Unit 9

Organic Compounds

This unit online, with its interactives:
science-playground.com/s/9a9

Look around a Nepali kitchen. The gas in the cylinder, the rice and the sugar, the ghee and the mustard oil, the vinegar in the achar, the kerosene for the lamp, the plastic bucket, the sanitizer by the door, even the cotton of your clothes: every one of them is made of molecules built around carbon atoms. So are you. Chemists keep a register of every substance they have described, and it holds more than 290 million of them; most are compounds of carbon.

One element, and almost all of chemistry's variety. Why can carbon build so much? And with so many compounds, how do chemists give each one a name that tells you exactly what it is? This unit answers both questions: what makes carbon special, how its compounds fall into families, and how to read and write their names the way chemists everywhere do.

9.1 Organic compounds

What an organic compound is

Two hundred years ago, chemists sorted substances by where they came from. Sugar, oils, urea, alcohol and dyes came from living things, plants and animals; salt, metals, sand and limestone came from the non-living earth. The Swedish chemist Jöns Jacob Berzelius was the first to draw a line between the two: compounds from living things he called **organic**, the rest **inorganic**. In 1810 he stated that living things work by a mysterious **vital force**, and many chemists believed that only a living thing, with its vital force, could make an organic compound.

Today the name "organic" has nothing to do with life. The plastic of a bucket and the drug in a tablet are organic compounds made in factories. What all organic compounds share is **carbon**, almost always joined to hydrogen:

Organic compounds are the compounds of carbon, mostly with hydrogen (the hydrocarbons) and the compounds made from them by putting other atoms, such as oxygen, nitrogen, sulphur or chlorine, in place of some of their hydrogen atoms. The study of these compounds is **organic chemistry**.

A STORY FROM SCIENCE

Urea without a kidney

In 1828 the German chemist Friedrich Wöhler heated a white salt, ammonium cyanate, which anyone could make from minerals, and found that it had turned into **urea**, the compound in urine. He wrote to Berzelius, his teacher: "I can make urea without the use of kidneys, or indeed of any animal, be it man or dog." An organic compound had been made from inorganic ones in a flask. The vital force theory didn't die at once (historians say the story of its sudden death has grown in the telling), but over the next decades chemists made acetic acid, fats and sugars from simple starting materials, and the idea faded away.

A few simple carbon compounds are counted as inorganic, because they behave like minerals and were studied with them: carbon monoxide (CO), carbon dioxide (CO_2), carbonic acid (H_2CO_3), the **carbonates** such as limestone ($CaCO_3$) and the **hydrogencarbonates** such as baking soda ($NaHCO_3$), the **cyanides** such as KCN, and the **carbides** such as calcium carbide (CaC_2).



Figure 9.1 *Friedrich Wöhler (1800–1882), whose urea of 1828 showed that an organic compound can be made without a living thing.*
Photo: Wellcome Collection, CC BY 4.0

Examples

Organic compounds come from plants and animals, from coal, petroleum and natural gas (the remains of living things buried millions of years ago), and from factories that build them from simpler ones.

6. Write the formulas

a. Write the condensed and structural formulas of: a. 2-methylpropane, b. but-2-ene, c. ethanol.

b. Write the condensed formulas of: a. 2,2-dimethylbutane, b. propanal, c. butanone, d. methoxyethane, e. ethanoic acid, f. 3-methylbut-1-ene.

c. Find the mistake in each name and correct it: a. 3-methylbutane, b. 2-ethylpropane, c. but-3-ene, d. 1-methylpropane.

7. Numerical problems

Use C = 12, H = 1, O = 16.

a. An alkane has a molecular mass of 58. Find its formula, and write the condensed formulas of the two compounds it could be.

b. An aldehyde has a molecular mass of 44. Find its formula and IUPAC name.

c. An alkene has a molecular mass of 70. Find its formula. Write the IUPAC names of two straight-chain alkenes with this formula.

d. An alkane has 22 hydrogen atoms. How many carbon atoms does it have? What are its name and molecular mass?

e. The first member of a homologous series has a molecular mass of 46. What is the molecular mass of its fifth member? Which series could it be?

f. **Think:** A student writes the name of $CH_2{=}CH{-}CH_2{-}CH(CH_3){-}CH_3$ as "2-methylpent-4-ene", numbering from the right so that the methyl gets the number 2. Is the student right? Give the correct name and explain the rule.

Found a mistake? Please tell us.

4. Answer the following questions

a. What are organic compounds? Which carbon compounds are not counted as organic? Give four examples of organic compounds from daily life.

b. Explain tetracovalency of carbon, with the electron dot structure of methane.

c. What is catenation? Why does carbon show catenation much more than any other element?

d. What is meant by multiple bonding? Draw the structural formulas of ethene and ethyne.

e. Define a homologous series. Write its four characteristics, with the alcohols as an example.

f. What are an alkyl group and a functional group? Name the alkyl groups from methane, ethane and propane, and write the functional groups of alcohols, aldehydes, ketones and carboxylic acids, with one example each.

g. Write the rules for giving the IUPAC name of a branched alkane, and use them to name $CH_3–CH(CH_3)–CH(CH_3)–CH_3$.

5. Write the IUPAC names

a. $CH_3–CH(CH_3)–CH_2–CH_2–CH_3$

b. $CH{\equiv}C–CH_2–CH_3$

c. $CH_3–CH_2–CH(OH)–CH_2–CH_3$, $CH_3–CH_2–O–CH_2–CH_2–CH_3$, $CH_3–CH_2–CH_2–CH_2–CHO$ and $CH_3–CH(CH_3)–CH_2–COOH$

d. $CH_3–CH_2–CO–CH_2–CH_3$

e. HCOOH, $CH_3–CH_2–COOH$ and $CH_3–CH(CH_3)–COOH$

f. Name the structure below.

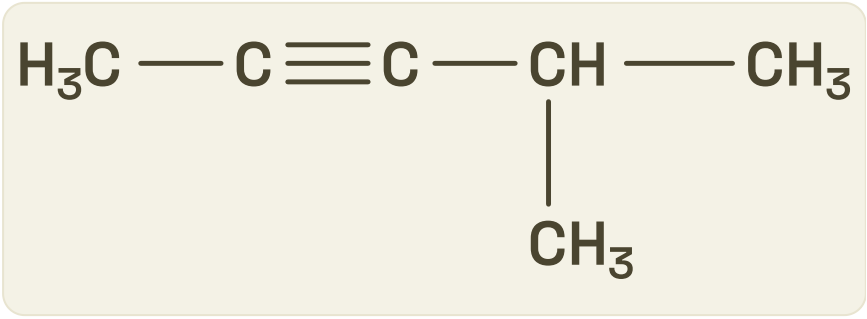


Figure 9.21 *Name this structure.*

Compound	Formula	Where you meet it
methane	CH_4	biogas (gobar gas), natural gas
propane and butane	C_3H_8, C_4H_{10}	LPG, the cooking gas in cylinders
ethanol	C_2H_5OH	hand sanitizer, spirit lamps, alcoholic drinks
ethanoic acid (acetic acid)	CH_3COOH	vinegar, achar
methanal (formaldehyde)	HCHO	formalin, which keeps specimens in a school lab
propanone (acetone)	CH_3COCH_3	nail polish remover
urea	$CO(NH_2)_2$	urine; the most used fertilizer in Nepal's fields
glucose and sucrose	$C_6H_{12}O_6$, $C_{12}H_{22}O_{11}$	fruit and honey; table sugar
polythene	$(C_2H_4)_n$	plastic bags and bottles
starch, cellulose, proteins, fats, DNA	very large molecules	rice and wheat; cotton and paper; meat, milk and dal; ghee and oil; every living cell

How organic and inorganic compounds differ

Organic compounds are held together by **covalent bonds**: their atoms share electrons. Many inorganic compounds, like common salt, are **ionic**: they are made of charged ions held by the pull between opposite charges. That one difference explains most of the others.

Organic compounds	Inorganic compounds
Always contain carbon, nearly always hydrogen.	May contain any elements; most contain no carbon.
Covalent bonds.	Many are ionic (salts, bases).
Low melting and boiling points; many are gases or liquids.	Ionic ones have high melting and boiling points.
Most don't dissolve in water, but dissolve in organic solvents such as kerosene, alcohol or ether.	Many dissolve in water; few dissolve in organic solvents.
Most burn, and leave a black char of carbon if heated without enough air.	Most don't burn.
Don't conduct electricity, melted or dissolved (they have no ions).	Ionic ones conduct when melted or dissolved in water.
React slowly, since their covalent bonds must break.	Ionic ones often react at once (ions are already free).
Very many; the same formula can belong to several compounds.	Far fewer.

CAREFUL

A tendency, not a law

"Organic compounds don't dissolve in water" is only mostly true. Sugar, ethanol, ethanoic acid (vinegar), urea and propanone are organic, and all of them dissolve in water, because they carry groups such as –OH or C=O that attract water molecules. And some inorganic compounds, such as marble (calcium carbonate) and sand, don't dissolve. In an exam, write that *most* organic compounds are insoluble in water and *most* inorganic salts are soluble, and give an example of each.

Check 1

Which of these is an organic compound?

a carbon dioxide, CO_2
b calcium carbonate, $CaCO_3$
c ethanol, C_2H_5OH
d sodium chloride, NaCl

b. Which of these is counted as an inorganic compound, although it contains carbon?

a CH_4
b CH_3COOH
c Na_2CO_3
d C_2H_5OH

c. The angle between any two bonds of the carbon atom in methane is:

a 90°
b 104.5°
c 109.5°
d 120°

d. The general formula of the alkenes is:

a C_nH_{2n+2}
b C_nH_{2n}
c C_nH_{2n-2}
d C_nH_{2n+1}

e. Which functional group do ketones have?

a –CHO
b –COOH
c a C=O between two carbon atoms
d –O–

f. Which compound is the third member of the homologous series of carboxylic acids?

a ethanoic acid
b propanoic acid
c butanoic acid
d methanoic acid

g. Which pair has the same molecular formula?

a ethanol and methoxymethane
b ethanol and ethanal
c propanone and propan-2-ol
d ethene and ethyne

2. Give reasons

a. Carbon forms covalent compounds rather than ionic ones.

b. The number of organic compounds is very large.

c. Ethanol boils at 78 °C, but methoxymethane, with the same formula, boils at −25 °C.

d. The –CHO group of an aldehyde never needs a number in its name.

