears in a region that is usually free of other strong absorption, and by its exact frequency gives much

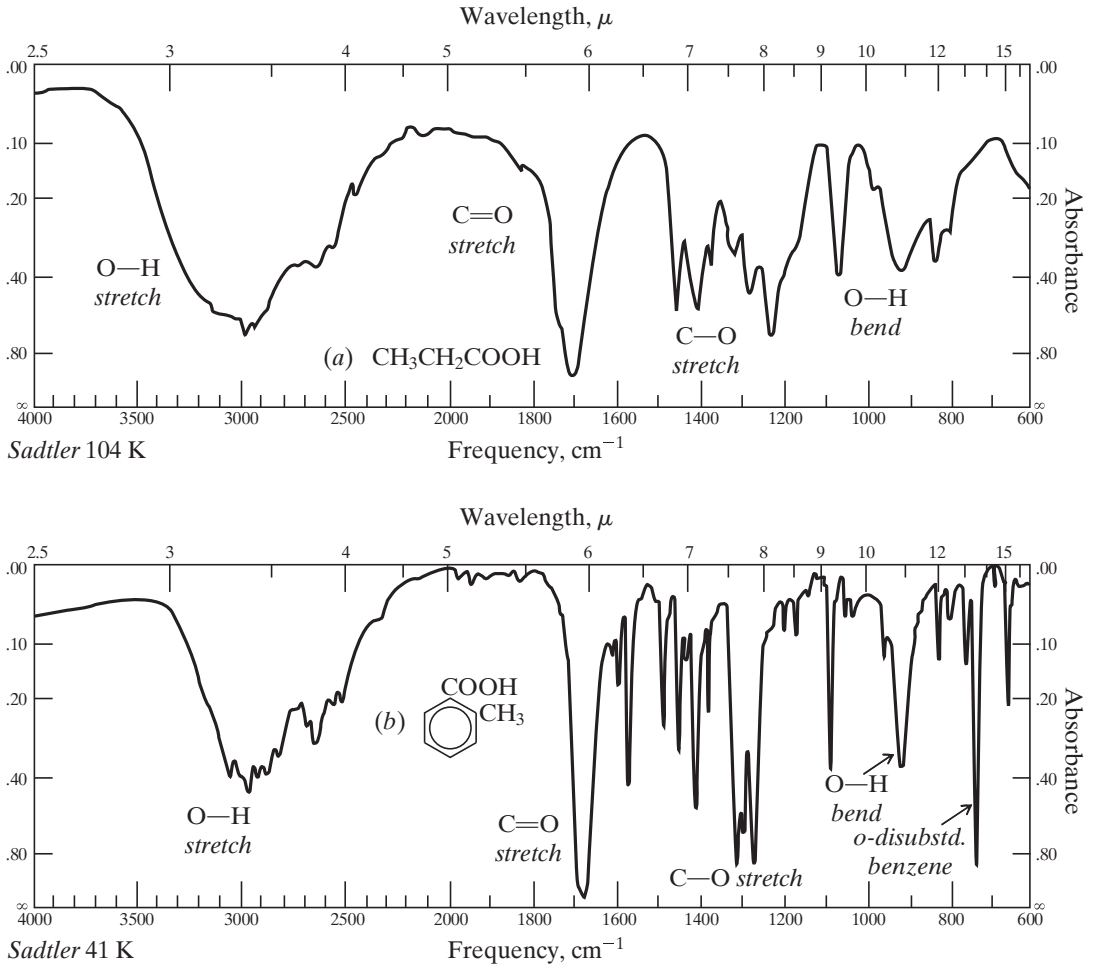
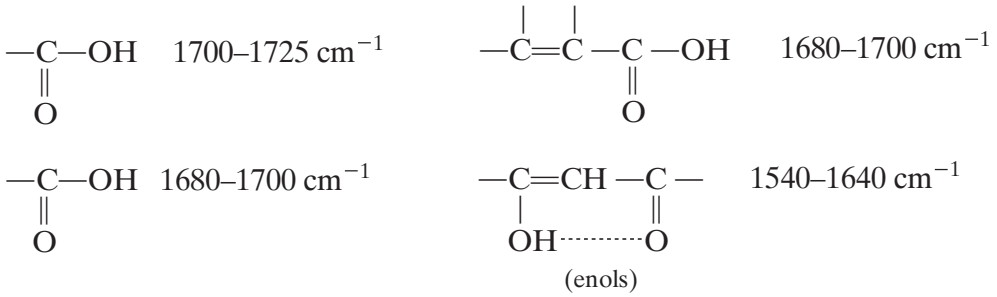


