

Organic chemistry and biochemistry

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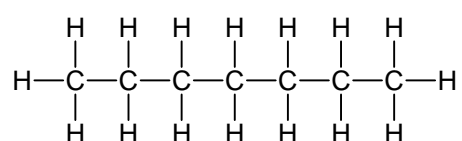
Preface

The human being is a complex organism, completely made up of chemical compounds, of which most are *organic*. Organic compounds are in general made up of the atoms carbon, hydrogen, oxygen and nitrogen, even though other elements may occur as well, in smaller amounts. This document is meant to perspicuously describe organic chemistry and the compounds located and processes taking place in the human body. First, we shall study the structures and properties of the chemical compounds; then, we will study how these are digested and utilized in the body. We shall also study some of the chemical compounds used in products in the modern society as *plastics*, and other industrial applications of organic compounds.

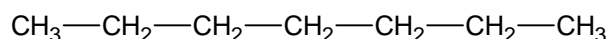
Part I: Organic chemistry

We shall begin to study the simplest organic compounds, the *hydrocarbons*, which only consist of carbon and hydrogen atoms.

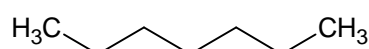
Having four valence electrons, the carbon atom is able to covalently share four pairs of electrons with up to four other atoms. This is the fundamental principle concerning how hydrocarbons are formed. Besides the “normal” chemical formulas, discussing organic compounds, we also use structural formulas, specifying how the atoms are bonded to each other. A complete two-dimensional structural formula consists of all atoms drawn on a plane with straight lines between them; each line symbolizes a shared pair of electrons. However, because organic compounds often are very large (containing many atoms), structural formulas are often abbreviated. Often hydrocarbons can be written as *chains* of carbon and hydrogen atoms, such as with heptane:



This formula may be abbreviated. First, we can write each “segment” as a local “normal” formula:



Furthermore, we can let all “standard segments” (CH_2) be pre-understood:



At each joint, thus, there is a CH_2 group.

Extremely many organic compounds are known, and many of them occur naturally on earth and have industrial applications (especially in the chemical, pharmaceutical and food industries). As a consequence, in this document, we will only mention the occurrences and applications of the very most common organic compounds.

Alkanes

Alkanes are hydrocarbons where every carbon atom bonds four other atoms. Below, the simplest alkanes are described. The “C” column specifies the number of carbon atoms the compound contains, and the “phase” column specifies the phase (s: solid; l: liquid; g: gas) of the compound at STP (Standard Conditions for Temperature and Pressure; 273.15 K and 100 kPa).

C	Name	Trivial name	Formula	Structural formula	Phase
1	methane		CH_4	CH_4	g
2	ethane		C_2H_6	$\text{H}_3\text{C}-\text{CH}_3$	g
3	propane		C_3H_8	$\text{H}_3\text{C}-\text{CH}_2-\text{CH}_3$	g
4	butane		C_4H_{10}	$\text{H}_3\text{C}-\text{CH}_2-\text{CH}_2-\text{CH}_3$	g
5	pentane		C_5H_{12}	$\text{H}_3\text{C}-\text{CH}_2-\text{CH}_2-\text{CH}_2-\text{CH}_3$	l
6	hexane		C_6H_{14}	$\text{H}_3\text{C}-\text{CH}_2-\text{CH}_2-\text{CH}_2-\text{CH}_2-\text{CH}_3$	l


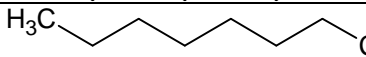

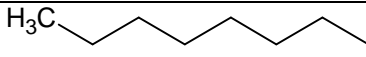
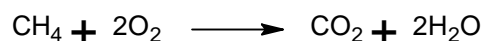
C	Name	Trivial name	Formula	Structural formula	Phase
7	heptane		C ₇ H ₁₆		l
8	octane		C ₈ H ₁₈		l
9	nonane		C ₉ H ₂₀		l
10	decane		C ₁₀ H ₂₂		l

Table 1 Alkanes

All alkanes to the alkane with 13 carbon atoms, tridecane (C₁₃H₂₈) are liquids at STP. The 14 carbon atom alkane, tetradecane (C₁₄H₃₀), has a melting point of 5.5 °C; all larger alkanes are solids at STP.

The simplest hydrocarbon, methane is an odourless gas. In industrial production of the gas, however, odouriferous gasses are often added (often sulphurous compounds), so that gas leak-ages easily can be detected. Methane is abundant in the earth's mantle and on the ocean bed, and is a main component in natural gas, which is used as a fuel, for instance for heating and generation of electricity.

Through the reaction



methane is fully combusted.

The process of digestion of some animals also produces methane. Moreover, methane is abundant on other celestial bodies in our solar system, for instance on Jupiter's moon Titan, the only moon in the solar system known to have a thick atmosphere, of which approximately 1.6 % is methane. Methane has also been detected in interstellar gas clouds. Also many larger alkanes are naturally occurring, both on earth and at other locations in space.

Petrol, which is used as a fuel in smaller engines (e.g. motorcycles, cars and smaller aircraft), is largely a solution of alkanes; often, the carbon atom numbers are between six and ten.

Isomers

Two compounds sharing the same chemical formula but having two distinct structural formulas are *isomers* to each other. There are different types of isomerism, described by the list below.

- Structural isomerism
 - Chain isomerism
 - Position isomerism
 - Functional group isomerism
- Stereoisomerism
 - Cis-trans isomerism
 - Enantiomers isomerism

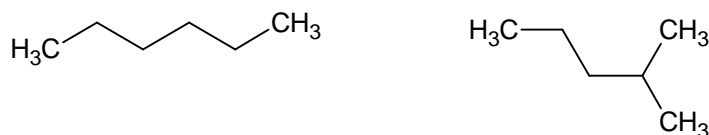
Structural isomerism occurs between two compounds when the atoms in the first compound are not bonded to the corresponding atoms in the second compound. Concerning stereoisomerism, on the other hand, all atoms in the first compound are in fact bonded to corresponding atoms in the second compound, but in *different directions* in three-dimensional space.

Chain isomerism and nomenclature

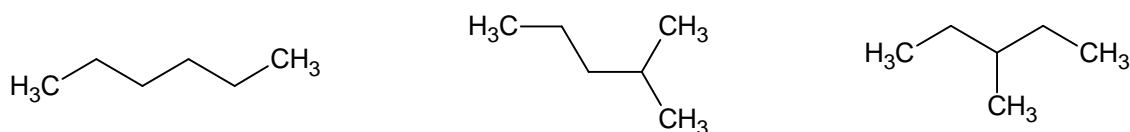
Chain isomerism occurs when the carbon chains differ between two molecules. For instance, the following molecules are chain isomers to each other.



The two molecules share the common formula C_5H_{12} , but the atoms are bonded to each other forming two distinct structures. We recognize the first molecule as pentane. Thus, the second molecule is an isomer of pentane, or *iso-pentane*. We can also find an isomer of hexane:



The first molecule is hexane, whereas the other may be called *iso-hexane*. However, there are more than one candidates of the “*iso-hexane*” name. Below, all possible chain isomers of hexane are drawn.