3. Differentiate between

i. Organic compounds and inorganic compounds

ii. Aldehyde and ketone

iii. Alcohol and ether

iv. Saturated and unsaturated hydrocarbons

IN SHORT

- **Organic compounds** are compounds of carbon, mostly with hydrogen (oxides of carbon, carbonates, hydrogencarbonates, cyanides and carbides are counted as inorganic). Wöhler made urea in 1828, the first blow to the idea that only living things can make them.
- Organic compounds are covalent: low melting and boiling points, most insoluble in water but soluble in organic solvents, they burn, don't conduct and react slowly.
- **Tetracovalency:** carbon shares its four outer electrons to make four covalent bonds, pointing to the corners of a tetrahedron, 109.5° apart.
- **Catenation:** carbon atoms join to each other in chains, branches and rings, because the C–C bond is strong and stable in air.
- **Multiple bonding:** carbon makes double (C=C, C=O) and triple (C≡C) bonds; more bonds are shorter and stronger.
- An **alkyl group** is an alkane less one hydrogen, C_nH_{2n+1}– (methyl, ethyl, propyl…), written R.
- A **functional group** decides a family's chemical properties: C=C (-ene), C≡C (-yne), –OH (-ol), –O– (alkoxyalkane), –CHO (-al), C=O in the chain (-one), –COOH (-oic acid).
- A **homologous series** has one functional group and one general formula; neighbors differ by CH_2 (mass 14), with similar chemical properties and gradually changing physical ones.
- An **IUPAC name** = branches with their numbers + word root (longest chain) + -ane/-ene/-yne + the group's suffix with its number. Number the chain to give the lowest numbers to the group first, then the multiple bond, then the branches.

Exercise

1. Choose the correct option

a. Who first made an organic compound, urea, from an inorganic one?

a Berzelius
b Wöhler
c Kekulé
d van 't Hoff

Check 2

Most organic compounds have low melting and boiling points because:

a they contain carbon
b their molecules are held together only weakly, as they have no ions
c they burn easily
d they dissolve in kerosene

9.2 Unique properties of carbon

Silicon sits just below carbon in the periodic table, and also has four outer electrons. Yet silicon's compounds with hydrogen are few and catch fire in air, while carbon's run to millions. Three properties, found together only in carbon, make the difference: it makes **four bonds** (tetracovalency), it joins to **itself** in chains (catenation), and it makes **double and triple bonds** (multiple bonding).

Tetracovalency of carbon

A carbon atom has 6 protons and 6 electrons: 2 in the first shell and **4** in the outer shell. To have a full outer shell of 8, it would have to gain four electrons (C^{4-}) or lose all four (C^{4+}). Both cost far too much energy: four extra electrons crowded onto a small atom repel each other strongly, and pulling four away from a small nucleus that holds them tightly is just as hard. So carbon does neither. It **shares** its four outer electrons, one with each of four other atoms, and each partner shares one back. Each shared pair is a **covalent bond**, and carbon ends up with eight electrons around it, counting the shared ones.

Tetracovalency is carbon's property of forming four covalent bonds: its valency is four.

Each of carbon's four bonds can join a different atom, or group of atoms: four hydrogens in methane, three hydrogens and a chlorine in chloromethane (CH_3Cl), two oxygens in carbon dioxide (through two double bonds). The four bonds spread out in three dimensions, so carbon compounds have real shapes, which matters for how they behave: the shape of a molecule decides which other molecules it fits, as a key fits its lock, and that is how your nose tells one smell from another and how a medicine finds its target.

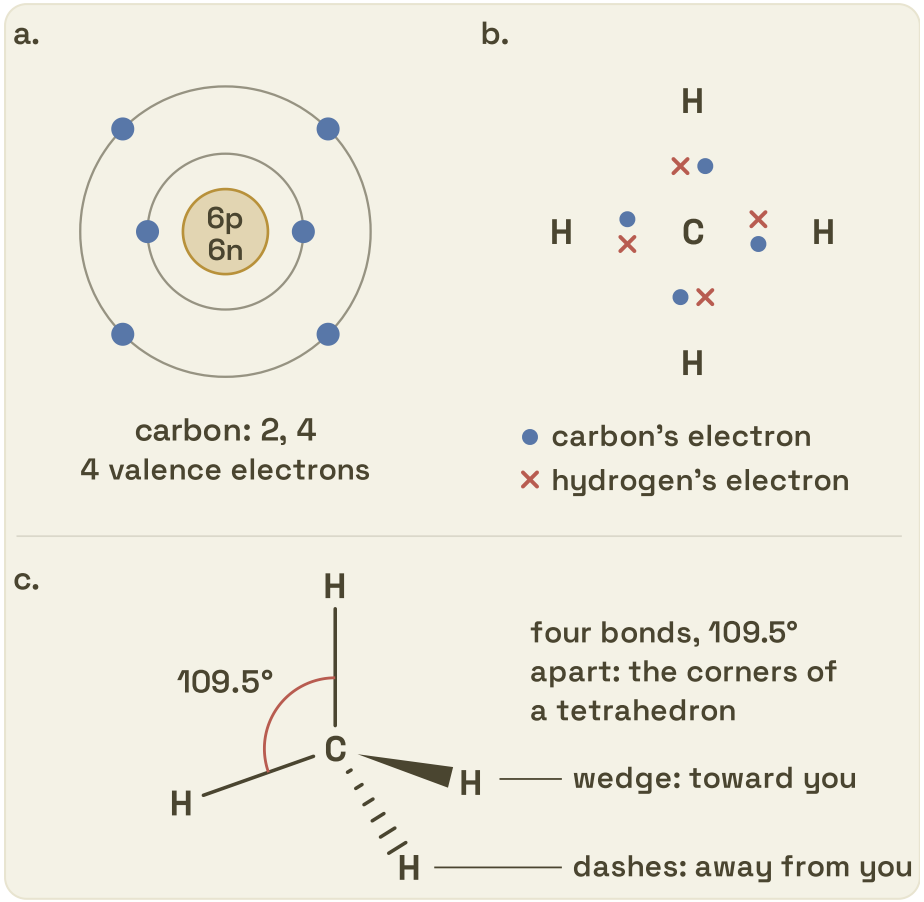


Figure 9.2 *Carbon's four bonds.* **a.** *The carbon atom: 2 electrons in the first shell, 4 in the second.* **b.** *Methane, CH_4: each of carbon's four outer electrons (dots) pairs with one hydrogen electron (crosses), making four shared pairs, four covalent bonds. Now carbon has 8 electrons around it and each hydrogen 2, the same as helium.* **c.** *The four bonds push each other as far apart as they can, so they point to the corners of a* ***tetrahedron****, 109.5° apart; methane is not flat.*

WORKED EXAMPLE

Name the acids

a. $CH_3–CH_2–COOH$
b. $CH_3–CH(CH_3)–COOH$
c. $HOOC–CH_2–CH_2–CH_3$

Answer

a. Three carbons, counting the –COOH carbon: **propanoic acid.**
b. Three carbons in the chain, numbered from the –COOH carbon (1); the methyl is on carbon 2: **2-methylpropanoic acid.**
c. The same as $CH_3CH_2CH_2COOH$ written backwards: four carbons, **butanoic acid.**

Name it

IUPAC name	Condensed formula	Common name	Named after
methanoic acid	HCOOH	formic acid	Latin *formica*, ant
ethanoic acid	CH_3COOH	acetic acid	Latin *acetum*, vinegar
propanoic acid	CH_3CH_2COOH	propionic acid	Greek for “first fat”
butanoic acid	$CH_3CH_2CH_2COOH$	butyric acid	Latin *butyrum*, butter
hexanoic acid	$CH_3(CH_2)_4COOH$	caproic acid	Latin *caper*, goat

Carboxylic acids are weak acids: in water, a few of their molecules give away the H of the –COOH as a hydrogen ion. So they taste sour, turn blue litmus red, and react with carbonates to give carbon dioxide (vinegar fizzes on baking soda).

Methanoic acid is in the stings of ants and some other insects, which is where its old name, formic acid, comes from. **Ethanoic acid** makes vinegar sour: vinegar is about 4–8% ethanoic acid in water, made by bacteria from alcohol, and it keeps achar and pickles from going bad, since most germs can’t grow in acid. Pure ethanoic acid freezes into ice-like crystals at 17 °C, so it is called glacial acetic acid. **Butanoic acid** gives rancid butter and old ghee their smell. Long-chain acids, such as stearic acid ($C_{17}H_{35}COOH$, 18 carbons), are found in fats and oils, joined to glycerol; boiled with an alkali, they become **soap**.

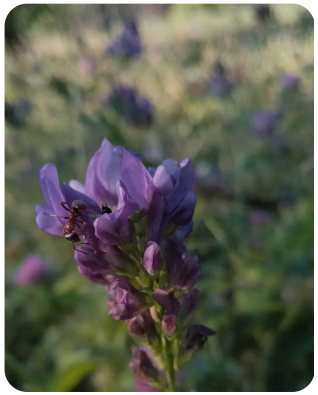


Figure 9.19 *A red wood ant (Formica rufa). Ants of its kind spray methanoic acid to defend themselves; in 1671 the English naturalist John Ray first collected the acid by distilling a large number of ants.*
Photo: Foraminifera1991, CC BY 4.0

A STORY FROM SCIENCE

Carbon with four hands

In 1858 two chemists, August Kekulé in Germany and the Scot Archibald Scott Couper, working in Paris, each proposed the same idea on his own: carbon always has four bonds, and carbon atoms can link to one another into a backbone. It was the start of drawing molecules as structures, with every bond a line, the way this unit draws them. In 1874 Jacobus van ’t Hoff and Joseph Le Bel added the third dimension: the four bonds point to the corners of a tetrahedron. Van ’t Hoff won the first Nobel Prize in Chemistry, in 1901 (for other work).

Catenation

Carbon atoms can bond to **each other**, one after another, in long chains, in chains with branches, and in rings. This property is called **catenation** (from the Latin *catena*, a chain).

