SCH4U-C

7

Functional Groups

Introduction

The properties of organic compounds depend on the arrangement of atoms or groups of atoms that are found within them. An atom or group of atoms that determines the properties of compounds is called a functional group. Recognizing functional groups within a compound makes it easier to predict the properties that the compound may have.

In this lesson, you will learn about the structure, properties, and applications of everyday compounds that contain each of the functional groups introduced in the lesson. You will also see how many of the physical properties of these compounds are related to their intermolecular forces of attraction.

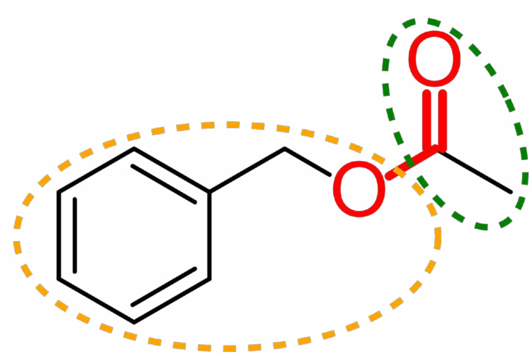


Figure 7.1: Benzyl acetate has an ester functional group (in red), an acetyl group (circled with green), and a benzyloxy group (circled with orange).

Source: http://en.wikipedia.org/wiki/File:Benzyl_acetate_-_functional_groups_and_moieties.svg

Planning Your Study

You may find this time grid helpful in planning when and how you will work through this lesson.

Suggested Timing for This Lesson (Hours)	
Introduction to Functional Groups	½
Organic Halides and Amines	1
Alcohols	1½
Ethers, Aldehydes, and Ketones	1
Key Questions	1

What You Will Learn

After completing this lesson, you will be able to

- name and draw the structural formula of organic compounds containing functional groups
- predict the physical and chemical properties of these compounds
- predict the results of reactions involving these compounds
- assess the impact of organic compounds containing functional groups on human health, society, and the environment

Introduction to Functional Groups

Common examples of functional groups that you've already encountered are the double and triple bonds of alkenes and alkynes, respectively. Functional groups can be as simple as an atom, such as a halogen, in an organic compound like trichloroethylene, TCE. Others contain larger groups of atoms. Table 7.1 summarizes the functional groups that you will encounter in this lesson. The symbols R or R' (pronounced R prime) represent two different alkyl side chains. Additional functional groups are presented in Lesson 8.

Table 7.1: Common organic functional groups

General structure	Functional group name	Example	Structural formula of example
R—X, where X is a halogen	Organic halide	Chloromethane	CH_3Cl
$R—NH_2$	Amine	Ethanamine	$CH_3CH_2NH_2$
R—OH	Alcohol	Ethanol	CH_3CH_2OH
R—OR'	Ether	Methoxyethane	$CH_3OCH_2CH_3$
$R-\overset{\overset{\displaystyle O}{\Vert}}{C}-H$	Aldehyde	Propanal	$CH_3CH_2-\overset{\overset{\displaystyle O}{\Vert}}{C}-H$
$R-\overset{\overset{\displaystyle O}{\Vert}}{C}-R'$	Ketone	Butanone	$CH_3CH_2-\overset{\overset{\displaystyle O}{\Vert}}{C}-CH_3$

Organic Halides and Amines

Halides and amines are classes of organic compounds in which their functional group substitutes for a hydrogen atom on a main alkane chain. In other words, the functional group appears on the main alkane chain, instead of a hydrogen atom.

Organic Halides

Organic halides are organic compounds that have halogen atoms attached to the principal carbon chain. Trichloroethylene (TCE), which you learned about in Lesson 6, is an example of an organic halide.

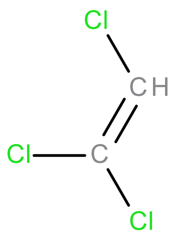


Figure 7.2: Trichloroethylene

Like TCE, many organic halides are useful as all-purpose cleaning solvents. For example, most dry cleaners still use organic halides as their principal cleaning solvent. Organic halides have also been used to make pesticides.