To unambiguously name an isomer, one has decided to use the following rules:

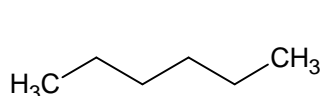
1. Find the longest continuous carbon chain in the molecule; this is called the *root chain*. The straight alkane with the same number of carbon atoms as the root chain will make up the “last name” of the molecule. To be able to follow the following steps, we must also number the carbon atoms in the root chain, so that the carbon atom bonding a branch and being as close to one of the two ends of the root chain as possible, will be assigned a number as low as possible.
2. The groups branched from the root chain will be named individually and receive the new “-yl” suffix, declaring that they are just groups branched from the root chain. Concerning alkanes, these groups will get the “-yl” suffix instead of “-ane”.
3. The names of all groups will be written before the “last name” of the molecule. Before each group name, the number of the carbon atom to which the group is bonded, is declared. Between numbers and names and between different group declarations, hyphens are used as separators.
4. If a certain group occurs more than once, a “counter” is written before the group name (without any separator), according to the table to the right. The carbon atom numbers of the groups are separated by commas.

one	(mono)
two	di
three	tri
four	tetra

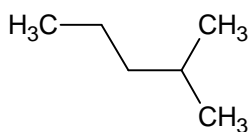
Table 2: Counters

5. The group names before the “last name” of the molecule are sorted alphabetically. Counters (di, tri, and tetra) are excluded.

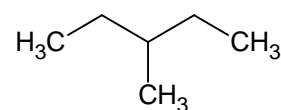
For instance, the two isomers of hexane will be named as follows.



hexane

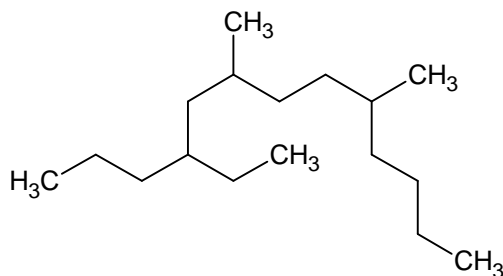


2-methyl-pentane



3-methyl-pentane

Below is a somewhat more complicated example.

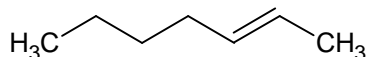


4-ethyl-6, 9-dimethyl-tridecane

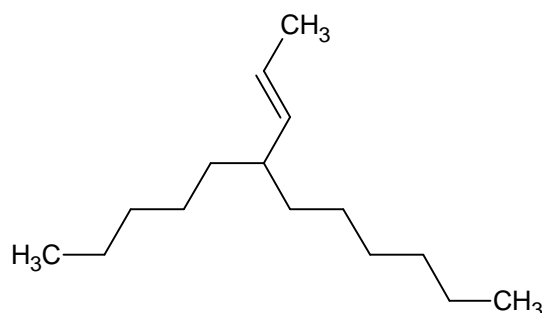
Alkenes

Sometimes a carbon atom bonds only three other atoms; in such cases, exactly one of these bonds must be a *double bond*, i.e. two pairs of electrons are shared between these atoms. A compound with one or more double bonds is said to be *unsaturated*, and is able to *add* two new atoms at the position of the double bond, which then will be converted to a single bond. In structural formulas, double bonds are drawn as two parallel lines. The “last name” of a molecule containing double bonds will end with “-ene” instead of “-ane”. Concerning the carbon numbering, it is important to make sure, that the carbon atoms participating in the double bond will be located in the root chain and receive as low numbers as possible. This is more important than the root chain’s being as long as possible. The number of a double bond equals the number of the carbon atom participating in the bond and being as close as possible to one of the terminating points of the chain. The number of the double bond is written just before the “last name” of the molecule.

Study the two following structures as examples.



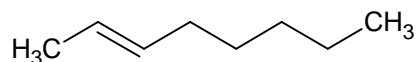
2-heptene



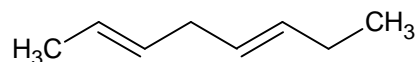
4-pentyl-2-decene

A more “technical” name of the second molecule above would be 6-[1-propene-1-yl]-dodecane.

If two or more double bonds exist within the same molecule (on the same root chain), the correct counter is written before the “-ene” suffix of the “last name”. The numbers of the double bonds are separated by commas. Study the examples below.

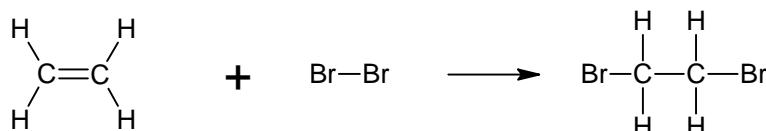


2-octene



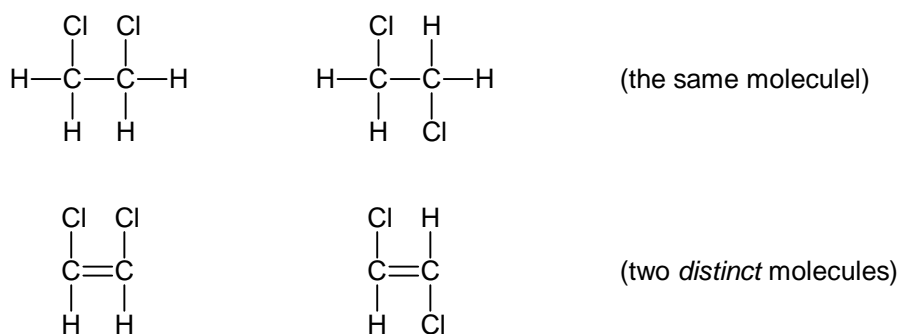
2, 5-octadiene

An unsaturated compound can be *saturated* by adding extra atoms and losing the double bond in the process. The following reaction is a typical *addition reaction*.



Ethene (ethylene) is a transmitter substance (a hormone) in plants and is also a very technically important alkene. Ethene is first and foremost used for production of polyethene (polyethylene) plastics – one of the most commonly used plastics in the modern society. Polyethene is a *polymer* of ethene, i.e. a macromolecule compiled of numerous small ethene molecules.

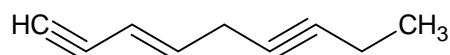
Double bonds are – unlike single bonds – not dynamic: the two sides of the bond cannot rotate in relation to each other. Below, four molecules are drawn. The molecules on the first row are derivatives of alkanes, where the molecules on the second row are derivatives of alkenes. Whereas the two alkane derivatives are identical to each other, the two alkene derivatives represent two distinct molecules, being stereoisomers to each other.



Alkynes

Triple bonds, where three pairs of electrons are shared, are dealt with analogous to double bonds. Here the “-yne” suffix is used instead of “-ene” that is used for alkenes.

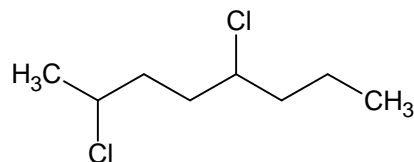
In the following example, in the name of the molecule, we specify the position numbers of the double and triple bonds just before the “-ene” and “-yne” suffixes.



non-3-ene-1, 6-diyne

Haloalkanes

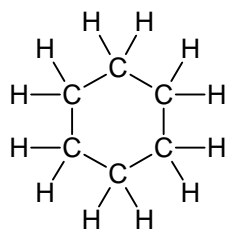
Hydrogen atoms in hydrocarbons may be substituted for other atoms, particularly halogens. These molecules are called *haloalkanes*, and are named by adding the names of the halogen atoms and their positions before the “last name” of the molecule. Study the following example.