Figure 13.5 Infrared spectra of (*a*) propionic acid and (*b*) *o*-toluic acid.

information about structure. For (hydrogen-bonded) acids, the C=O band is at about 1700 cm^{-1}.

C=O stretching, *strong*



Acids also show a C—O stretching band at about 1250 cm^{-1}, and bands for O—H bending near 1400 cm^{-1} and 920 cm^{-1} (*broad*).

Enols, too, show both O—H and C=O absorption; these can be distinguished by the particular frequency of the C=O band. Aldehydes, ketones, and esters show carbonyl absorption, but the O—H band is missing.

NMR The outstanding feature of the NMR spectrum of a carboxylic acid is the absorption far downfield (δ 10.5–12) by the proton of —COOH. (Compare the absorption by the acid proton of phenols, ArOH.)

CMR In the CMR spectrum of a carboxylic acid we see the far downfield absorption by carbonyl carbon, δ 165–185. This is in the same general region as for functional derivatives of carboxylic acids, but somewhat upfield from the absorption by aldehydes and ketones.

EXERCISE

1. Give the common names and IUPAC names for the straight-chain saturated carboxylic acids containing the following numbers of carbon atoms: 1, 2, 3, 4, 5, 6, 8, 10, 12,16, 18.

2. Give the structural formula and, where possible, a second name (by a different system) for each of the following:

(a) isovaleric acid
(b) trimethylacetic acid
(c) α,β-dimethylcaproic acid
(d) 2-methyl-4-ethyloctanoic acid
(e) phenylacetic acid
(f) γ-phenylbutyric acid
(g) adipic acid
(h) *p*-toluic acid
(i) phthalic acid
(j) isophthalic acid
(k) terephthalic acid
(l) *p*-hydroxybenzoic acid
(m) potassium α-methylbutyrate
(n) magnesium 2-chloropropanoate
(o) maleic acid
(p) α,α-dibromosuccinic acid
(q) isobutyronitrile
(r) 2,4-dinitrobenzonitrile

3. Write equations to show how each of the following compounds could be converted into benzoic acid:

(a) toluene
(b) bromobenzene
(c) benzonitrile
(d) benzyl alcohol
(e) benzotrichloride
(f) acetophenone

4. Write equations to show how each of the following compounds could be converted into *n*-butyric acid:

(a) *n*-butyl alcohol
(b) *n*-propyl alcohol
(c) *n*-propyl alcohol (a second way)
(d) methyl *n*-propyl ketone

Which of the above methods could be used to prepare trimethylacetic acid?

5. Write equations to show how tetrahydrofuran could be converted into:

(a) succinic acid
(b) glutaric acid
(c) adipic acid

6. Write equations to show the reaction (if any) of benzoic acid with:

(a) KOH
(b) Al
(c) CaO
(d) Na_2CO_3
(e) NH_3(aq)
(f) H_2, Ni, 20 °C, 1 atm
(g) $LiAlH_4$
(h) hot $KMnO_4$
(i) PCl_5
(j) PCl_3
(k) $SOCl_2$
(l) Br_2/Fe
(m) $Br_2 + P$
(n) HNO_3/H_2SO_4
(o) fuming sulfuric acid
(p) $CH_3Cl, AlCl_3$
(q) *n*-propyl alcohol, H^+

7. Answer Problem 6 for *n*-valeric acid.

8. Write equations to show how isobutyric acid could be converted into each of the following, using any needed reagents;

(a) ethyl isobutyrate
(b) isobutyryl chloride
(c) isobutyramide
(d) magnesium isobutyrate
(e) isobutyl alcohol

9. Write equations to show all steps in the conversion of benzoic acid into:

(a) sodium benzoate
(b) benzoyl chloride
(c) benzamide
(d) *n*-propyl benzoate
(e) *p*-tolyl benzoate
(f) *m*-bromophenyl benzoate
(g) benzyl alcohol

10. Write equations to show how phenylacetic acid could be converted into each of the following, using any needed reagents.