A notorious example of one of these organic halides is dichlorodiphenyltrichloroethane, or DDT—a potent insecticide that was first synthesized in the late 1930s. When DDT was first introduced, it was extremely effective at controlling pests such as lice, mosquitoes, bedbugs, and other insect populations. Because it is so chemically stable, this compound remains where it has been sprayed, for a long time. The advantage of this property is that DDT doesn't have to be sprayed often. However, the stability of DDT also creates a major ecological problem. Some insects can safely ingest DDT (they are DDT-resistant), and so they persist, and even expand in the areas sprayed with DDT. And, if DDT persists in an ecosystem, eventually many larger organisms ingest it too, as they eat the DDT-resistant insects, rodents, and other insectivorous animals, and drink the DDT-contaminated water.

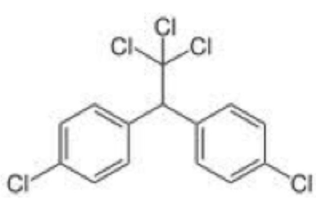


Figure 7.3: DDT structure

Figure 7.4: Ingesting DDT makes eggshells too thin, killing the chicks inside.

Source: http://commons.wikimedia.org/wiki/File:Orange_egg_shell_shadow.png

Because DDT is non-polar, it readily dissolves in the fatty tissue of these DDT-resistant organisms. When they are eaten by organisms higher up in the food chain, the DDT stored in their fatty tissue is passed along the food chain. Soon, the greatest concentrations of DDT appear in the organisms at the top of the food chain—organisms that are not resistant to DDT. This process became known as bio-amplification. High tissue concentrations of DDT almost resulted in the extinction of many large predators, such as the bald eagle. General use of DDT has now been banned, although a few countries still use it to kill the mosquitoes that transmit malaria in rural villages.

Many organic halides have also been used in refrigeration. In the 1930s, organic halides such as Freon® were introduced as a safe and effective refrigerant gas. Soon, Freon and other similar compounds, or chlorofluorocarbons (CFCs), were used worldwide in refrigerators and air-conditioning units. However, by the 1970s, scientists began to notice that holes were appearing in the earth's ozone layer. Ozone, O_3, is a form of oxygen that exists in the stratosphere (between about 10 km and 50 km above the earth's surface). Ozone is produced naturally during lightning storms and is critical because it absorbs most of the harmful UV rays from the sun, preventing them from reaching the earth's surface.

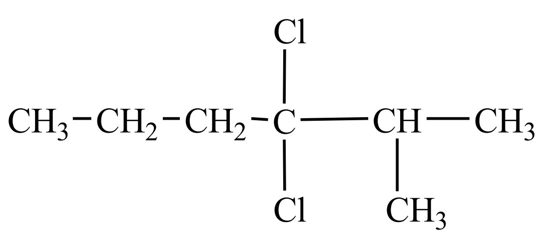
Refrigerant gases leaking from air-conditioning units and refrigerators during the mid-twentieth century drifted upwards and reacted with ozone. This resulted in a reduction in the concentration of atmospheric ozone. In the latter part of the twentieth century, Freon was banned and new ozone-friendly refrigerant gases were developed. As a result, the levels of atmospheric ozone have increased, although they are not yet back to their pre-twentieth-century levels.

Naming Organic Halides

To name an organic halide, consider it as having a carbon backbone or a chain of carbon atoms. The short side chains are attached to the principal carbon chain. Use a prefix to identify the halogen. The most common side chains discussed in this course are "fluoro," "chloro," and "bromo."

Example

Name this compound:



Solution

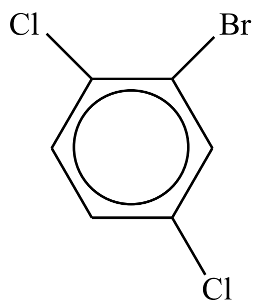
The compound is 3,3-dichloro-2-methylhexane.

Example

Draw the structural formula for 1-bromo-2,5-dichlorobenzene.

Solution

The structural formula for 1-bromo-2,5-dichlorobenzene is shown below:



Properties of Organic Halides

Halogen atoms are highly electronegative. The presence of a halogen makes most of these compounds polar. Consequently, the intermolecular attraction that exists between these molecules is a dipole–dipole attraction. As you learned in Lesson 3, dipole–dipole attractions are significantly stronger than London forces (which are the only type of intermolecular bonding in non-polar compounds). That's why the boiling points of organic halides are much higher than those of comparable alkanes, as shown in Table 7.2.