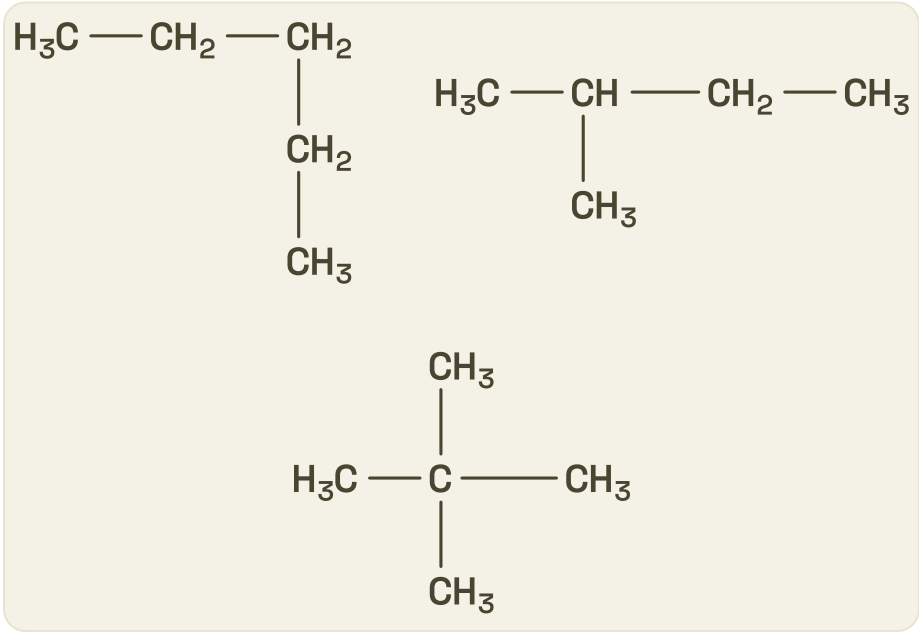


Figure 9.3 *Five carbon atoms joined in three ways, from left to right: an unbranched chain (drawn with a bend, but every carbon is still in one line of bonds), a chain with one branch, and a chain with two. Carbon chains can also close up into rings, like the six-carbon ring of cyclohexane. Every carbon still makes four bonds: each CH_3, CH_2 or CH shows the hydrogens it holds.*

Other elements can catenate a little. Sulphur makes rings of eight atoms, and silicon makes short chains with hydrogen. But only carbon makes chains of any length that are stable in air. The reason is in the strength of the bonds:

- The **C–C bond is strong**, about 347 kJ/mol (the energy needed to break a mole of them), and about as strong as carbon's bonds to hydrogen (413 kJ/mol) and oxygen (358 kJ/mol). A carbon chain would give out energy by burning in the oxygen of the air, but first some of its strong bonds must break, and at room temperature that doesn't happen: the chain simply stays as it is. (A flame gives it the energy to start, which is why fuels need a match.)
- The bonds between atoms of other elements are weaker: N–N about 160 and O–O about 146 kJ/mol, so long chains of nitrogen or oxygen fall apart. Silicon's bonds to itself are much weaker than its bonds to oxygen (Si–O, 452 kJ/mol), so silicon chains react with air: silane, SiH_4, catches fire by itself. That is why the silicon on Earth is locked up with oxygen, in sand and rocks, while carbon's chains are everywhere in living things.

Chains can be very long. In polythene they run to tens of thousands of carbon atoms, and the single DNA molecule of one of your chromosomes holds from about a billion carbon atoms (in the smallest) to about five billion (in the largest): about 20 carbons in each of its 47 million to 250 million base pairs.

DID YOU KNOW?

More ways than people

Catenation lets the same atoms join in different ways. With 4 carbons and 10 hydrogens (C_4H_{10}) there are 2 different compounds; with 10 carbons and 22 hydrogens ($C_{10}H_{22}$), 75; with $C_{20}H_{42}$, 366,319; with $C_{30}H_{62}$, more than four billion (4,111,846,763), each with its own structure, all made of only carbon and hydrogen with single bonds. Compounds with the same formula and different structures are called **isomers**; you will meet them again in later grades.

Multiple bonding

Two carbon atoms can share more than one pair of electrons with each other. Sharing one pair makes a **single bond** (C–C), two pairs a **double bond** (C=C), and three pairs a **triple bond** (C≡C). Carbon also makes double bonds with oxygen (C=O) and triple bonds with nitrogen (C≡N). This property is called **multiple bonding**.

Each carbon still makes four bonds in all, with a double bond counted as two and a triple bond as three. In ethene, $H_2C{=}CH_2$, each carbon has a double bond to the other

Carboxylic acids

General formula: $C_nH_{2n}O_2$, or R–COOH (R may be H). **Ending:** -oic acid (alkane − e + oic acid). **Functional group:** –COOH, the carboxyl group: a C=O and an –OH on the same carbon.

Like an aldehyde's carbon, the –COOH carbon is part of the main chain and is always carbon 1.

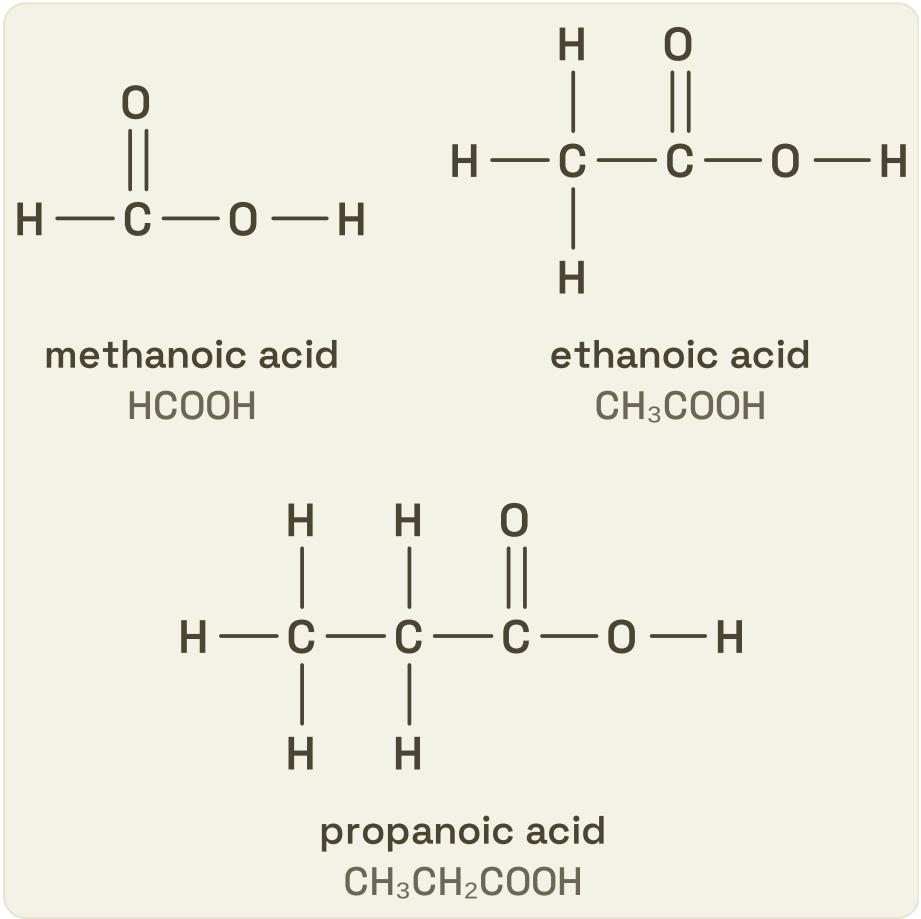


Figure 9.18 *The first carboxylic acids. The carboxyl carbon has a double bond to one oxygen and a single bond to an –OH. It is the H of this –OH that an acid gives away in water.*

CAREFUL

–CHO, not –COH

The aldehyde group is written **–CHO**, with the C first: its carbon is joined to the chain, to H and to O. Writing it "–COH" makes it look like an –OH on a carbon, an alcohol, which it isn't.

Ketones

General formula: $C_nH_{2n}O$ (from n = 3), or R–CO–R′. **Ending:** -one (alkane − e + one). **Functional group:** C=O with a carbon on each side, the carbonyl (keto) group.

The chain is numbered from the end nearer the C=O, and its number goes before -one. The simplest ketone has 3 carbons: a C=O on the end carbon of a chain would be an aldehyde.

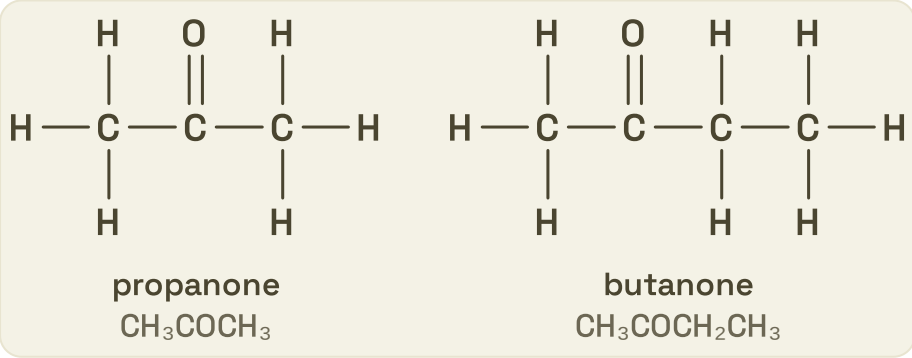


Figure 9.17 *The first two ketones. The C=O is inside the chain, with a carbon on both sides.*

IUPAC name	Condensed formula	Common name
propanone (propan-2-one)	CH_3COCH_3	acetone, dimethyl ketone
butanone (butan-2-one)	$CH_3COCH_2CH_3$	ethyl methyl ketone
pentan-2-one	$CH_3COCH_2CH_2CH_3$	methyl propyl ketone
pentan-3-one	$CH_3CH_2COCH_2CH_3$	diethyl ketone

Propanone (acetone) dissolves paints, varnish and nail polish, and evaporates quickly (it boils at 56 °C), so it is the main ingredient of nail polish remover and a common solvent in factories and labs. Your body makes small amounts of propanone too, when it burns fat for energy, for example after a long fast.

carbon and two single bonds to hydrogens: 2 + 1 + 1 = 4. In ethyne, HC≡CH, each carbon has a triple bond and one single bond: 3 + 1 = 4.