(a) sodium phenylacetate
(b) ethyl phenylacetate
(c) phenylacetyl chloride
(d) phenylacetamide
(e) *p*-bromophenylacetic acid
(f) *p*-nitrophenyiacetic acid
(g) β-phenyl ethyl alcohol
(h) α-bromophenylacetic acid
(i) α-aminophenylacetic acid
(j) α-hydroxyphenylacetic acid
(k) phenylmalonic acid, $C_6H_5CH(COOH)_2$

11. Complete the following, giving the structures and names of the principal organic products.

(a) $C_6H_5CH{=}CHCOOH + KMnO_4 + OH^- + \text{heat}$
(b) $p\text{-}CH_3C_6H_4COOH + HNO_3 + H_2SO_4$
(c) succinic acid + $LiAlH_4$, followed by H^+
(d) $C_6H_5COOH + C_6H_5CH_2OH + H^+$
(e) product (d) + $HNO_3 + H_2SO_4$
(f) *n*-butyric acid + Br_2, P
(g) *cyclo*-C_6H_{11} MgBr + CO_2, followed by H_2SO_4
(h) product (g) + $C_2H_5OH + H^+$
(i) product (g) + $SOCl_2$ + heat
(j) $m\text{-}CH_3C_6H_4OCH_3 + KMnO_4 + OH^-$
(k) mesitylene + $K_2Cr_2O_7 + H_2SO_4$
(l) isobutyric acid + isobutyl alcohol + H^+
(m) salicylic acid (o-HOC_6H_4COOH) + Br_2, Fe
(n) sodium acetate + *p*-nitrobenzyl bromide
(o) linolenic acid + excess H_2, Ni
(p) oleic acid + $KMnO_4$, heat
(q) linoleic acid + O_3, then H_2O, Zn
(r) benzoic acid ($C_7H_6O_2$) + H_2, Ni, heat, pressure $\longrightarrow$ $C_7H_{12}O_2$
(s) benzoic acid + 1,2-ethanediol + $H^+ \longrightarrow$ $C_{16}H_{14}O_4$
(t) phthalic acid + ethyl alcohol + $H^+ \longrightarrow$ $C_{12}H_{14}O_4$
(u) oleic acid + Br_2/CCl_4
(v) product (u) + KOH (alcoholic)
(w) oleic acid + HCO_2OH

12. Outline a possible laboratory synthesis of the following labeled compounds, using $Ba^{14}CO_3$ or $^{14}CH_3OH$ as the source of ^{14}C.

(a) $CH_3CH_2CH_2{}^{14}COOH$
(b) $CH_3CH_2{}^{14}CH_2COOH$
(c) $CH_3{}^{14}CH_2CH_2COOH$
(d) $^{14}CH_3CH_2CH_2COOH$

13. Outline all steps in a possible laboratory synthesis of each of the following compounds from toluene and any needed aliphatic and inorganic reagents.

(a) benzoic acid
(b) phenylacetic acid
(c) *p*-toluic acid
(d) *m*-chlorobenzoic acid
(e) *p*-chlorobenzoic acid
(f) *p*-bromophenylacetic acid
(g) α-chlorophenylacetic acid

14. Outline a possible laboratory synthesis of each of the following compounds from benzene, toluene, and alcohols of four carbons or fewer, using any needed inorganic reagents.