2, 5-dichloro-octane

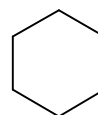
Cycloalkanes

A *cycloalkane* is a cyclic alkane, i.e. an alkane without any terminating ends.



cyclohexane

or, abbreviated,

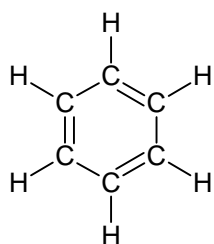


cyclohexane

Cyclohexane and cyclopentane are quite stable cycloalkanes, compared to cyclobutane and the unstable cyclopropane molecule.

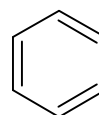
Aromatic hydrocarbons

Hydrocarbons derived from *benzene* are called *aromatic hydrocarbons*. Benzene is a cyclic hydrocarbon where – as one said some years ago – every other carbon-carbon-bond is a double bond. This definition, however, is inappropriate, because benzene does not behave as an unsaturated compound.



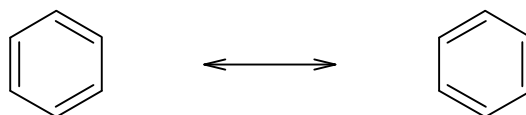
benzene

or, abbreviated,

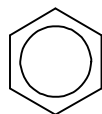


benzene

With modern terminology, one realizes that the two following (resonance) structures are possible:



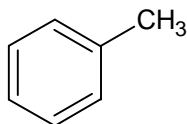
Instead of writing these two possible forms of benzene, one usually says that the six¹ additional bonding electrons are *delocalized* and belong equally to every carbon atom. To draw this, the delocalized electrons are drawn as a circle:



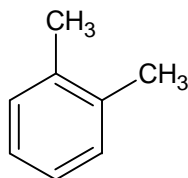
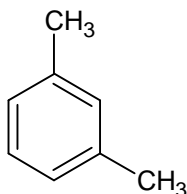
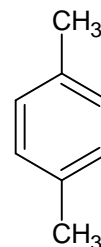
benzene

One can consider the two “conventional” double bond models above as two “extremes” of electron positions in the molecule, whereas the model of the benzene molecule should be described using the modern form, a “mean” of the two extremes, or a *resonance hybrid*. The resonance hybrid is more stable than any of its extremes. Benzene is a colourless and fragrant liquid at room temperature (melting point at 5.5 °C) and has been shown to be a carcinogen.

Two common derivatives of benzene are methylbenzene (*toluene*) and dimethylbenzene (*xylene*). These compounds can be derived from benzene if one or two hydrogen-to-methyl-substitutions are performed, respectively.

methylbenzene
toluene

Of course, there are three structural isomers of xylene:

1, 2-dimethylbenzene
ortho-xylene1, 3-dimethylbenzene
meta-xylene1, 4-dimethylbenzene
para-xylene

Toluene and xylene are colourless liquids. They are, for instance, used in petroleum, as solvents and in synthesis of other chemicals.

Alcohols

We shall now study more complex organic compounds than simple hydrocarbons (and haloalkanes, which we also have studied). If a hydrogen atom in a hydrocarbon is replaced with another group (not a hydrocarbon group), the molecule may obtain completely new properties. Such a group is called a *functional group*. First, we will study alcohols, organic compounds with the –OH functional group, the *hydroxyl* group. We shall begin to study alcohols that are

¹ Why six? Every carbon atom has four valence electrons. Two of these are used to form bonds to the nearby carbon atoms and one is used to form a bond to the hydrogen atom. Thus, each carbon atom will have one valence electron left. The molecule consists of six carbon atoms and will therefore get six electrons left. These are equally shared by all carbon atoms, depicted by the circle.

direct derivatives of the alkanes, with only one of the two outermost hydrogen atoms substituted with a hydroxyl group. The names of these compounds are derived from the name of the corresponding alkane, adding the “-ol” suffix.

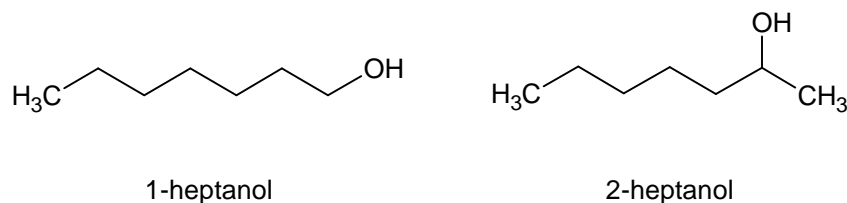
C	Name	Trivial name	Formula	Structural formula	Phase
1	methanol	wood alcohol	CH ₃ OH	H ₃ C—OH	l
2	ethanol	grain alcohol	C ₂ H ₅ OH	H ₃ C—CH ₂ —OH	l
3	propanol		C ₃ H ₇ OH	H ₃ C—CH ₂ —CH ₂ —OH	l
4	butanol		C ₄ H ₉ OH	H ₃ C—CH ₂ —CH ₂ —CH ₂ —OH	l
5	pentanol		C ₅ H ₁₁ OH	H ₃ C—CH ₂ —CH ₂ —CH ₂ —CH ₂ —OH	l
6	hexanol		C ₆ H ₁₃ OH	H ₃ C—CH ₂ —CH ₂ —CH ₂ —CH ₂ —CH ₂ —OH	l
7	heptanol		C ₇ H ₁₅ OH	H ₃ C—CH ₂ —CH ₂ —CH ₂ —CH ₂ —CH ₂ —CH ₂ —OH	l
8	octanol		C ₈ H ₁₇ OH	H ₃ C—CH ₂ —CH ₂ —CH ₂ —CH ₂ —CH ₂ —CH ₂ —CH ₂ —OH	l
9	nonanol		C ₉ H ₁₉ OH	H ₃ C—CH ₂ —CH ₂ —CH ₂ —CH ₂ —CH ₂ —CH ₂ —CH ₂ —CH ₂ —OH	l
10	decanol		C ₁₀ H ₂₁ OH	H ₃ C—CH ₂ —CH ₂ —CH ₂ —CH ₂ —CH ₂ —CH ₂ —CH ₂ —CH ₂ —CH ₂ —OH	l

Table 3 Some simple alcohols

We see that the alcohols in general have higher boiling points than the corresponding alkanes, which, of course, is true because the hydroxyl groups allow the molecules to form hydrogen bonds. Having a melting point at 24-27 °C, dodecanol, C₁₂H₂₅OH is the first alcohol in this category being a solid at room temperature. Methanol and ethanol are sometimes used as solvents and, increasingly often, as fuels (particularly ethanol). These compounds are also produced by anaerobic bacteria. Despite being a toxic, in some cultures ethanol is used as beverage. Furthermore, essentially all alcohols mentioned above have industrial applications.

Position isomerism

Two molecules being identical to each other except for a functional group's being bonded to distinct atoms are *positional isomers* to each other. Thus, to name a particular positional isomer of an alcohol, the position of the hydroxyl group must be specified. Study the following molecules as an example.



To be correct, we should accordingly name the alcohols in the table above 1-propanol, 1-butanol, 1-pentanol etc.

Molecules containing more than one hydroxyl group

An alcohol may contain more than one (1) hydroxyl group. The name of such an alcohol must specify the positions of all hydroxyl groups, and add the correct counter before the “-ol” suffix. We shall now study some common compounds containing multiple hydroxyl groups.