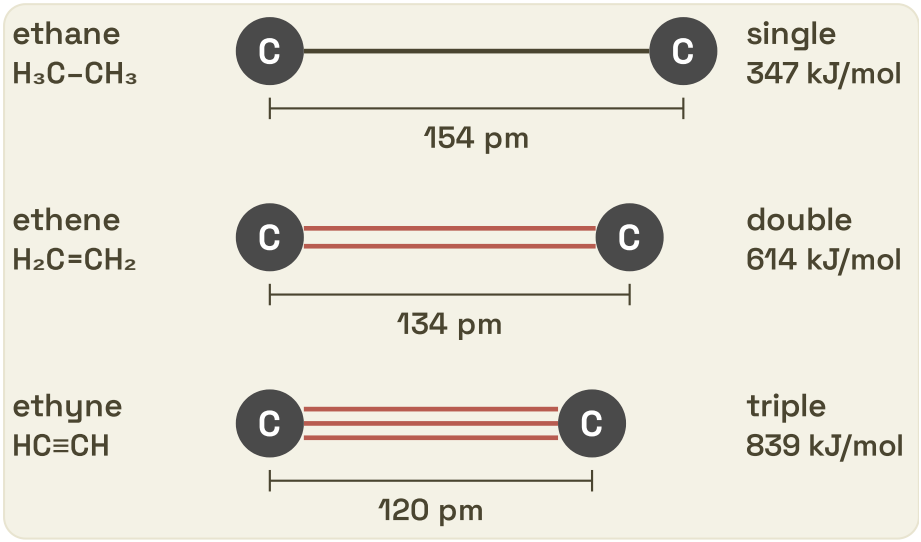


Figure 9.4 *The carbon–carbon bond in ethane, ethene and ethyne, drawn to scale. The more electron pairs the two atoms share, the closer together they are held and the more energy it takes to break the bond (average values; 1 pm, a picometer, is a millionth of a millionth of a meter).*

A double bond is not twice as strong as a single one (614 kJ/mol, not 2 × 347 = 694), because its second bond is weaker than the first. That is why compounds with double and triple bonds react more readily than those with only single bonds: their extra bond opens easily, and other atoms add on there. In later grades you will learn the names of the two kinds of bond, sigma and pi.

Compounds with only single bonds between their carbon atoms are **saturated**: each carbon holds as many hydrogen atoms as it can. Compounds with a double or triple bond are **unsaturated**: they could take on more hydrogen.

Check 3

Which property of carbon allows it to form the long chains in polythene?

a tetracovalency
b catenation
c multiple bonding
d allotropy

Check 4

How many electrons do the two carbon atoms share between them in ethyne, HC≡CH?

a 2 b 3
c 4 d 6

9.3 Alkyl group, functional group and homologous series

The simplest organic compounds contain only carbon and hydrogen: the **hydrocarbons**. Those with only single bonds between carbon atoms are the **alkanes** (methane, ethane, propane…); those with a double bond are the **alkenes** (ethene, propene…), and those with a triple bond the **alkynes** (ethyne, propyne…).

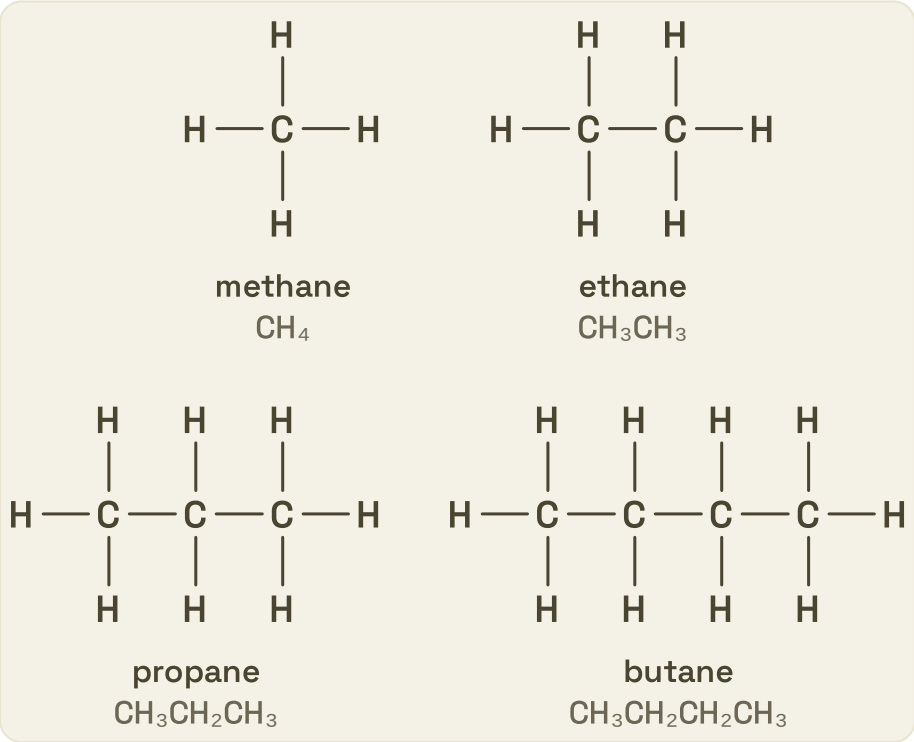


Figure 9.5 *The first four alkanes. Each carbon makes four bonds; each hydrogen makes one.*

All the other families can be pictured as hydrocarbons with something added in place of a hydrogen. Three ideas let you sort the millions of compounds into a few dozen families: the alkyl group, the functional group and the homologous series.

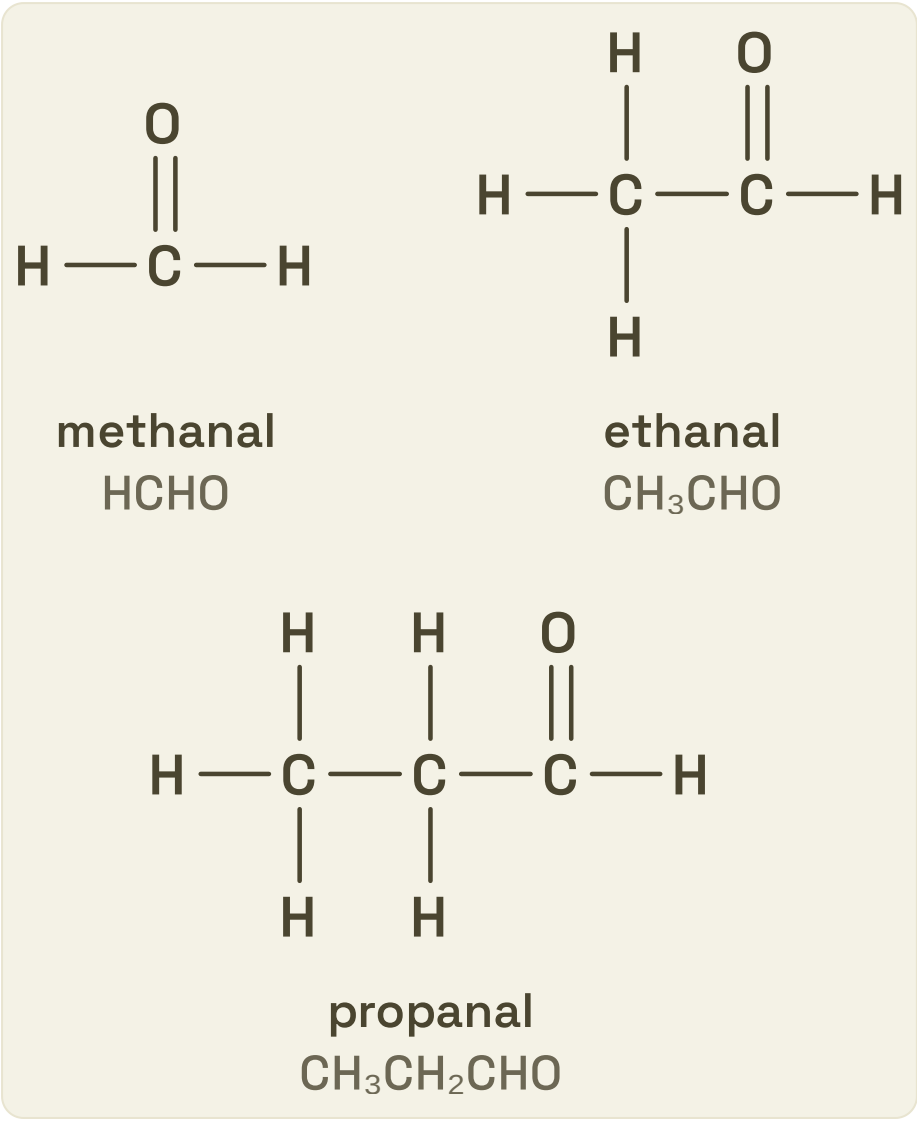


Figure 9.16 *The first aldehydes. The carbon of the –CHO group has a double bond to oxygen and a single bond to hydrogen; in methanal it has two hydrogens.*

WORKED EXAMPLE

Name the ethers

a. $CH_3–O–CH_2–CH_3$

b. $CH_3–CH_2–O–CH_2–CH_3$

Answer

a. The longer side has 2 carbons (ethane); the shorter side is $CH_3O–$, methoxy: **methoxyethane** (ethyl methyl ether).

b. Both sides have 2 carbons: ethoxy on ethane, **ethoxyethane** (diethyl ether).

Aldehydes

General formula: $C_nH_{2n}O$, or R–CHO (R may be H). **Ending:** -al (alkane − e + al). **Functional group:** –CHO, a carbon with a double bond to oxygen and a hydrogen.

The –CHO carbon is part of the main chain and is always carbon 1, so the -al never needs a number.

IUPAC name	Condensed formula	Common name
methanal	HCHO	formaldehyde
ethanal	CH_3CHO	acetaldehyde
propanal	CH_3CH_2CHO	propionaldehyde
butanal	$CH_3CH_2CH_2CHO$	butyraldehyde
2-methylpropanal	$CH_3CH(CH_3)CHO$	isobutyraldehyde

A solution of about 37–40% methanal in water is **formalin**, used to preserve specimens (it kills germs and hardens tissues) and to make plastics and glues. Many larger aldehydes have strong smells and tastes: cinnamaldehyde gives dalchini (cinnamon) its flavor and vanillin gives vanilla its taste. Ethanal is made in your liver when it breaks down ethanol, and is thought to cause some of the sickness that drinking brings.