(a) ethyl α-methylbutyrate
(b) 3,5-dinitrobenzoyl chloride
(c) α-amino-*p*-bromophenylacetic acid
(d) α-hydroxypropionic acid
(e) $p\text{-}HO_3SC_6H_4COOH$
(f) 2-pentenoic acid

(g) *p*-toluamide
(h) *n*-hexyl benzoate
(i) 3-bromo-4-methylbenzoic acid
(j) α-methylphenylacetic acid
(k) 2-bromo-4-nitrobenzoic acid
(l) 1,2,4-benzenetricarboxylic acid

15. Without referring to tables, arrange the compounds of each set in order of acidity:

(a) butanoic acid, 2-bromobutanoic acid, 3-bromobutanoic acid, 4-bromobutanoic acid
(b) benzoic acid, *p*-chlorobenzoic acid, 2,4-dichlorobenzoic acid, 2,4,6-trichlorobenzoic acid
(c) benzoic acid, *p*-nitrobenzoic acid, *p*-toluic acid
(d) α-chlorophenylacetic acid, *p*-chlorophenylacetic acid, phenylacetic acid, α-phenylpropionic acid
(e) *p*-nitrobenzoic acid, *p*-nitrophenylacetic acid, β-(*p*-nitrophenyl)propionic acid
(f) acetic acid, acetylene, ammonia, ethane, ethanol, sulfuric acid, water
(g) acetic acid, malonic acid, succinic acid

16. Arrange the monosodium salts of the acids in Problem 15(f) in order of basicity.

17. The two water-insoluble solids, benzoic acid and *o*-chlorobenzoic acid, can be separated by treatment with an aqueous solution of sodium formate. What reaction takes place?

18. Arrange the compounds of each set in order of reactivity in the indicated reaction:

(a) esterification by benzoic acid: *sec*-butyl alcohol, methanol, *tert*-pentyl alcohol, *n*-propyl alcohol
(b) esterification by ethyl alcohol: benzoic acid, 2,6-dimethylbenzoic acid, *o*-toluic acid
(c) esterification by methanol: acetic acid, formic acid, isobutyric acid, propionic acid, trimethylacetic acid

19. Give stereochemical formulas of compounds A–F:

(a) racemic β-bromobutyric acid + one mole Br_2, P $\longrightarrow$ A + B
(b) fumaric acid + $HCO_2OH \longrightarrow$ C ($C_4H_6O_6$)
(c) l,4-cyclohexadiene + $CHBr_3$/*t*-BuOK $\longrightarrow$ D ($C_7H_8Br_2$)
D + $KMnO_4 \longrightarrow$ E ($C_7H_8Br_2O_4$)
E + H_2, Ni(base) $\longrightarrow$ F ($C_7H_{10}O_4$)

20. Give structures of compounds G–J:

$$\text{acetylene} + CH_3MgBr \longrightarrow G + CH_4$$

$$G + CO_2 \longrightarrow H \xrightarrow{H^+} I(C_3H_2O_2)$$

$$I \xrightarrow{H_2O,\ H_2SO_4,\ HgSO_4} J(C_3H_4O_3)$$

$$J + KMnO_4 \longrightarrow CH_2(COOH)_2$$

21. Describe simple chemical tests (other than color change of an indicator) that would serve to distinguish between:

(a) propionic acid and *n*-pentyl alcohol
(b) isovaleric acid and *n*-octane
(c) ethyl *n*-butyrate and isobutyric acid
(d) propionyl chloride and propionic acid
(e) *p*-aminobenzoic acid and benzamide
(f) $C_6H_5CH{=}CHCOOH$ and $C_6H_5CH{=}CHCH_3$

Tell exactly what you would *do* and *see*.

22. Tell how you would separate by chemical means the following mixtures, recovering each component in reasonably pure form:

(a) caproic acid and ethyl caproate
(b) di-*n*-butyl ether and *n*-butyric acid
(c) isobutyric acid and 1-hexanol
(d) sodium benzoate and triphenylmethanol

Tell exactly what you would *do* and *see*.