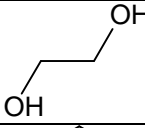
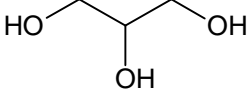
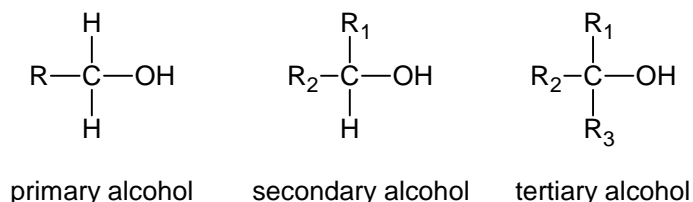
C	Name	Trivial name	Formula	Structural formula	Phase
2	ethane-1,2-diol	ethylene glycol	$C_2H_4(OH)_2$		l
3	propane-1,2,3-triol	glycerol, glycerin, glycerine	$C_3H_5(OH)_3$		l

Table 4 Some alcohols containing multiple hydroxyl groups

The most well-known application of ethanediol is probably as a component in automotive antifreeze. If the antifreeze solution in a car consists of 50 % ethanediol and 50 % water, the freezing point of the solution will drop to $-35\text{ }^\circ\text{C}$, preventing the solution from freezing during winter. Propanetriol is a main component of all fats.

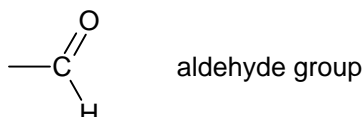
An alcohol is said to be *primary* (with respect to a specific hydroxyl group) if the carbon atom bonding the hydroxyl group at most forms a bond to *one* other carbon atom. If it, on the contrary, forms bonds to two other carbon atoms, the alcohol is said to be *secondary*; if it bonds three other carbon atom, the alcohol is said to be *tertiary*. All alcohols in Table 3 are primary. Ethanediol is primary with respect to its both hydroxyl groups as well as the outermost hydroxyl groups in propanetriol, whereas the hydroxyl group in the middle actually is secondary.



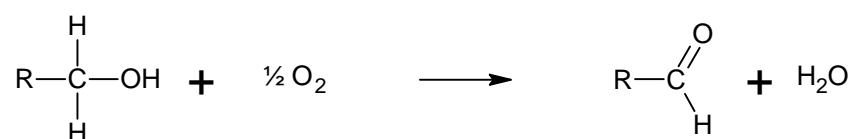
R_n symbolizes any hydrocarbon chain. Now, we shall study what happens when primary, secondary and tertiary alcohols are oxidized.

Aldehydes

Aldehydes are compounds containing the $-\text{CHO}$ functional group, the *aldehyde* group.



Aldehydes are formed when primary alcohols are oxidized. The reaction is shown below.



If we oxidize the (primary) alcohols from Table 3, we will obtain the simplest aldehydes. These are named adding the “-al” suffix to the name of the corresponding alkane, in analogy to how alcohols are named (using the “-ol” suffix).

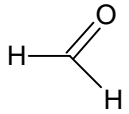
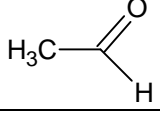
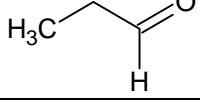
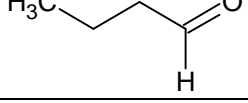
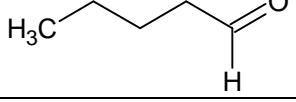
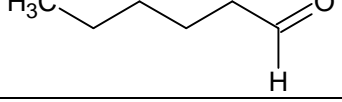
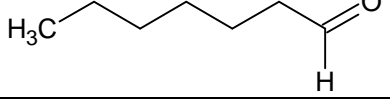
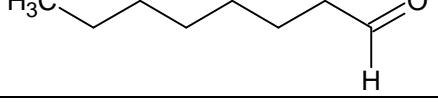
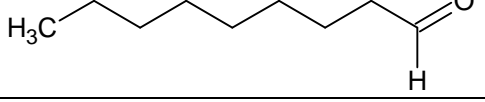
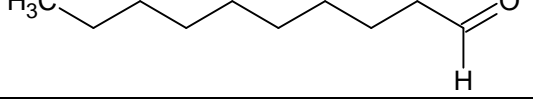
C	Name	Trivial name	Formula	Structural formula	Phase
1	methanal	formaldehyde	HCHO		g
2	ethanal	acetaldehyde	CH ₃ CHO		l
3	propanal	propionaldehyde	C ₂ H ₅ CHO		l
4	butanal		C ₃ H ₇ CHO		l
5	pentanal		C ₄ H ₉ CHO		l
6	hexanal		C ₅ H ₁₁ CHO		l
7	heptanal		C ₆ H ₁₃ CHO		l
8	octanal		C ₇ H ₁₅ CHO		l
9	nonanal		C ₈ H ₁₇ CHO		l
10	decanal		C ₉ H ₁₉ CHO		

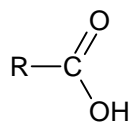
Table 5 Some aldehydes

Methanal is produced naturally during forest fires and is also present in automobile exhaust gasses and tobacco smoke. Killing bacteria, methanal-water solution (*formalin*) is industrially used as a disinfectant and preservative to, for instance, animals in glass jars at museums. Methanal is also used to dry out skin, for instance to treat warts and in the plastics industry. Chiefly, however, methanal is used to synthesize other compounds.

Ethanal is produced by plants and is naturally occurring in bread and in ripe fruits. Industrially, ethanal is mostly used in the synthesis of other compounds. Both methanal and ethanal are suspected to be carcinogenic. Heptanal and octanal are used in paints, and several of the aldehydes above are used within the pharmaceutical industry.

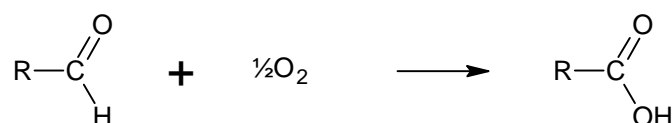
Carboxylic acids

If we oxidize an aldehyde, we will obtain a new, distinct compound, belonging to the *carboxylic acids* class. A carboxylic acid is a molecule containing the -COOH functional group, the *carboxyl* group.



the carboxyl group

The common formula describing an aldehyde oxidizing to a carboxylic acid is shown below.



If we oxidize the aldehydes from Table 5 above, we will obtain the simplest carboxylic acids. The name of a carboxylic acid equals the name of the corresponding alkane (with the same number of carbon atoms, including the carbon atom in the carboxyl group) adding the “-oic acid” suffix to it.

C	Name	Trivial name	Formula	Structural formula	Phase
1	methanoic acid	formic acid	HCOOH		1
2	ethanoic acid	acetic acid	CH_3COOH		1
3	propanoic acid	propionic acid	$\text{C}_2\text{H}_5\text{COOH}$		1
4	butanoic acid	butyric acid	$\text{C}_3\text{H}_7\text{COOH}$		1
5	pentanoic acid	valeric acid	$\text{C}_4\text{H}_9\text{COOH}$		1
6	hexanoic acid	caproic acid	$\text{C}_5\text{H}_{11}\text{COOH}$		1
7	heptanoic acid	enanthic acid	$\text{C}_6\text{H}_{13}\text{COOH}$		1
8	octanoic acid	caprylic acid	$\text{C}_7\text{H}_{15}\text{COOH}$		1