Alkyl group

Take one hydrogen atom off an alkane, and what is left has one bond free to join something else. This group is an **alkyl group** (or alkyl radical). Its general formula is $\mathbf{C_nH_{2n+1}–}$, and it is named by changing the alkane's ending **-ane** to **-yl**:

Alkane	Alkyl group	Name
methane, CH_4	$CH_3–$	methyl
ethane, C_2H_6	$CH_3CH_2–$ ($C_2H_5–$)	ethyl
propane, C_3H_8	$CH_3CH_2CH_2–$ ($C_3H_7–$), joined by an end carbon	propyl
propane, C_3H_8	$(CH_3)_2CH–$, joined by the middle carbon	isopropyl (1-methylethyl)
butane, C_4H_{10}	$CH_3CH_2CH_2CH_2–$ ($C_4H_9–$)	butyl

Propane gives two different alkyl groups, because its end and middle carbons are different: a hydrogen taken from an end carbon gives propyl, one from the middle carbon gives isopropyl. Chemists often write any alkyl group as **R** (for "radical" or "rest of the molecule"), so that R–OH stands for any alcohol: $CH_3–OH$, $C_2H_5–OH$ and so on.

Check 5

What is the formula of the alkyl group with four carbon atoms?

a $C_4H_{10}–$ b $C_4H_9–$

c $C_4H_8–$ d $C_4H_{11}–$

Functional group

Methane, chloromethane, methanol and methanoic acid all have one carbon, yet one is a fuel gas, one a gas once used to cool refrigerators, one a poisonous liquid and one the acid in an ant's sting. What makes them so different is the group in place of a hydrogen. Alkyl groups react hardly at all; the action happens at the special group.

A **functional group** is an atom or group of atoms in an organic molecule that decides its chemical properties. All the compounds with the same functional group form one **family**, and react in much the same way, whatever the size of the rest of the molecule.

Family	Functional group	General form	General formula	Name ends in	First member
alkane	none (only C–C single bonds)	R–H	C_nH_{2n+2}	-ane	methane, CH_4
alkene	C=C, double bond		C_nH_{2n}	-ene	ethene, $CH_2{=}CH_2$
alkyne	C≡C, triple bond		C_nH_{2n-2}	-yne	ethyne, CH≡CH
alcohol	–OH, hydroxyl	R–OH	$C_nH_{2n+1}OH$	-ol	methanol, CH_3OH
ether	–O–, ether oxygen	R–O–R′	$C_nH_{2n+2}O$	alkoxyalkane	methoxymethane, CH_3OCH_3
aldehyde	–CHO, aldehyde (formyl) group	R–CHO	$C_nH_{2n}O$	-al	methanal, HCHO
ketone	C=O inside the chain, carbonyl (keto) group	R–CO–R′	$C_nH_{2n}O$	-one	propanone, CH_3COCH_3
carboxylic acid	–COOH, carboxyl group	R–COOH	$C_nH_{2n}O_2$ (R–COOH: $C_nH_{2n+1}COOH$, where n counts only R's carbons)	-oic acid	methanoic acid, HCOOH

In the table, R and R′ are alkyl groups (the same or different); in an aldehyde and an acid, R may also be just a hydrogen atom. The aldehyde and the ketone both have a C=O; the difference is where it is. In an aldehyde it is at the end of the chain, with a hydrogen on the same carbon (–CHO); in a ketone it is inside the chain, with carbon on both sides. A carboxyl group has a C=O and an –OH on the **same** carbon, and together they behave as one new group, an acid, not as an alcohol.

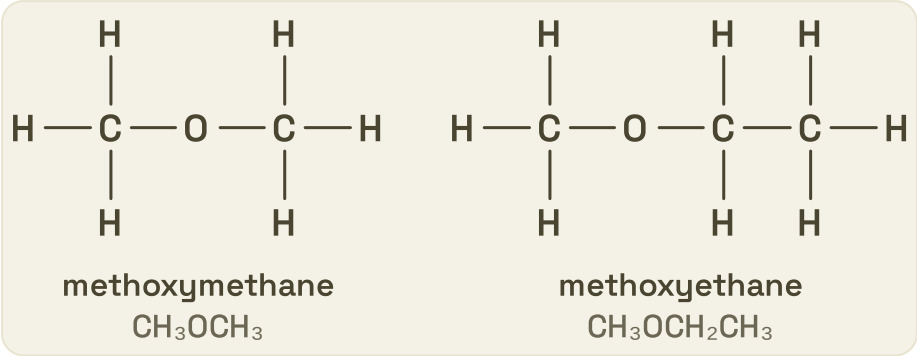


Figure 9.15 *The first two ethers. In each, an oxygen atom joins two carbon atoms; no hydrogen is on the oxygen.*

Ethers have the same general formula as alcohols, but no –OH: methoxymethane and ethanol are both C_2H_6O, yet ethanol boils at 78 °C and methoxymethane at −25 °C. Without an –OH, ether molecules hardly hold on to each other.

A STORY FROM SCIENCE

The ether day

On 16 October 1846, at the Massachusetts General Hospital in Boston, a dentist named William Morton had a young printer, Edward Gilbert Abbott, breathe ethoxyethane vapor from a glass inhaler with an ether-soaked sponge inside, and the surgeon John Collins Warren removed part of a tumor from his neck while he slept. "Gentlemen, this is no humbug," Warren told the doctors watching. It was the first public demonstration of surgery without pain; until then most patients were awake, held down by assistants. Ether made painless surgery possible, and news of it crossed the world within months. Ether catches fire easily, and safer anesthetics replaced it during the 20th century; ethoxyethane is still used in laboratories as a solvent, and evaporates quickly (it boils at 35 °C).

Methanol is a solvent and a fuel, and is used to make methanal and plastics. It is **poisonous**: the body turns it into methanal and methanoic acid, and even a small amount can cause blindness or death. Methylated spirit is ethanol with methanol added on purpose, so that no one drinks it. **Ethanol** is the alcohol of alcoholic drinks, made by yeast fermenting sugar or starch; it is the main ingredient of most hand sanitizers (at least 60% alcohol kills most germs on the hands), the fuel of spirit lamps, and a solvent for medicines and perfumes. **Propan-2-ol** is the rubbing alcohol on the swabs a nurse wipes your arm with before an injection.

WORKED EXAMPLE

Name the alcohols

a. $CH_3–CH_2–CH(OH)–CH_3$

b. $CH_3–C(CH_3)(OH)–CH_3$

Answer

a. Four carbons (butan-); the –OH is on carbon 2 counted from the right, which is nearer it (from the left it would be 3): **butan-2-ol.**

b. The longest chain through the –OH carbon has 3 carbons (propan-). The middle carbon, carbon 2, carries both the –OH and a methyl group: **2-methylpropan-2-ol.**

Ethers

General formula: $C_nH_{2n+2}O$ (from n = 2), or R–O–R′. **Functional group:** –O–, an oxygen between two carbon atoms.

An ether is named as an **alkane with an alkoxy group** on it. The longer of the two alkyl groups is the alkane; the shorter one together with the oxygen is the **alkoxy** group, named by changing -yl to **-oxy**: $CH_3O–$ is **methoxy**, $C_2H_5O–$ is **ethoxy**. Their everyday names list the two alkyl groups in alphabetical order, then the word ether.

IUPAC name	Condensed formula	Common name
methoxymethane	CH_3OCH_3	dimethyl ether
methoxyethane	$CH_3OCH_2CH_3$	ethyl methyl ether
ethoxyethane	$CH_3CH_2OCH_2CH_3$	diethyl ether
1-methoxypropane	$CH_3OCH_2CH_2CH_3$	methyl propyl ether
2-methoxypropane	$CH_3OCH(CH_3)CH_3$	isopropyl methyl ether

Check 6

$CH_3–CH_2–CHO$ belongs to which family?

a alcohol
b aldehyde
c ketone
d carboxylic acid

Check 7

Which pair of families has the same general formula, $C_nH_{2n}O$?

a alcohols and ethers
b aldehydes and ketones
c alkenes and alkynes
d alkanes and alcohols

Homologous series

Line up the alkanes: CH_4, C_2H_6, C_3H_8, C_4H_{10}, C_5H_{12}. Each one is the one before it with one more **$–CH_2–$** unit put into the chain. The alcohols do the same: CH_3OH, C_2H_5OH, C_3H_7OH… So do the acids, the aldehydes and every other family. A family laid out like this is a homologous series.

A **homologous series** is a series of organic compounds with the same functional group, in which each member differs from the next by a $–CH_2–$ group. Its members are called **homologs**.

The members of a homologous series:

1. have the same **functional group**, and so similar **chemical properties**: every alcohol reacts with sodium to give hydrogen; every carboxylic acid turns blue litmus red;
2. can be written with one **general formula** (C_nH_{2n+2} for the alkanes, $C_nH_{2n+1}OH$ for the alcohols);
3. differ from the next member by **CH_2**, so their molecular masses differ by **14** ($12 + 2 \times 1$);
4. show a **gradual change in physical properties**: as the molecule grows, the boiling point, melting point and density rise steadily, and the smaller members of the alcohols and acids mix with water while the larger ones don't;
5. can be made by similar methods.

So the functional group decides how a compound **reacts**, and the size of its chain decides how it **looks and behaves physically**: whether it is a gas, a liquid or a solid, and how easily it boils. Methane (1 carbon) is a gas, octane (8) is a liquid in petrol, and the alkanes in candle wax have about 20 to 40 carbons and are solid.