23. An unknown compound is believed to be one of the following. Describe how you would go about finding out which of the possibilities the unknown actually is. Where possible, use simple chemical tests; where necessary, use more elaborate chemical methods like quantitative hydrogenation, cleavage, neutralization equivalent, etc. Make use of any needed tables of physical constants.

(a) acrylic acid (CH_2=CHCOOH, b.p. 142 °C) and propionic acid (b.p. 141 °C)
(b) mandelic acid ($C_6H_5CHOHCOOH$, m.p. 120 °C) and benzoic acid (m.p. 122 °C)
(c) *o*-chlorobenzoic acid (m.p. 141 °C), mesotartaric acid (m.p. 140 °C), *m*-nitrobenzoic acid (m.p. 141 °C), and suberic acid ($HOOC(CH_2)_6COOH$, m.p. 144 °C)
(d) chloroacetic acid (b.p. 189 °C), α-chloropropionic acid (b.p. 186 °C), dichloroacetic acid (b.p. 194 °C), and *n*-valeric acid (b.p. 187 °C)
(e) 3-nitrophthalic acid (m.p. 220 °C) and 2,4,6-trinitrobenzoic acid (m.p. 220 °C)
(f) *p*-chlorobenzoic acid (m.p. 242 °C), *p*-nitrobenzoic acid (m.p. 242 °C), *o*-nitrocinnamic acid (*o*-$O_2NC_6H_4CH$=CHCOOH, m.p. 240 °C)
(g) The following compounds, all of which boil within a few degrees of each other:

o-chloroanisole	isodurene
β-chlorostyrene	linalool
p-cresyl ethyl ether	4-methylpentanoic acid
cis-decalin	α-phenylethyl chloride
2,4-dichlorotoluene	*o*-toluidine (*o*-$CH_3C_6H_4NH_2$)

24. *Tropic acid* (obtained from the alkaloid atropine, found in deadly nightshade, *Atropa belladona*), $C_9H_{10}O_3$, gives a positive CrO_3/H_2SO_4 test and is oxidized by hot $KMnO_4$ to benzoic acid. Tropic acid is converted by the following sequence of reactions into *hydratropic acid*:

$$\text{tropic acid} \xrightarrow{HBr} C_9H_9O_2Br \xrightarrow{OH^-} C_9H_8O_2 \text{ (atropic acid)}$$

$$\text{atropic acid} \xrightarrow{H_2, Ni} \text{hydratropic acid } (C_9H_{10}O_2)$$

(a) What structure or structures are possible at this point for hydratropic acid? For tropic acid?
(b) When α-phenylethyl chloride is treated with magnesium in ether, the resulting solution poured over Dry Ice, and the mixture then acidified, there is obtained an acid whose amide has the same melting point as the amide of hydratropic acid. A mixed melting point determination shows no depression. Now what is the structure of hydratropic acid? Of tropic acid?

25. Give a structure or structures consistent with each of the following sets of proton NMR data:

(a) $C_3H_5ClO_2$
a doublet, δ 1.73, 3H
b quartet, δ 4.47, 1H
c singlet, δ 11.22, 1H

(b) $C_3H_5ClO_2$
a singlet, δ 3.81, 3H
b singlet, δ 4.08, 2H

(c) $C_4H_7BrO_2$
a triplet, δ 1.30, 3H
b singlet, δ 3.77, 2H
c quartet, δ 4.23, 2H

(d) $C_4H_7BrO_2$
a triplet, δ 1.08, 3H
b quintet, δ 2.07, 2H
c triplet, δ 4.23, 1H
d singlet, δ 10.97, 1H

(e) $C_4H_8O_3$
a triplet, δ 1.27, 3H
b quartet, δ 3.66, 2H
c singlet, δ 4.13, 2H
d singlet, δ 10.95, 1H

26. Compare benzoic acid and sodium benzoate with respect to:

(a) volatility
(b) melting point
(c) solubility in water and (d) in ether
(e) degree of ionization of solid
(f) degree of ionization in water
(g) acidity and basicity

Does this comparison hold generally for acids and their salts?