Table 7.2: Comparison of the boiling points of organic halides and alkanes

Alkane	Boiling point (°C)	Organic halide	Boiling point (°C)
CH_4	–164	CH_3Cl	–24
C_2H_6	–89	C_2H_5Cl	12
C_3H_8	–42	C_3H_7Cl	14

Synthesis of Organic Halides

The formation of organic halides was illustrated in Lesson 5, where a substitution reaction occurred with alkanes. The organic halide can also form by an addition reaction with alkenes, discussed in Lesson 6.

Organic Amines

Organic amines consist of one or more amino groups, —NH_2, attached to a main carbon chain. Perhaps the best-known amines are the amino acids—compounds that are the building blocks of proteins. You will learn more about these in Lesson 8. Another useful amine is 1,6-diaminohexane, $NH_2(CH_2)_6NH_2$—one of the two ingredients necessary to manufacture the synthetic fibre called nylon. Amines are very common in nature. Some common hormones, such as adrenaline, are amines. Many amines have powerful or distinctive aromas. For example, the characteristic smells of urine and decaying fish are caused by amines. Like the organic halides, many of these compounds are polar, making them soluble in water.

Reactions of Amines

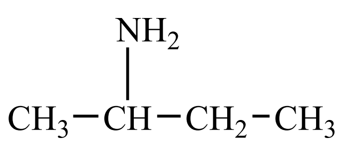
Like ammonia, NH_3, amines are weak bases. As a result, amines undergo neutralization reactions with acids. For example, a squirt of lemon juice (citric acid) eliminates the "fishy" odour of a cooked fish because it neutralizes amines on the fish's surface.

Naming Amines

As with organic halides, amines are named by considering the amino group as a side chain of the principal carbon chain. Consider the following examples.

Example

Name this compound:



Solution

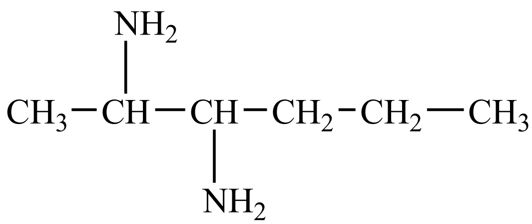
Here we have a 4-carbon alkane having the amino group as a side chain. The compound is 2-aminobutane.

Example

Draw the structural formula for 2,3-diaminohexane.

Solution

We draw the 6-carbon alkane (hexane) in a straight line and then add the two amino (diamino) groups where indicated (at carbon 2 and 3). The structural formula for 2,3-diaminohexane is shown below.



Support Questions

Be sure to try the Support Questions on your own before looking at the suggested answers provided.

24. Draw the structural formula for:

a) 1,2-dichlorobenzene

b) 1,2,3-trichlorobutane

c) tetrafluoroethene

d) 3-bromo-1-chlorocyclohexane

e) 1,3-diaminopentane

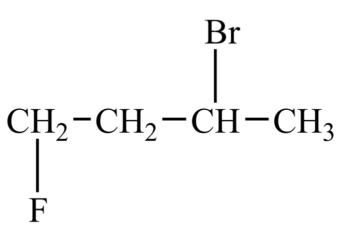
f) aminobenzene

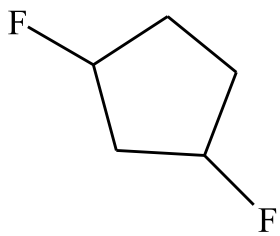
g) 1,3,5-triaminocyclohexane

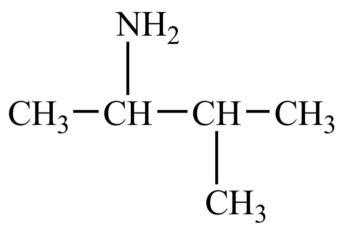
Suggested answer

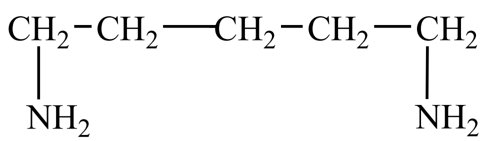
25. Name the following compounds:

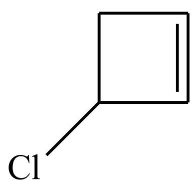
a)



b) 

c) 

d) 

e) 

Suggested answer

26. Write a substitution reaction that would form 2-chloropropane. Draw structural formulas for all organic compounds. You may wish to look back at Lesson 5 to review substitution reactions.