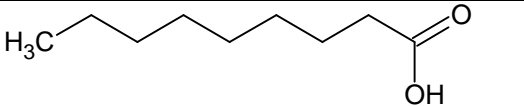
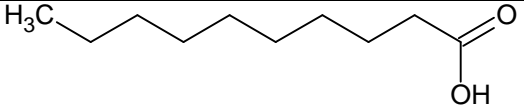
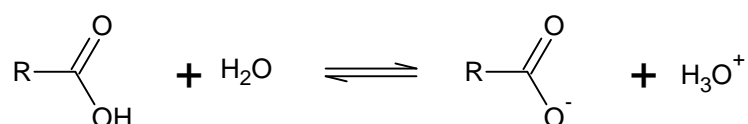
C	Name	Trivial name	Formula	Structural formula	Phase
9	nonanoic acid	pelargonic acid	C ₈ H ₁₇ COOH		s
10	decanoic acid	capric acid	C ₉ H ₁₉ COOH		s

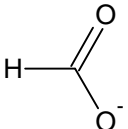
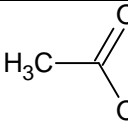
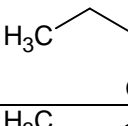
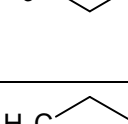
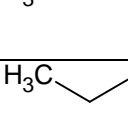
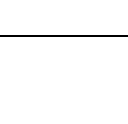
Table 6 Some carboxylic acids

Formic acid is secreted from, for instance, venom glands of some species of bees and ants, and is the strongest of all carboxylic acids in the table above; carboxylic acids are in general quite weak acids. Thanks to its antiseptic and preservative properties, the water solution of acetic acid is used in cooking. Acetic acid is also used within the paint, pharmaceutical and plastics industry. Fodder is rinsed in propionic acid (or its ammonium salt) to restrict bacterial reproduction. Butyric acid is often formed in old butter, giving it a characteristic odour.

A carboxylic acid can – as all acids can – give away a hydrogen ion (proton) while in water. This process is described by the general formula below.



The anion formed in this process is called a *carboxylate ion*. Carboxylate ions are named using the “-oate” suffix. The following table shows the carboxylate ions forming when the carboxylic acids from Table 6 give away protons.

C	Name	Trivial name	Formula	Structural formula
1	methanoate	formate	HCOO ⁻	
2	ethanoate	acetate	CH ₃ COO ⁻	
3	propanoate	propionate	C ₂ H ₅ COO ⁻	
4	butanoate	butyrate	C ₃ H ₇ COO ⁻	
5	pentanoate	valerate	C ₄ H ₉ COO ⁻	
6	hexanoate		C ₅ H ₁₁ COO ⁻	

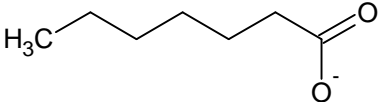
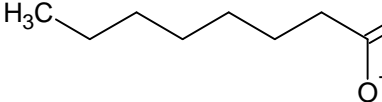
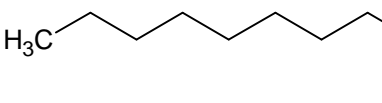
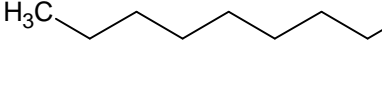
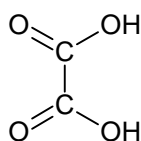
C	Name	Trivial name	Formula	Structural formula
7	heptanoate		$C_6H_{13}COO^-$	
8	octanoate		$C_7H_{15}COO^-$	
9	nonanoate		$C_8H_{17}COO^-$	
10	decanoate		$C_9H_{19}COO^-$	

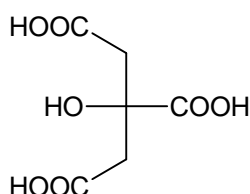
Table 7 Some carboxylate ions

There are also carboxylic acids with more than one carboxyl group. The simplest *dicarboxylic acid* is *oxalic acid*, a solid water-soluble substance. For instance, oxalic acid exists in rhubarb, giving it its sour taste. Oxalic acid is also present in the spermatophyte Common wood sorrel (*Oxalis acetosella*); thus the name. The anion of oxalic acid is named *oxalate*. The calcium oxalate salt is sparingly soluble in water; the most common type of kidney stone (60 % of all cases in Sweden) is a mixture of calcium oxalate and calcium phosphate, whereas 20 % of all cases are made-up of calcium oxalate alone². Binding to important nutritive substances, extensive intake of oxalic acid may lead to deficiency syndromes, at least in humans suffering from kidney diseases.



oxalic acid

There are also *tricarboxylic acids*, such as *citric acid*. As the name suggests, citric acid occurs naturally in lemons. The acid is also used within the food industry as an acidity regulator. The anion of citric acid is called *citrate*.

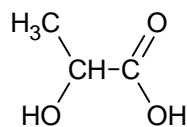


citric acid

If two or more distinct functional groups, such as one hydroxyl and one carboxyl group, are present in the same molecule, their positions are not specified using “ordinary” numbering, but “Greek numbering”. Greek numbering means that the carbon atom *closest* to the (in this case) carboxyl group will be called α , and the following atoms β , γ etc. The α -

² Source: H. G. Tiselius, Karolinska Institutet

hydroxypropanoic acid (*lactic acid*) is an example of a *hydroxyl acid*. The corresponding anion is called *lactate*.

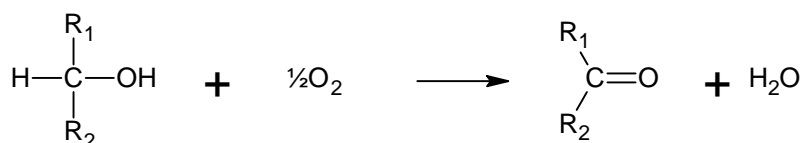


lactic acid

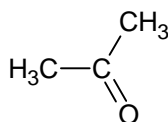
If a carboxylic acid is oxidized, the carbon chain will disintegrate. Eventually, we will obtain water and carbon dioxide.

Ketone

Chemical compound including the functional group “>C=O”, the *ketone* group, are called *ketones*. Ketones are formed while heating (oxidizing) secondary alcohols, according to the formula below. Ketones are named by adding the “-one” suffix to the “last name”.

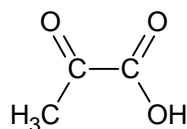


The simplest secondary alcohol is 2-propanol; thus, the simplest ketone is 2-propanone (*acetone*), a colourless liquid that is highly water-soluble. Industrially, acetone is perhaps chiefly used as a solvent, but the molecule is also formed naturally in the human body during catabolism of fats. At special conditions, such as starvation and diabetes, when the fatty metabolism increases due to a decline in carbohydrate metabolism, sweat and saliva may actually smell of acetone.



acetone

In the same way a molecule – such as lactic acid – can be both a carboxylic acid and alcohol at the same time, a molecule can be both a carboxylic acid and a ketone at the same time. Concerning these *keto acids*, the Greek α , β , γ designations are used as well. A simple example of an α keto acid is *pyruvic acid*, having the corresponding anion *pyruvate*.



pyruvic acid

Oxidizing ketones, the carbon chain disintegrates and we obtain water and carbon dioxide.

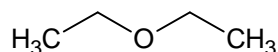
Thiols

If we substitute the oxygen atom with a sulphur atom in the hydroxyl group –OH, we will obtain a new functional group, –SH. Molecules containing this group are named *thiols* or

mercaptans. The simplest thiol is methanethiol (methyl mercaptans), $\text{CH}_3\text{-SH}$. Being the sulphur analogue to alcohols, thiols often react similarly.