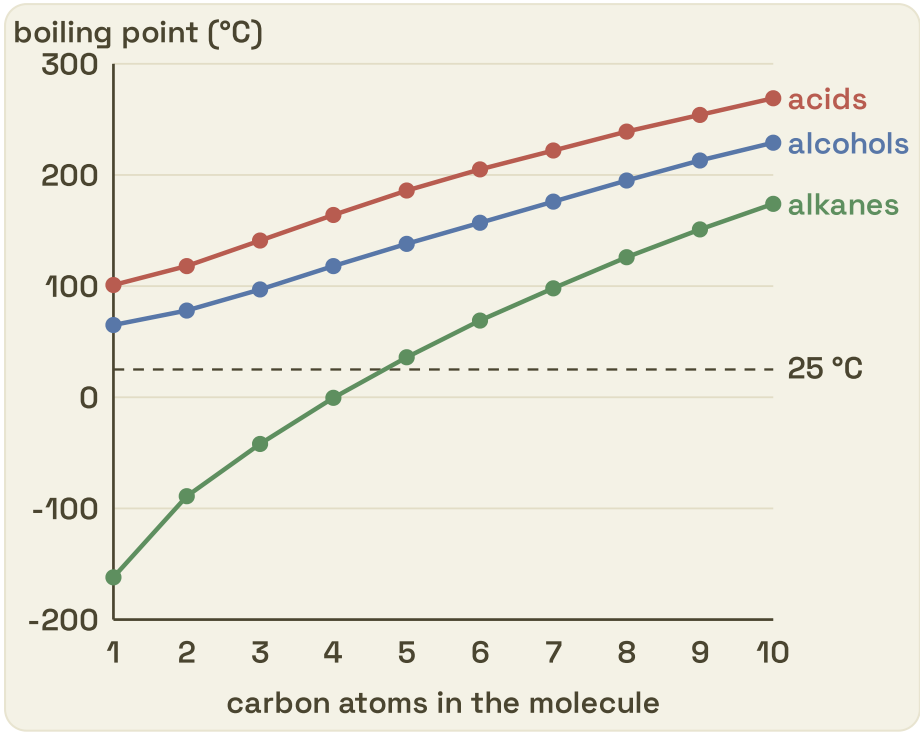


Figure 9.6 *Boiling points of the first ten alkanes, alcohols and carboxylic acids (straight chains, at 1 atm). Each series climbs as CH_2 units are added, by less each time: methane to ethane is 73 °C, nonane to decane 23 °C. Below the dashed line, 25 °C, a compound is a gas in a warm room: only the first four alkanes. An alcohol boils far above the alkane of about the same mass (ethanol, mass 46, at 78 °C; propane, mass 44, at −42 °C), because its –OH groups hold the molecules together; the acids boil higher still.*

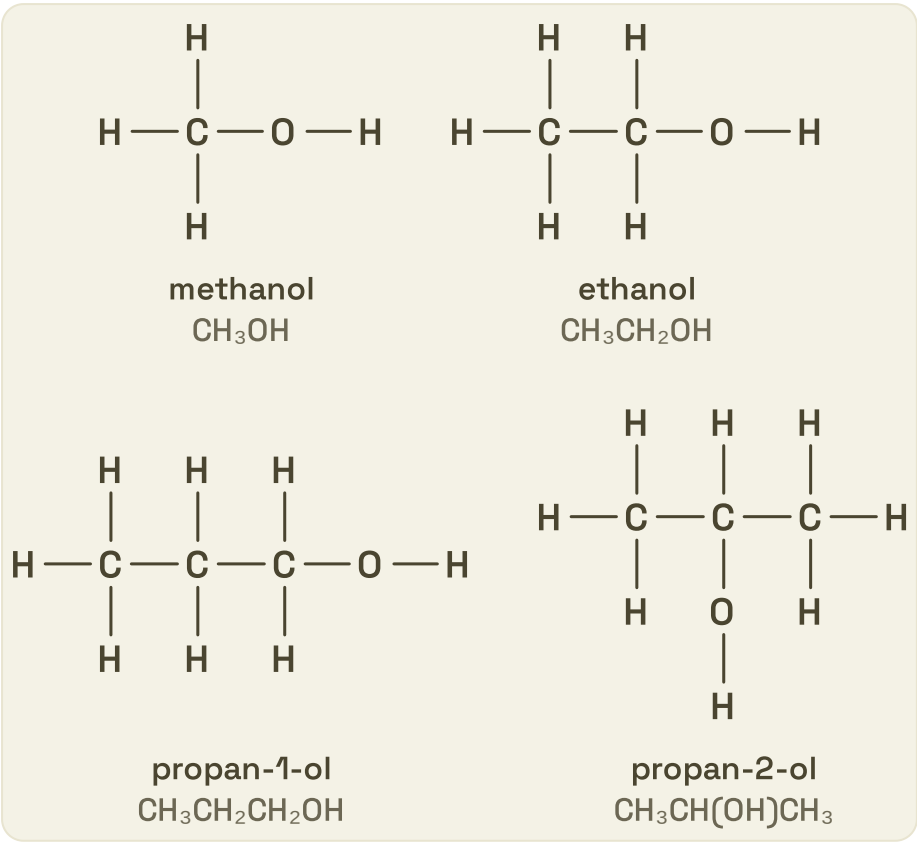


Figure 9.14 *The first alcohols. Propan-1-ol and propan-2-ol have the same formula, C_3H_8O, but their –OH is on a different carbon.*

IUPAC name	Condensed formula	Common name
methanol	CH_3OH	methyl alcohol, wood spirit
ethanol	CH_3CH_2OH	ethyl alcohol
propan-1-ol	$CH_3CH_2CH_2OH$	propyl alcohol
propan-2-ol	$CH_3CH(OH)CH_3$	isopropyl alcohol
butan-1-ol	$CH_3CH_2CH_2CH_2OH$	butyl alcohol

The –OH group is not the hydroxide ion (OH^-) of a base: it is joined to carbon by a covalent bond and doesn't break off in water, so alcohols are not alkaline. Like water's own –OH, though, it attracts water molecules, so the first three alcohols mix with water in any amount.

Figure 9.12 *The first alkynes. In each, two carbons share three pairs of electrons; each of them has one bond left, to a hydrogen or to the rest of the chain.*

Name	Condensed formula	Common name
ethyne	CH≡CH	acetylene
propyne	CH≡CCH$_3$	methylacetylene
but-1-yne	CH≡CCH$_2$CH$_3$	ethylacetylene
but-2-yne	CH$_3$C≡CCH$_3$	dimethylacetylene

Ethyne burns in pure oxygen with a flame hotter than 3,000 °C, hot enough to melt steel, so the **oxy-acetylene torch** is used to weld and cut metal. Miners and cyclists once carried "carbide lamps": water dripping onto calcium carbide, CaC$_2$, gives off ethyne, which burns with a bright white flame.

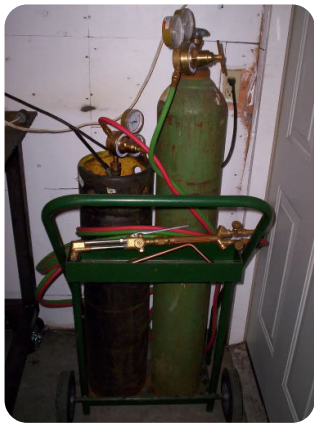


Figure 9.13 *An oxy-acetylene welding set: one cylinder holds oxygen, the other ethyne (acetylene). The two gases mix in the torch and burn at its tip.*
Photo: Paul Anderson, CC BY 2.0

Alcohols

General formula: C$_n$H$_{2n+1}$OH, or R–OH. **Ending:** -ol (alkane − e + ol). **Functional group:** –OH, the hydroxyl group.

The chain is numbered from the end nearer the –OH, and its number goes before -ol: propan-1-ol, propan-2-ol.

WORKED EXAMPLE

Members of a series

a. Write the molecular formula and mass of the alkane with 6 carbon atoms, and of the members just before and after it.

b. Write the formula of the third member of the alcohols.

Answer

Masses use C = 12, H = 1, O = 16.

a. C$_n$H$_{2n+2}$ with n = 6: **C$_6$H$_{14}$** (hexane), mass 6 × 12 + 14 × 1 = **86**. One CH$_2$ less: **C$_5$H$_{12}$**, mass 72; one more: **C$_7$H$_{16}$**, mass 100. Each differs from hexane by 14.

b. C$_n$H$_{2n+1}$OH with n = 3: **C$_3$H$_7$OH** (propanol), mass 36 + 7 + 16 + 1 = 60.

WORKED EXAMPLE

From mass to formula

A carboxylic acid has a molecular mass of 88. Find its formula and name it.

Answer

The general formula is C$_n$H$_{2n}$O$_2$, so the mass is 12n + 2n + 32 = **14n + 32**.
14n + 32 = 88, so 14n = 56 and n = 4.
C$_4$H$_8$O$_2$. Written as a straight chain, CH$_3$CH$_2$CH$_2$COOH, it has four carbons counting the –COOH carbon: **butanoic acid**. Check: 4 × 12 + 8 + 2 × 16 = 48 + 8 + 32 = 88. (The same formula also fits a branched acid, 2-methylpropanoic acid, which you will name in 9.4.)

YOUR TURN

Which alkyne?

An alkyne has a molecular mass of 54. What is its formula?

Hint

C$_n$H$_{2n-2}$ has a mass of 12n + 2n − 2 = 14n − 2.

Answer

14n − 2 = 54, so 14n = 56 and n = 4: **C$_4$H$_6$**, a butyne. Check: 48 + 6 = 54.

9.4 IUPAC name, condensed formula and structural formula

Three ways to write a formula

There are three common ways to write an organic compound, each telling you more than the last. Take butane:

Molecular formula: how many atoms of each element are in one molecule: $\mathbf{C_4H_{10}}$. It doesn't say how they are joined.

Structural formula: every atom and every bond drawn as a line. It shows exactly which atom is joined to which.