Suggested answer

27. **a)** Draw the structures of C_2HCl_3 and C_2Cl_4.

b) Use intermolecular forces to explain why C_2HCl_3 has a higher boiling point than C_2Cl_4.

Suggested answer

Alcohols

Alcohols are organic compounds that contain the hydroxyl functional group, —OH. Perhaps the best-known alcohol is ethanol, which is made from fermented plants. This is the alcohol that is found in alcoholic beverages. In addition to its intoxicating effects, ethanol also burns well and produces a great deal of energy. That's why it's a common additive in gasoline. Currently, as much as 10% of any given tank of gasoline sold in Ontario consists of ethanol.

At first glance, ethanol appears to be the ideal fuel—it burns cleanly, releases a great deal of energy, and seems to be carbon neutral. Ethanol is carbon neutral because, in theory, the amount of carbon dioxide that is released when ethanol burns equals the carbon dioxide removed from the atmosphere by the plants grown to manufacture ethanol. However, fossil fuels (petroleum products) are used to make the fertilizers and pesticides required to grow today's crops. Also, a lot of energy is used to operate irrigation pumps and the machines that till soil, plant seeds, apply chemicals, and harvest crops. When you consider all of the fuel that it takes to grow and process ethanol crops, the use of crop-based ethanol as an alternative to gasoline is not carbon neutral.

Naming Alcohols

The procedure for naming alcohols is very similar to naming other organics containing a functional group.

Step 1: Find the longest carbon chain containing the functional group, OH. Write the name as if it was an alkane.

Step 2: Replace the name's final "e" with the suffix for alcohols, "-ol."

Step 3: Number the carbon chain, giving priority to the location of the functional group, OH. The location of the functional group must have the smallest possible number. Place the number for the OH location in front of the alcohol name.

For example, there are two different propanols, as shown below.

$$\mathrm{CH_3-CH_2-CH_2-OH}$$

1-propanol

$$\begin{array}{c}\mathrm{CH_3-CH-CH_3}\\ |\\ \mathrm{OH}\end{array}$$

2-propanol

Figure 7.5: The hydroxyl group in propanol can exist in two different locations.

Many alcohols contain more than one hydroxyl group. When naming these compounds, "di-" or "tri-" is added before the "-ol" ending. For example, automotive antifreeze contains 1,2-ethandiol (also called ethylene glycol), and 1,2,3-propantriol (also called glycerine or glycerol) is a common ingredient in soaps and some food products. It contains three hydroxyl groups (seen in Figure 7.6).

Figure 7.6: 1,2-ethandiol (left) and 1,2,3-propantriol (right) are two well-known examples of alcohols containing more than one hydroxyl group.

Some alcohols are cyclic alcohols. Menthol, for example, gives peppermint candy its characteristic taste (see Figure 7.7). Cholesterol is responsible for the clogging of arteries. Phenol is a raw material used to create many commonly used consumer products, including medications and plastics.

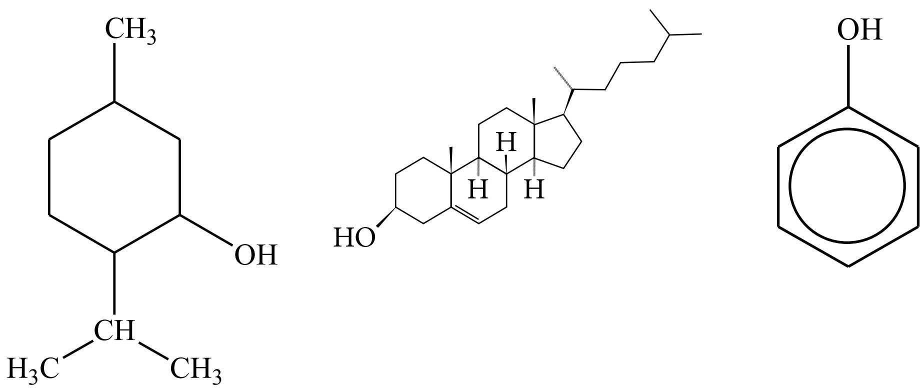


Figure 7.7: Cyclic alcohols. Menthol (left), cholesterol (middle), and hydroxybenzene, commonly known as phenol (right)

Common Names of Alcohols

Because alcohols have been around for a long time, many are recognized by their common names, rather than their official or "systematic" names. For example, ethyl alcohol is the common name for ethanol, while methanol is sometimes referred to as methyl alcohol or wood alcohol.