Ethers

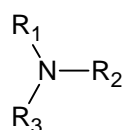
Molecules containing the -O- functional group, the *ether* group, are called *ethers*. An ether is named by letting the alkane corresponding to the longest carbon chain in the ether become the “last name” of it. The other chain will get the “-oxy” suffix instead of “-ane” (so that “methane” becomes “methoxy”), and will be written before the “last name”. For instance, study the colourless liquid *ethoxyethane* (*diethyl ether*, informally just “*ether*”). Until late 1960s, ethoxyethane was used as an anaesthetic agent³.



ethoxyethane

Amines

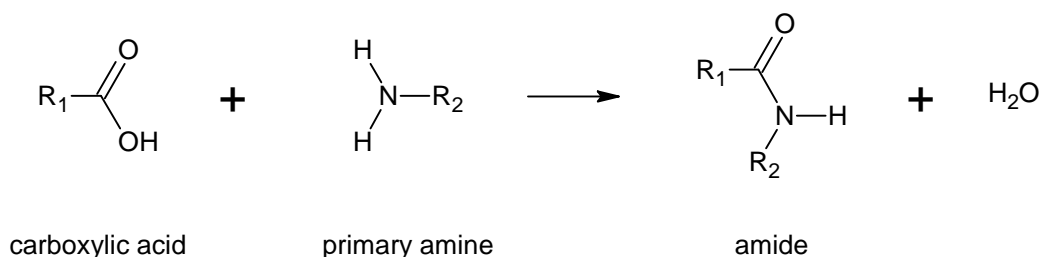
If one or more of the hydrogen atoms in ammonia (NH_3) is substituted with hydrocarbon chains ($\text{R}_1, \text{R}_2, \text{R}_3$), we obtain an *amine*. Thus, all amines can be written using the formula below, where R_n is a hydrogen atom or a hydrocarbon chain. If only one hydrogen atom has been replaced, the amine is said to be *primary*. If two or three (all) of the hydrogen atoms have been replaced, the amine is said to be *secondary* or *tertiary*, respectively. Amines are bases.



An amine

Amides

The condensation product⁴ of a carboxylic acid and an amine is called an *amide*. The common reaction forming an amide from a carboxylic acid and a primary amine is shown below.

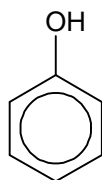


More aromatic compounds

If we substitute one of the hydrogen atoms in benzene with a hydroxyl group we obtain *phenol*, a solid with a strong odour. Previously, phenol was used as a disinfectant thanks to its antiseptic properties. Today, however, the use of the chemical is reduced due to its toxicity. Phenol is also used in the manufacturing of plastics.

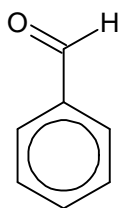
³ The boiling point of ethoxyethane is 34.6 °C.

⁴ A condensation reaction is a reaction combining two molecules to a larger molecule, leaving a minor molecule left in the process.

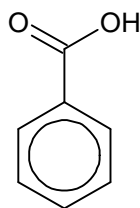


phenol

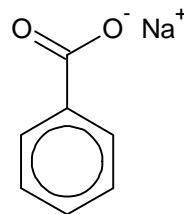
If we instead substitute the hydrogen atom with a carboxyl group, we will obtain the white solid *benzoic acid*. The corresponding anion is called *benzoate*. Many benzoate salts, such as sodium benzoate, are used as food preservatives.



benzaldehyde

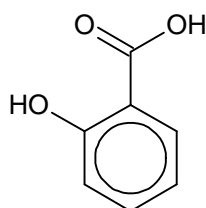


benzoic acid

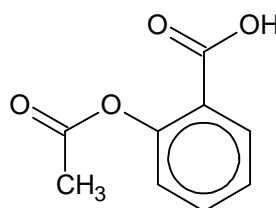


sodium benzoate

Considering a benzene molecule, if we substitute two hydrogen atoms with one hydroxyl group and one carboxyl group (in *ortho* position), we obtain *salicylic acid*. Furthermore, if we substitute the hydrogen atom in the hydroxyl group of salicylic acid with an acetyl group ($\text{CH}_3\text{CO}-$), we obtain *acetylsalicylic acid (aspirin)*, a very common analgesic, antipyretic and anti-inflammatory drug.

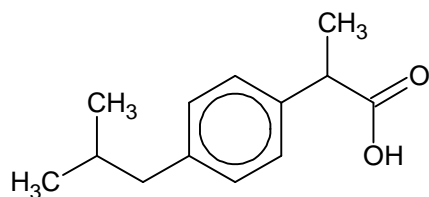


salicylic acid

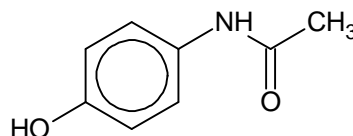


acetylsalicylic acid

Another very common active substance in similar drugs is *ibuprofen*; also *paracetamol* is commonly used.

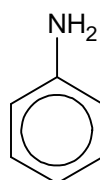


ibuprofen



paracetamol

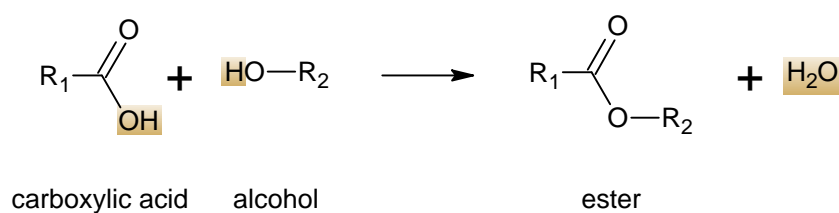
If we substitute one hydrogen atom in benzene with a primary amino group, we obtain a molecule named *aniline*, a liquid widely industrially used (particularly within the pharmaceutical industry).



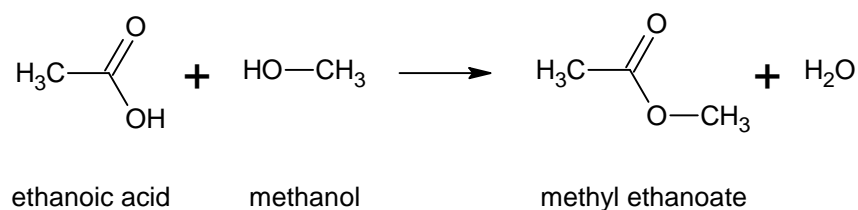
aniline

Esters

Esters are condensation products of carboxylic acids and alcohols. Below, the general condensation reaction formula is shown. This reaction, esterification, often requires the addition of an acid catalyst, such as sulphuric acid (H_2SO_4).



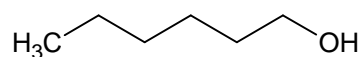
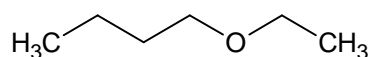
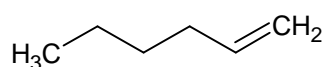
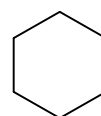
An ester is named using the carboxylic acid's anion as "last name", preceded by the group (alkyl) name of the alcohol. Study the following reaction as an example.



Short esters are often very well-scented and naturally occurring. For instance, ethyl butanoate gives pineapples their characteristic scent and flavour. In addition, many esters are used as food additives, making food scent and taste more or differently. For instance, methyl butanoate smells pineapple/apple, pentyl ethanoate smells banana, pentyl pentanoate smells apple and pentyl butanoate smells pear/apricot.