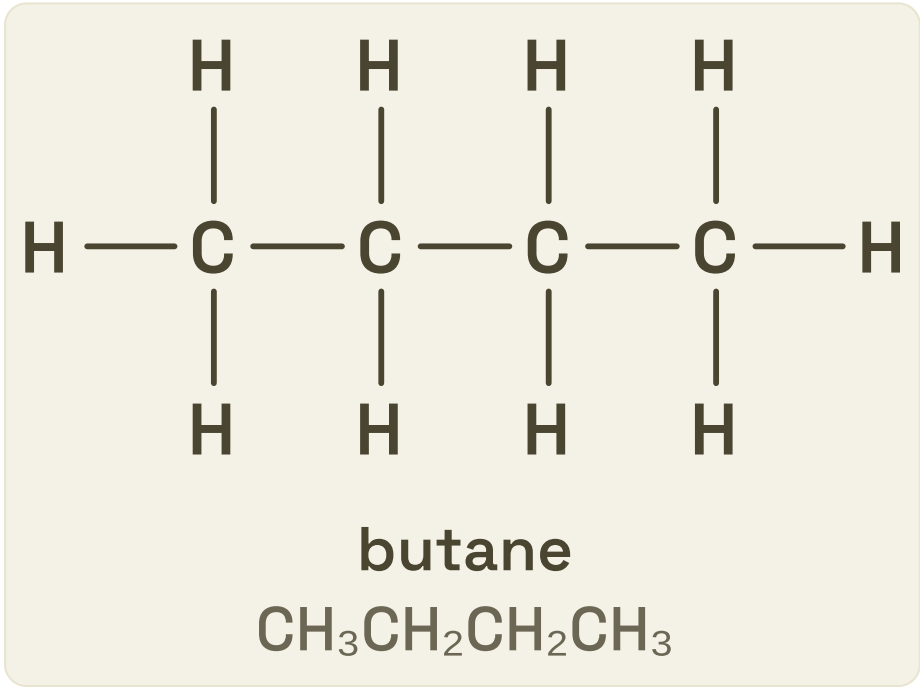
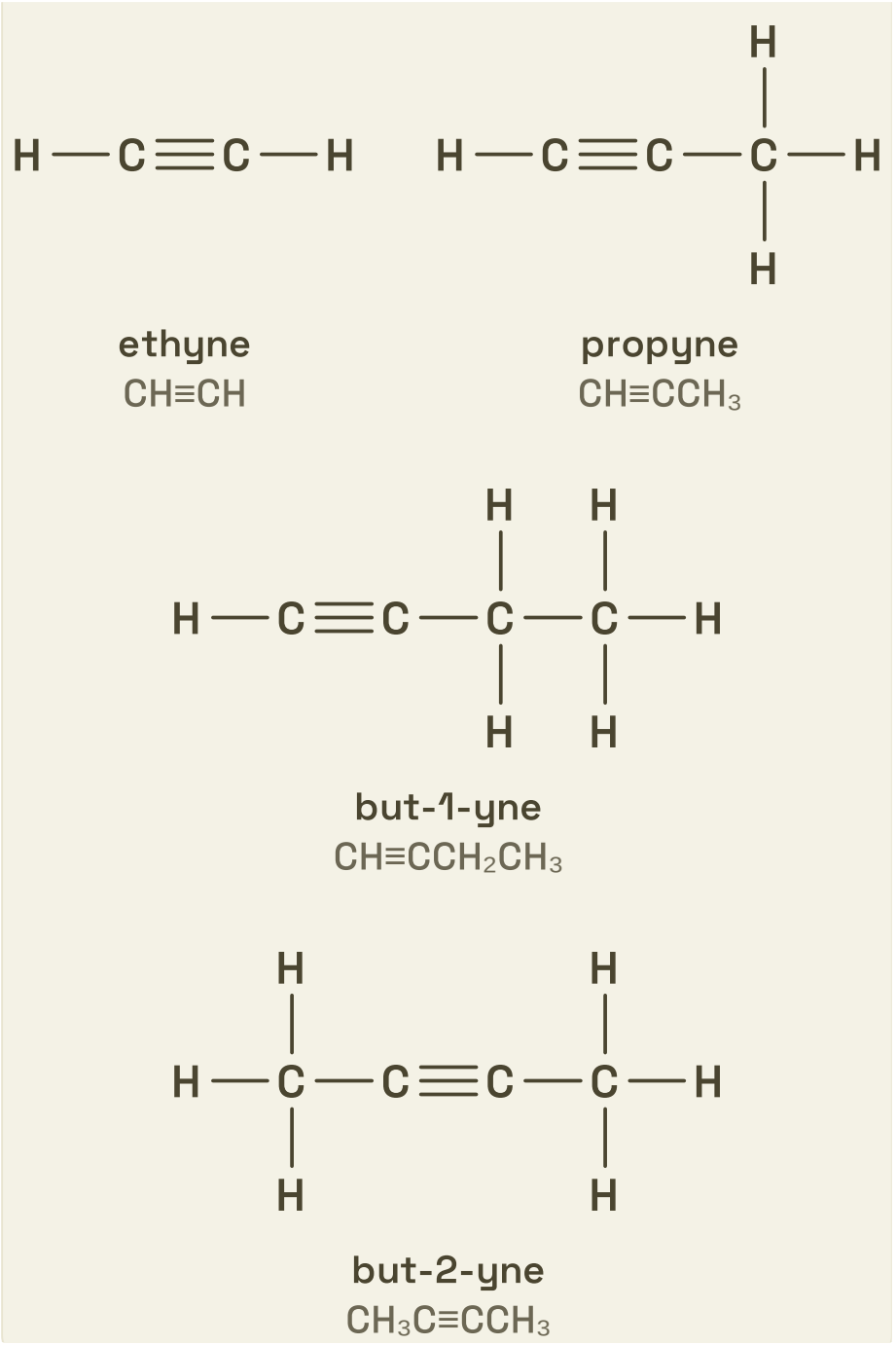


Figure 9.7 *The structural formula of butane: four carbons in a chain, each with four bonds, the rest to hydrogen. Under it, its condensed formula.*

Condensed formula: each carbon written with the hydrogens joined to it, one group after another: $\mathbf{CH_3CH_2CH_2CH_3}$, or $CH_3–CH_2–CH_2–CH_3$ with its bonds shown. A branch is written in brackets after the carbon it hangs from: $(CH_3)_2CHCH_3$ or $CH_3CH(CH_3)CH_3$ is a three-carbon chain with a methyl group on the middle carbon. A double or triple bond is always shown: $CH_2{=}CHCH_3$.



A molecular formula can stand for more than one compound: C_4H_{10} is both butane, $CH_3CH_2CH_2CH_3$, and 2-methylpropane, $CH_3CH(CH_3)CH_3$. A structural or condensed formula stands for only one. That is why chemists name compounds from their structures.

Check 8

Which is the condensed formula of propan-1-ol?

a C_3H_8O
b $CH_3CH_2CH_2OH$
c $CH_3CH(OH)CH_3$
d $CH_3OCH_2CH_3$

The IUPAC system

Ethanoic acid is called acetic acid in shops, sirka in Nepali kitchens, and *Essigsäure* in Germany. Old books call methanol “wood spirit” and ethene “olefiant gas”. With millions of compounds, everyday names can’t keep up, and they say nothing about the structure. So in 1892 chemists meeting in Geneva agreed on a system of names built from the structure itself. Today it is kept by the **IUPAC**, the International Union of Pure and Applied Chemistry (founded in 1919), and an IUPAC name is the same everywhere: from the name you can draw the molecule, and from the molecule you can work out the name.

An IUPAC name is built from parts, like a word from syllables:

prefix (branches) + word root (chain) + primary suffix (bonds) + secondary suffix (gr

Word root: the number of carbon atoms in the main chain.

Carbons	1	2	3	4	5	6	7	8	9	10
Word root	meth-	eth-	prop-	but-	pent-	hex-	hept-	oct-	non-	dec-

Primary suffix: the bonds in the main chain: **-ane** (all single), **-ene** (a double bond), **-yne** (a triple bond).

Secondary suffix: the functional group, if any: **-ol** (alcohol), **-al** (aldehyde), **-one** (ketone), **-oic acid** (carboxylic acid). The final “e” of -ane is dropped before a suffix starting with a vowel: propane + ol = propan**ol**.

Prefix: the branches (methyl, ethyl…), and in an ether the alkoxy group (methoxy, ethoxy…), each with the number of the carbon it is on.

So **propan-2-ol** is a chain of 3 carbons (prop-), all single bonds (-an-), with an –OH (-ol) on carbon 2. **2-methylbutane** is a chain of 4 carbons (but-), all single bonds (-ane), with a methyl branch on carbon 2.

Rules for naming

1. **Find the main chain**, the longest continuous chain of carbon atoms. It need not be drawn in a straight line: follow the bonds round corners. If the compound has a functional group (–OH, –CHO, C=O or –COOH), the chain must contain the group's carbon; if it has a double or triple bond, the chain is the one that contains it. The word root comes from this chain.
2. **Number the chain** from the end that gives the lowest numbers, in this order of importance: first to the carbon with the functional group, then to the double or triple bond, then to the branches.
3. **Name each branch** as an alkyl group (methyl, ethyl…), with the number of the carbon it is on. If the same branch comes twice or three times, write **di-** or **tri-**, with a number for each: 2,2-dimethyl, 2,3,4-trimethyl.
4. **Write branches in alphabetical order** (ethyl before methyl), ignoring di- and tri-.
5. **Write the name as one word** (except "acid"), with commas between numbers and hyphens between numbers and letters: 2,3-dimethylbutane, but-2-ene, propan-2-ol.
6. If two ways of numbering give the branches different sets of numbers, compare them number by number, and choose the set that is lower at the **first point of difference**: 2,2,4 is lower than 2,4,4.

CAREFUL

Where the number goes

CDC's own books (Grade 10 Science's ethane-1,2-diol and propane-1,2,3-triol; Grade 11 and 12 Chemistry's but-2-ene, propan-2-ol, pentan-3-one) put the number of a double bond or a group just before the part it numbers, as IUPAC has recommended since 1993, and so does this book: write names this way in your exam. Many other books use the older form, with every number in front: 2-butene, 2-propanol, 3-pentanone. Both name the same molecule, and the older form is also accepted. Where only one place is possible, the number is left out: propene, propanone, butanone.

Alkanes

General formula: C_nH_{2n+2}. **Ending:** -ane. **Functional group:** none; only C–C and C–H single bonds.