Properties of Alcohols

Because of the large electronegativity difference between hydrogen and oxygen, the bond between these elements is very polar. As a result, hydrogen bonding is the primary type of intermolecular bonding that occurs between alcohol molecules. Because of hydrogen bonding, the boiling points of alcohols are much higher than those of an alkane with a similar number of carbon atoms (Table 7.3).

Table 7.3: Boiling point comparison of methane and methanol

Substance	Boiling point (°C)	State at room temperature
Methane (an alkane)	–161.5	Gas
Methanol (an alcohol)	64.7	Liquid

Synthesis of Alcohols

Alcohols can be synthesized through fermentation, and through addition reactions.

Fermentation

Ethanol is produced on a large scale through a process called fermentation. This is a biological process in which yeast converts sugars into ethanol and carbon dioxide. Fermentation only occurs in the absence of oxygen. The chemical equation for the fermentation of glucose, a simple sugar, is:

$$C_6H_{12}O_{6(aq)} \rightarrow 2C_2H_5OH_{(l)} + 2CO_{2(g)}$$

Bakers rely on the carbon dioxide released by this reaction for leavening bread dough. As the live yeast organisms mixed into bread dough ferment the sugar, they create tiny carbon-dioxide bubbles. These bubbles become trapped and make the dough rise before it is baked. Winemakers use yeast fermentation to convert the sugars in grape juice into ethanol and carbon dioxide.

Recently, a significant portion of the North American corn crop has been diverted into the production of ethanol for use as a gasoline additive. As much as 10% of the gasoline sold in Ontario is ethanol. Since corn is such a key ingredient in so many food products, many groups have expressed concern over the use of corn to produce ethanol and the impact that this might have on the cost of food products. Much of our ethanol is produced through the fermentation of grains such as corn and wheat. Instead, however, we could be fermenting unwanted or unusable plant matter, such as algae or yard waste, for this purpose. Diverting grain production for the synthesis of ethanol raises social concerns. For instance, how will turning our limited grain supply into fuel impact the cost of food?

Addition Reactions

As you learned in Lesson 6, alcohols can also be made by the addition of a water molecule across the double bond in an alkene (Figure 7.8).

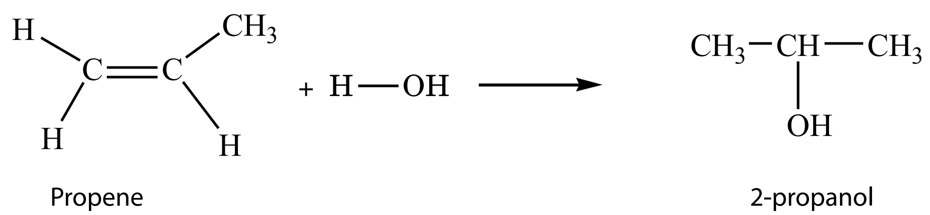


Figure 7.8: Synthesis of 2-propanol

Reactions of Alcohols

Much of the chemistry of alcohols is determined by the hydroxyl group (or groups).

Combustion Reactions

Like many hydrocarbons, alcohols are energy-rich molecules that are sometimes used as fuel. The chemical equation for the complete combustion of ethanol is:

$C_2H_5OH_{(l)} + 3O_{2(g)} \rightarrow 2CO_{2(g)} + 3H_2O_{(g)}$

The combustion of alcohols is typically much cleaner than that of hydrocarbons, and produces less soot in car exhaust. When looking only at exhaust, alcohols seem like an ideal substitute for gasoline and diesel fuel.

Elimination Reactions

In the presence of a strong acid and catalyst, the hydroxyl group of an alcohol can be removed to produce an alkene (Figure 7.9). The net result is a process that is the opposite of adding water to an alkene.