Functional group isomerism

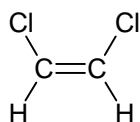
Two molecules sharing the same chemical formula but having two *distinct* functional groups are said to be functional group isomers to each other. Consider the following pairs of functional isomers as two examples (one pair/row).

hexanol ($\text{C}_6\text{H}_{14}\text{O}$)ethoxybutane ($\text{C}_6\text{H}_{14}\text{O}$)1-hexene (C_6H_{12})cyclohexane (C_6H_{12})

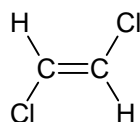
Stereoisomerism

Whereas structural isomerism means that the atoms are bonded to *distinct* atoms in the two molecules, stereoisomerism means that the bonds instead only differ concerning their directions in three-dimensional space.

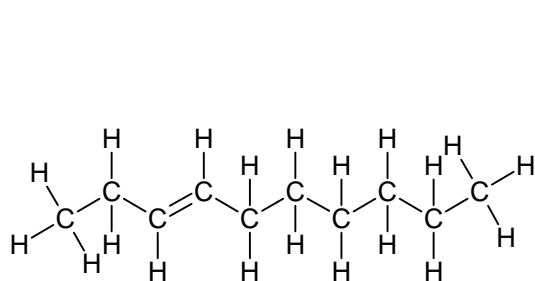
At a double or triple bond, that is not dynamic, the atoms can be arranged in two different ways in space. If two *similar* structures are located at the *same* side, the molecule is said to be the *cis* isomer; if the two structures are located at the *opposite* sides, the molecule is the *trans* isomer.



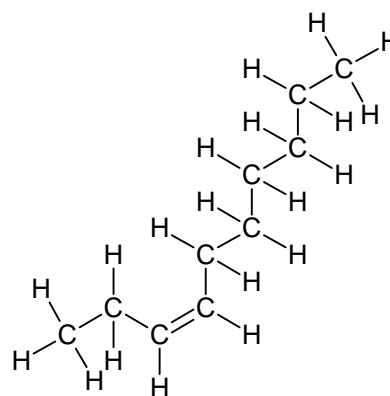
cis-1, 2-dichloroethene



trans-1, 2-dichloroethene



trans-3-decene



cis-3-decene

Another form of stereoisomerism occurs when a carbon atom (or another atom) forms four bonds to *different* groups or atoms; then two distinct isomers are possible. The atom binding to the four different groups is called the *chiral centre*. This type of isomerism is called *optical isomerism* and the molecules being isomers to each other are said to be *enantiomers* to each other. Thus, if a molecule has n chiral centres, then 2^n enantiomers are possible. The two enantiomers arising from a chiral centre are distinguished from each other using the “D” and “L” prefixes from the Latin words meaning right and left⁵.

Often, two enantiomers have quite similar chemical and physical properties, but there is one important difference between them: they rotate polarized light in different directions (clockwise or counter-clockwise). Thus, a solution of only one enantiomer is optically active, whereas a 1:1 mixture of two enantiomers (a *racemic mixture*) is optically inactive.

The two enantiomers of lactic acid constitute a typical example of optical isomerism. In nature (e.g. in a human muscle), only one enantiomer is present.

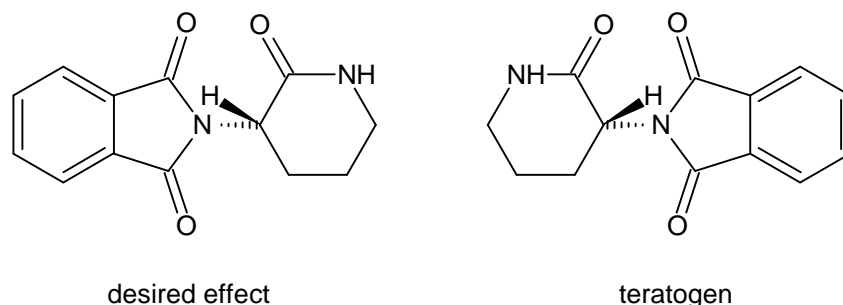
⁵ Latin: *dexter* (right) and *laevus* (left)



The two enantiomers of lactic acid

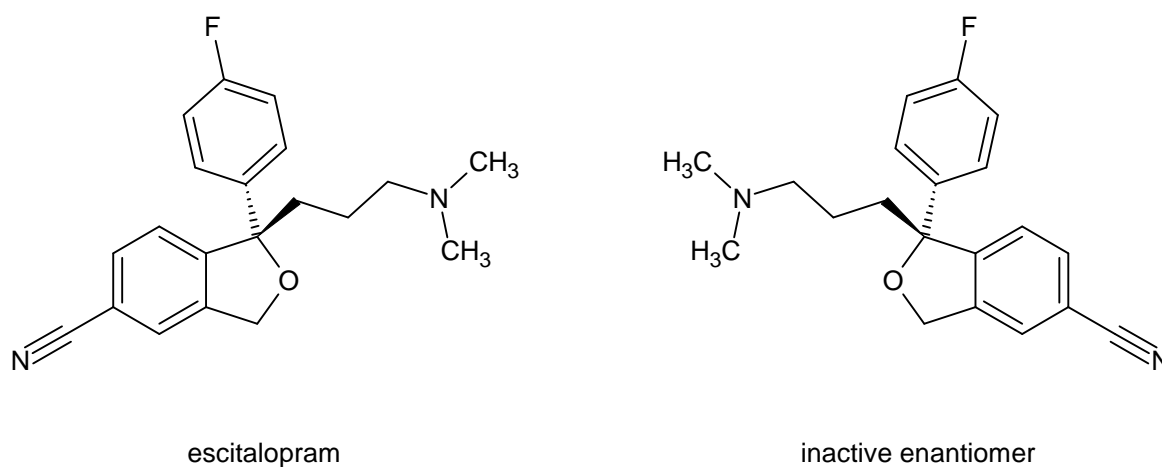
Concerning drugs, it is a common scenario that only one of several possible enantiomers is active in a desirable way; other enantiomers may even be hazardous. During the 1960s, a sleeping aid and an antiemetic drug named Neurosedyn was marketed in Sweden. The active substance was named *thalidomide*. This marketing, however, caused a disaster: in fact only one of the enantiomers had the desired effect; the other was a teratogen⁶.

The two enantiomers of thalidomide



Another example is the antidepressant drug citalopram, having two enantiomers, of which only one is thought to be effective. Early drugs used a mixture of the two enantiomers, whereas the later versions (sold as Cipralex in Sweden), only contain the active enantiomer. The new active substance was named escitalopram and is believed to be more effective (at least twice as effective, due to the doubling of the concentration). Escitalopram is sold as tablets containing an oxalate salt of it.

The two enantiomers of citalopram

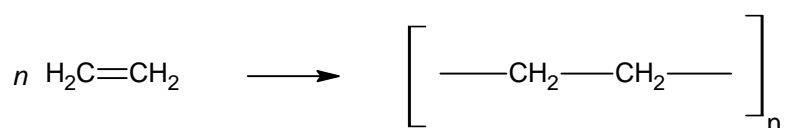


⁶ *Teratogen*: substance causing damage to foetus

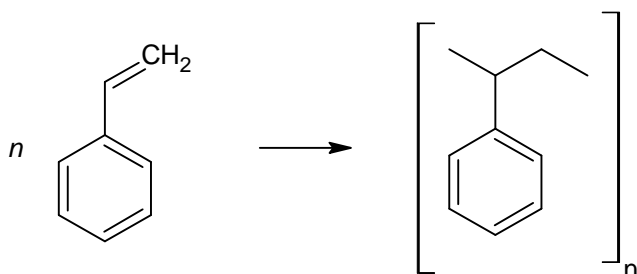
Polymers

A *polymer* is a very large molecule (macromolecule) consisting of many small (often identical) molecules, *monomers*, (most often covalently) bond to each other. Reactions forming polymers are called *polymerizations*. *Plastics*, artificial materials with a variety of properties extremely frequently used in the modern society, are made up of polymers (and additives, such as softeners and paints). A polymer consisting of more than one monomer is called a *heteropolymer* or *copolymer*.