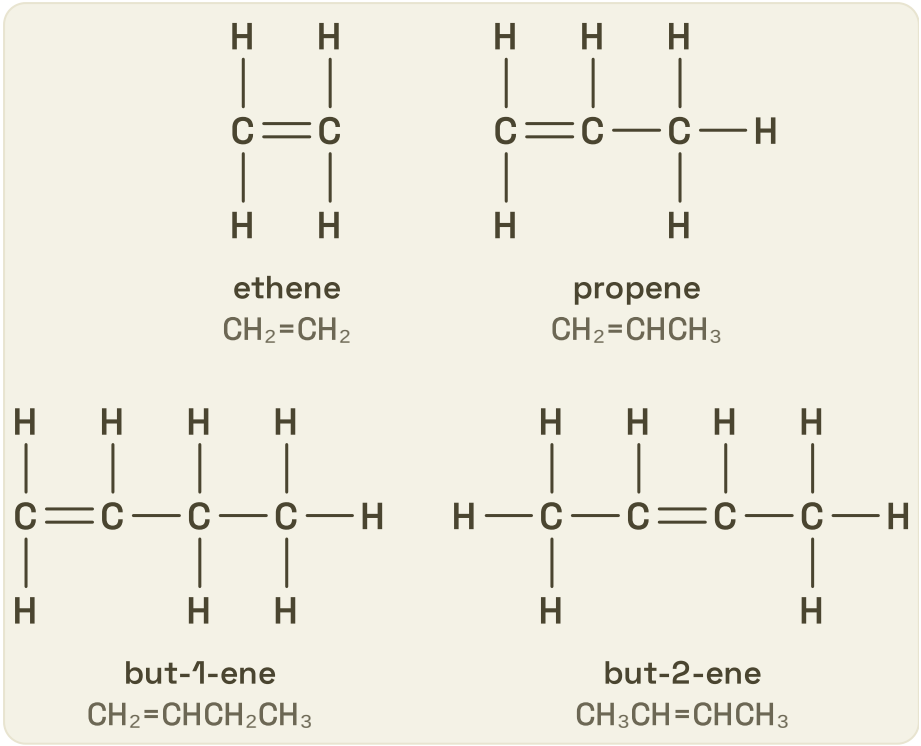


Figure 9.11 *The first alkenes. But-1-ene and but-2-ene have the same formula, C_4H_8, but the double bond is in a different place, so they are different compounds with different numbers in their names.*

WORKED EXAMPLE

Name the alkene

$CH_3–CH_2–CH=CH_2$

Answer

The chain has 4 carbons (but-) and a double bond (-ene). Numbered from the right, nearer the double bond, it lies between carbons 1 and 2, so its number is 1: **but-1-ene.** Numbered from the left it would be "but-3-ene", which is wrong: the double bond gets the lowest number.

Alkynes

General formula: C_nH_{2n-2} (from n = 2). **Ending:** -yne. **Functional group:** C≡C. They are numbered like alkenes.

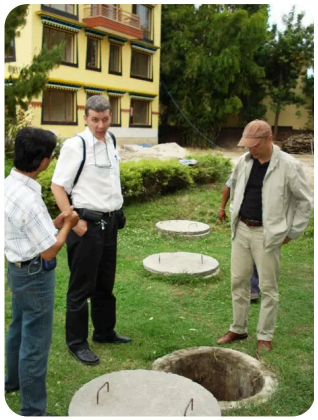


Figure 9.10 *The biogas plant at Shechen Monastery in Boudha, Kathmandu: the digester is under the ground, below the round covers. Inside it, bacteria break down dung and food waste without air and give off biogas, which is about half to two-thirds methane, CH_4: the simplest alkane, burned for cooking.*
Photo: SuSanA Secretariat, CC BY 2.0

Name	Condensed formula	Common name
ethene	$CH_2{=}CH_2$	ethylene
propene	$CH_2{=}CHCH_3$	propylene
but-1-ene	$CH_2{=}CHCH_2CH_3$	1-butene
but-2-ene	$CH_3CH{=}CHCH_3$	2-butene
2-methylprop-1-ene	$CH_2{=}C(CH_3)CH_3$	isobutylene

Ethene is made from petroleum in larger amounts than any other organic chemical. Most of it is joined into the long chains of **polythene**, the plastic of bags, bottles and water tanks; propene becomes **polypropene**, the plastic of chairs and buckets. Ethene is also a plant hormone: a ripe banana gives off ethene, which makes the fruit near it ripen too, and that is why a few ripe fruits in a closed sack ripen the rest quickly.

CAREFUL

Which chain, with a double bond?

Most school books take the main chain of an alkene or alkyne to be the longest chain **through** the double or triple bond, which was IUPAC's rule until 2013. Since 2013, IUPAC takes the longest chain first, even if the double bond ends up in a branch. Every compound in this unit has its double or triple bond in its longest chain, so both rules give the same name; here, and in your exam, use the chain through the double bond.

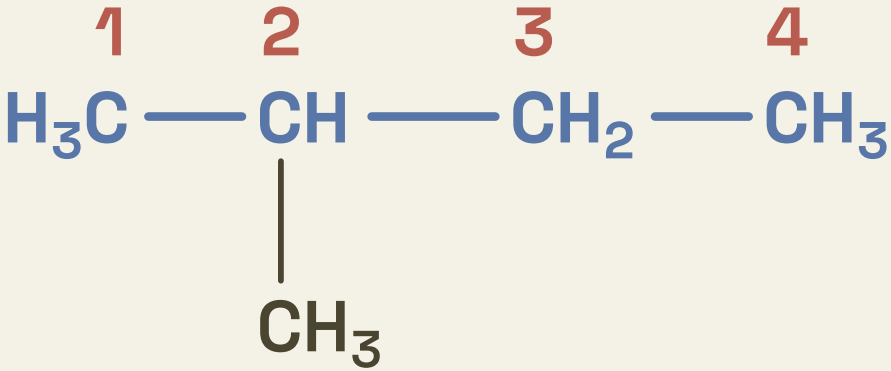


Figure 9.8 *2-methylbutane, $CH_3CH(CH_3)CH_2CH_3$. The longest chain (blue) has four carbons. Numbered from the left, the methyl branch is on carbon 2; from the right it would be on carbon 3. The lower number wins: 2-methylbutane, not 3-methylbutane.*

Name	Molecular formula	Condensed formula	Boiling point
methane	CH_4	CH_4	−162 °C
ethane	C_2H_6	CH_3CH_3	−89 °C
propane	C_3H_8	$CH_3CH_2CH_3$	−42 °C
butane	C_4H_{10}	$CH_3CH_2CH_2CH_3$	−0.5 °C
pentane	C_5H_{12}	$CH_3(CH_2)_3CH_3$	36 °C

Alkanes are also called **paraffins**, from the Latin for "little affinity": they react with little except oxygen (they burn) and, in sunlight, chlorine. Their reaction with oxygen is what we use them for: methane in biogas and natural gas, propane and butane in LPG, octane and its relatives in petrol, larger ones in kerosene and diesel, and the largest in wax and bitumen for roads.

WORKED EXAMPLE

Name these alkanes

a. $CH_3–CH_2–CH(CH_3)–CH_2–CH_3$

b. $CH_3–C(CH_3)_2–CH_3$

c. $CH_3–C(CH_3)_2–CH_2–CH(CH_3)–CH_3$

Answer

a. The longest chain has 5 carbons (pent-), all single bonds (-ane). A methyl hangs on the middle carbon: carbon 3 from either end. **3-methylpentane.**

b. Whichever way you go, the longest chain has 3 carbons (propane). Two methyls hang on the middle carbon, carbon 2: **2,2-dimethylpropane.** (Each methyl gets its own number, so "2,2-", and di- says there are two.)

c. The longest chain has 5 carbons. From the left, the methyls are on carbons 2, 2 and 4; from the right, on 2, 4 and 4. At the first point of difference (the second number), 2 is lower than 4, so number from the left: **2,2,4-trimethylpentane.**

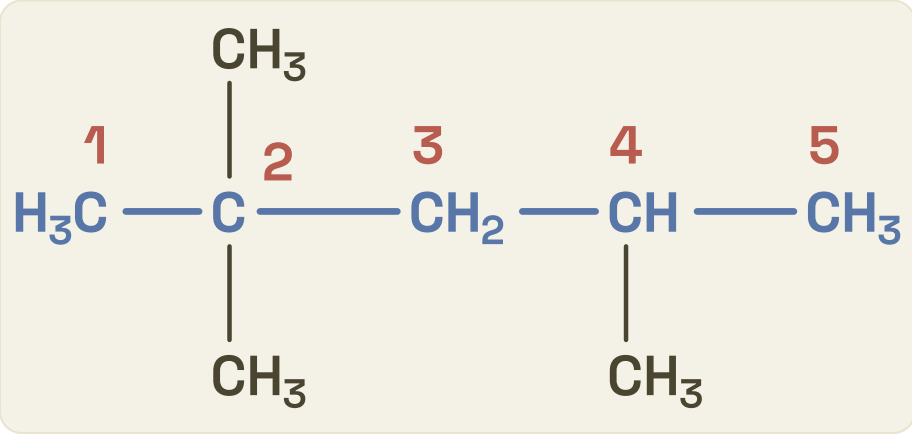


Figure 9.9 *2,2,4-trimethylpentane, numbered from the end that gives the lower set of numbers (2, 2, 4 rather than 2, 4, 4).*

A branched alkane has the same formula as the straight-chain one with the same number of carbons, but a different structure and name. Butane, $CH_3CH_2CH_2CH_3$, boils at −0.5 °C; 2-methylpropane, $CH_3CH(CH_3)CH_3$, also C_4H_{10}, boils at −12 °C.

DID YOU KNOW?

The octane number

2,2,4-Trimethylpentane is the "isooctane" of the **octane number** printed at petrol pumps. Petrol that burns too suddenly in an engine makes it "knock", a metallic rattle that wastes fuel and damages it. Isooctane burns smoothly and is given the number 100; heptane knocks badly and is given 0. A petrol rated 91 knocks as little as a mixture of 91% isooctane and 9% heptane. Its branched chain is what makes isooctane burn smoothly.

YOUR TURN

Name it

$CH_3–CH(CH_3)–CH_2–CH(C_2H_5)–CH_2–CH_3$

Hint

Count the longest chain, including the ethyl group's carbons if that makes it longer. Then number from the end nearer a branch, and write the branches in alphabetical order.

Answer

The longest chain has 6 carbons (hexane): from the CH_3 on the left through to the CH_2CH_3 at the right (or through the ethyl's two carbons, which gives a chain of the same length and the same name). From the left, the branches are a methyl on carbon 2 and an ethyl on carbon 4; from the right they would be on 3 and 5. Alphabetical order puts ethyl first: **4-ethyl-2-methylhexane.**

Alkenes

General formula: C_nH_{2n} (from n = 2). **Ending:** -ene. **Functional group:** C=C.

The chain is numbered from the end nearer the double bond, and the number given is that of the first of its two carbons.