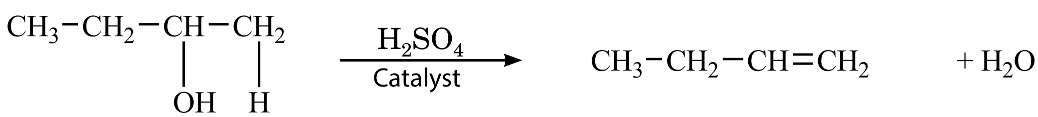


Figure 7.9: The elimination of an alcohol produces an alkene. This reaction is also called dehydration.

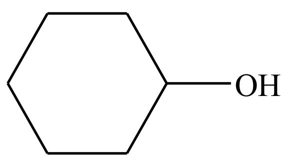
Note that, in this example, the hydrogen is removed from an end carbon atom, rather than an inner carbon atom. During these reactions, the carbon atoms with the most hydrogen tend to react first. This is a similar trend to the one observed in the addition reactions that you learned about in Lesson 6.

Support Questions

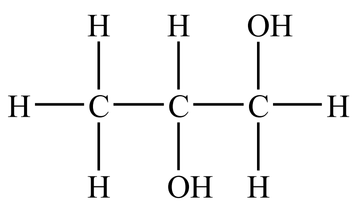
28. Name the following compounds:

a) $HO-CH_2-CH_2-CH_2-CH_2-CH_3$

b)



c)



Suggested answer

29. Draw the structural formula for:

a) 3-pentanol

b) 1,3-propandiol

c) 1,3-cyclopentandiol

d) 3,3-dimethyl-1-pentanol

Suggested answer

30. Write a chemical equation to synthesize 3-pentanol from an alkene. Use structural formulas for all organic compounds in your equations. (**Hint:** an addition reaction will be required. You may wish to look back at Lesson 6.)

Suggested answer

31. The following data give the solubility of alcohols in water. Examine the data and then answer the questions that follow.

Alcohol	Solubility in water
Methanol	Very soluble
Ethanol	Very soluble
1-propanol	Soluble
1-butanol	Slightly soluble
1-pentanol	Very slightly soluble
1-hexanol	Insoluble

a) Describe the trend in solubility.

b) Draw each alcohol in the table. In order for any substance to dissolve in water, the first criterion is that it must be attracted to water. Explain why all alcohols would be strongly attracted to water.

c) The second criterion for solubility in water is that the substance must be small enough that the water molecules have enough kinetic energy to tow them around. Explain the trend in solubility shown in the table.

Suggested answer

32. You learned that isomers are molecules that have the same molecular formula, yet different structures. Draw and name all isomers having the molecular formula $C_4H_{10}O$ that are alcohols. Name and draw a structural formula for each compound.

Check your structure by viewing these compounds online at 3D Models of Complex Molecules with Functional Groups.

Suggested answer

33. Methods of producing ethanol by fermenting the cellulose in plant cuttings like wood chips and grass clippings are currently being developed. Why is this method preferred over fermenting corn to produce ethanol?

Suggested answer

Ethers, Aldehydes, and Ketones

Ethers, aldehydes, and ketones are polar organic solvents that have a wide range of applications.

Ethers

The structure of ethers is simple, as shown in Table 7.1. The functional group is simply a single oxygen atom bonded on both sides to some alkyl (carbon) group.

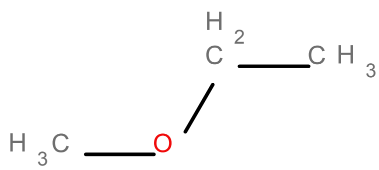


Figure 7.10: The ether methoxyethane (also named ethylmethylether)

Historically, ethers were one of the first anaesthetics used for surgery. Today, they are essential industrial solvents.

Properties of Ethers

Because of their angular or bent shape, ethers are polar solvents. Like alcohols, smaller ether molecules are soluble in polar solvents, such as water. They become less soluble as the size of the alkyl groups increases. Figure 7.11 shows a comparison of the structures of water, alcohols, and ethers.

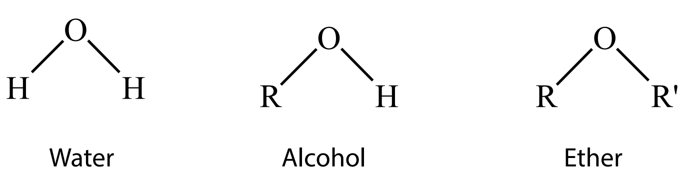


Figure 7.11: Comparison of the shapes of water, alcohol, and ether molecules. Characteristic of bonding to an oxygen atom, note that all have the "V" shape with the highly electronegative oxygen atom at the tip of the "V." This site where the "V" exists on the molecule has a significant negative charge where the oxygen atom is located. This "V" site has significant polarity.

Aldehydes and Ketones

Aldehydes and ketones are two of the most common organic compounds that contain the carbonyl functional group.

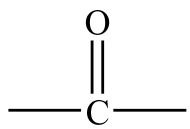


Figure 7.12: When a carbon atom is double-bonded to an oxygen atom, they are called a carbonyl functional group. This group has the above structure.

When the carbonyl functional group is at the end (not between two carbons) of the structure, the molecule is an aldehyde. When the carbonyl group is between two carbons of a carbon chain, the molecule is called a ketone. For example, the two smallest aldehydes are methanal (also called formaldehyde) and ethanal (also called acetaldehyde), as shown in Figure 7.13. Formaldehyde is a widely used preservative. Until recently, specimens such as the dead frogs used for dissection in high-school laboratories were stored in formaldehyde. However, health concerns over the prolonged exposure to formaldehyde have limited its use.

Methanal Ethanal

Figure 7.13: The two smallest aldehydes (notice that the suffix on the name of aldehydes is "-al")

Ketones are similar to aldehydes, except for the fact that the carbonyl group is found within the carbon chain, rather than at either end (Figure 7.14). Many ketones, such as propanone (commonly known as acetone), are used in solvents and glues.

Return to [3D Models of Complex Molecules with Functional Groups]() to view a molecular model of acetone and examine its structure.

Propanone is the smallest ketone.

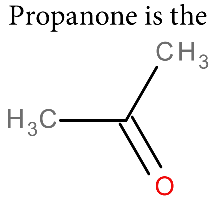


Figure 7.14: The shortest ketone, propanone. Notice that the suffix on the name of ketones is "-one." In this structural formula, we have specifically shown the "V" shape mentioned earlier.

Properties of Aldehydes and Ketones

Since both aldehydes and ketones are polar where the carbonyl group is located, smaller aldehydes and ketones are soluble in water. The polarity of small aldehydes and ketones makes them useful as solvents for polar compounds. Larger aldehydes and ketones have a large non-polar segment, so are more suitable as solvents for less polar (or even non-polar) compounds. Since these compounds are not capable of hydrogen bonding, their boiling points are lower than that of an alcohol compound of comparable size. Since these compounds have dipole–dipole attractions between their molecules, their boiling points are significantly higher than those of the comparable alkane. Table 7.4 compares the boiling points of four comparable compounds.

Table 7.4: Boiling points of 3-carbon compounds

Compound	Structure	Intermolecular forces	Boiling point (°C)
Propane	$CH_3CH_2CH_3$	London	–42
1-propanol	$CH_3CH_2CH_2OH$	Hydrogen bonding	97
Propanal	CH_3CH_2CHO	Dipole–dipole	49
Propanone	CH_3COCH_3	Dipole–dipole	56

Naming Aldehydes

You've now seen how alkenes, alkynes, and alcohols are named. It should be clear to you that the naming procedure for organic compounds containing functional groups is essentially the same. Here are the three steps for naming aldehydes:

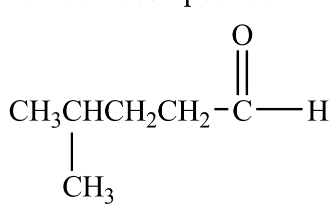
Step 1: Determine the longest carbon chain containing the carbonyl functional group in the molecule and write the name as if it were an alkane.

Step 2: Replace the name's final "e" with "-al," which is the suffix for an aldehyde.

Step 3: The carbon of the carbonyl group is always considered to be the first carbon of the longest chain. It has been stressed that the numbering of the carbon chain is always determined by the location of the functional group. Priority is given to the location of the functional group. Therefore, any side chains on the main carbon chain are numbered in relation to the functional group.

Example

Name this compound:



Solution

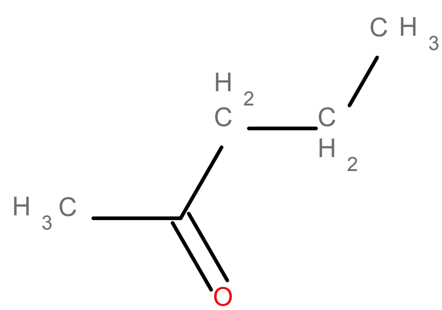
This compound is 4-methylpentanal. Notice that we would not name this 4-methyl-1-pentanal since the functional group on aldehydes is always the number 1 carbon.

Naming Ketones

The steps for naming ketones are identical to those of aldehydes and other compounds having a functional group. The only unique feature on the ketone name will be the suffix "-one," as mentioned earlier.

Example

Name this compound:



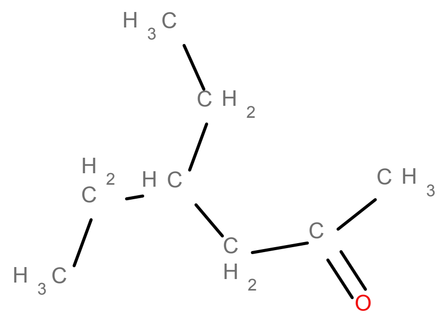
Solution

This compound is 2-pentanone. Again, notice the "V" shape at the carbonyl group, that would be polar.

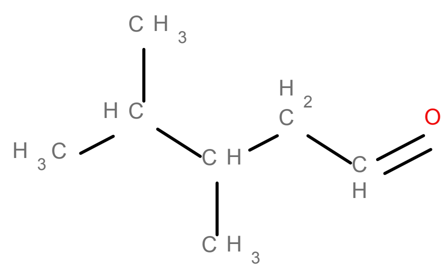
Support Questions

34. Name these compounds:

a)



b)



Suggested answer

35. Write the structural formula for each of the following. Indicate if an aldehyde or ketone is present.

a) 3-hexanone

b) 4-bromobutanal

c) 2-methyl-3-pentanone

Suggested answer

36. Explain why 1-butanone cannot exist. (**Hint:** what family does this belong to? Where is the functional group always found in that family?)

Suggested answer

37. Compare the boiling points of methane, methanal, and methanol. (**Hint:** consider all intermolecular forces present for each.)

Suggested answer

38. Some automotive engine-cleaning products contain ethers. Identify two hazards in using these compounds in a car engine.

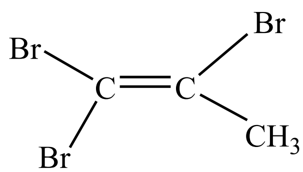
Suggested answer

Key Questions

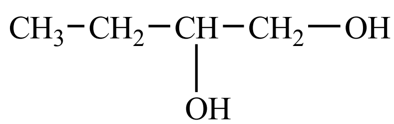
Now work on your Key Questions in the online submission tool. You may continue to work at this task over several sessions, but be sure to save your work each time. When you have answered all the unit's Key Questions, submit your work to the ILC.

24. Name the following compounds. **(6 marks total)**

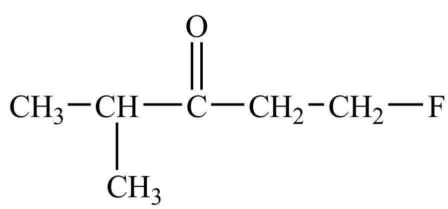
a)



b)



c)



25. Draw the structural formula for the following compounds. **(6 marks total)**

a) 4,4-dichloropentanal

b) 2-methylbutanol

c) 3,3-dichlorohexane

26. Draw and name all of the structural isomers that are ketones with five carbon atoms in its longest chain and the molecular formula $C_5H_{10}O$. Can this molecular formula also have an aldehyde structure? If so, illustrate and name the aldehyde. Can this be drawn as an ether? Explain. **(6 marks)**

27. Write chemical equations for the synthesis of 2-pentanol from an alkene. Use structural formulas for each organic compound. **(3 marks)**

28. The compounds 1-propanol and propanone have approximately the same molar mass. Based on differences in their intermolecular forces, rank these compounds in order of increasing boiling point. Justify your prediction. **(3 marks)**

Now go on to Lesson 8. Send your answers to the Key Questions to the ILC when you have completed Unit 2 (Lessons 5 to 8).