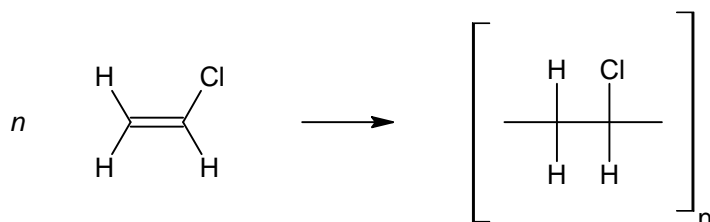
A very common plastic is *polyethene*. The polyethene (PE) polymer is synthesized from the simplest alkene, ethene. There are many different types of polyethene plastics, such as high density polyethene (HDPE) and low density polyethene (LDPE). Polyethene is very frequently used in the modern society, for instance in bottles, pots, plumbing, pipes, plastic films, plastics bags, electrical cable isolation materials and prosthesis. The principal reaction forming PE is shown below.



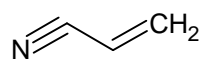
Another very common plastic today is *polypropene*; the polypropene (PP) polymer is synthesized from propene. Polypropene is used in, for instance, packages, boxes, casings, car interior decorations and electrical cables. *Polystyrene* is also a very common plastic and is used in the casing surrounding electrical devices (such as computers, monitors and other computer equipment, TV devices, DVD devices, loudspeakers and other home theatre equipment, remote controls, refrigerators and microwave ovens), packages, boxes, plastic single-use products, toy construction sets, optical media (CD/DVD) cases and cable isolation. The polymerization reaction forming polystyrene is shown below.



Polyvinyl chloride (PVC) is another very important plastic. PVC is mostly used within the construction industry (which uses 70 % of all produced PVC), to window frames, pipes and flooring. Polyvinyl chloride is formed from the vinyl chloride monomer, as shown below.



ABS is a heteropolymer of acrylonitrile, 1,3-butadiene and styrene monomers (thus the acronymic name). ABS is used for pipes, car parts, LEGO bricks (since 1969), casing for consumer electronics, streetlamps and musical instruments.



acrylonitrile

Part 2: Biochemistry

We shall now study the organic compounds building up living organisms. These compounds can be divided into the groups

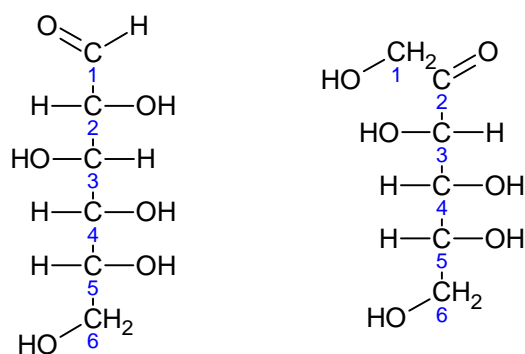
- carbohydrates,
- proteins,
- lipids and
- nucleic acids.

Carbohydrates

Carbohydrates include *monosaccharides* and polymers of such. The name “carbohydrate” is due to the fact that many carbohydrates have the $C(H_2O)$ empirical formula.

Monosaccharides are alcohols with frequently five or six carbon atoms. Their names end with “-ose” and they can be divided into different groups, depending on their chemical structure. Monosaccharides with five carbon atoms are called *pentoses*, whereas monosaccharides with six carbon atoms are called *hexoses*. Furthermore, pentoses and hexoses may be divided in different groups depending on if the molecules contain keto or aldehyde groups. Thus, there are *aldopentoses*, *aldohexoses*, *ketopentoses*, and *ketohexoses*.

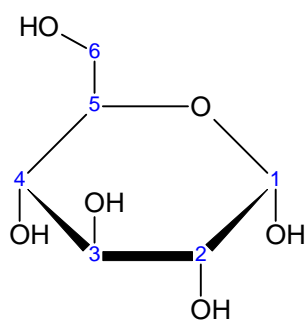
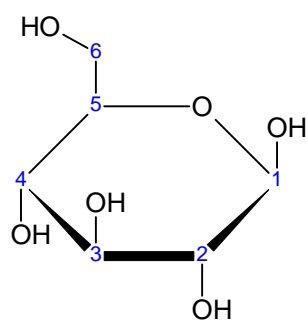
The aldohexose *glucose* and the ketohexose *fructose* are two very common monosaccharides.



D-glucose

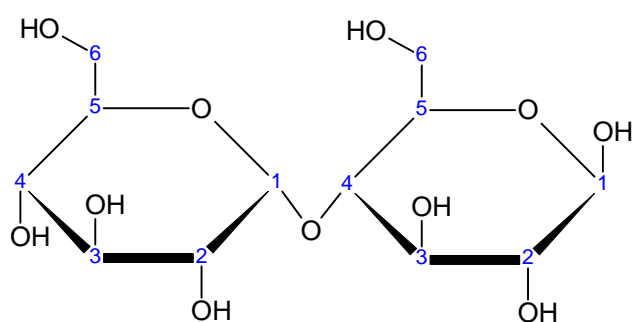
D-fructose

These molecules, however, are most often found in their cyclic forms. We shall now study the two cyclic forms of D-glucose, forming when atoms 1 and 5 are bonded to each other via an ether group: the oxygen atom constituting the ether group comes from the hydroxyl group from carbon atom 5. The hydrogen atom in the hydroxyl group instead forms a bond to the oxygen atom in the aldehyde group at carbon 1, so that a hydroxyl group is created at carbon 1. The two isomeric forms of cyclic D-glucose shown below are called α -D-glucose and β -D-glucose, respectively.

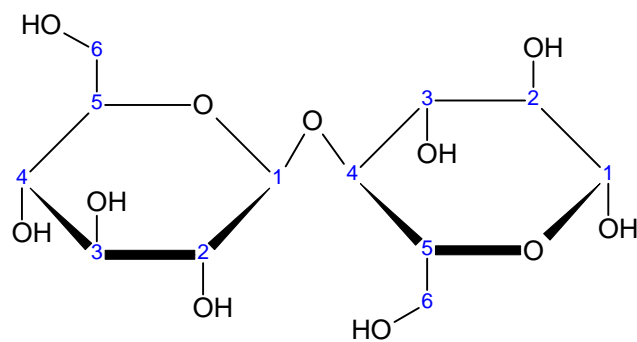
 α -D-glucose β -D-glucose

Glucose is a white solid, always consisting of *either* of the two cyclic isomers. However, the three forms of glucose (the non-cyclic and the two cyclic forms) naturally and continuously transform between each other if the glucose is solved in water; a dynamic equilibrium is reached. In a water solution, approximately 35 % of all glucose is α -D-glucose, 65 % β -D-glucose and just some 0.003 % non-cyclic D-glucose. Glucose is the main energy source of animals, and both glucose and fructose are common molecules in plants.

The condensation product of two monosaccharides is called a *disaccharide*. Two disaccharides that can be formed from two glucose molecules are *maltose* and *cellobiose*; in both cases, carbon atoms 1 and 4 from the glucose fragments are bonded. Concerning maltose, the left glucose fragment is α -glucose, whereas the left glucose fragment in cellobiose is β -glucose. The bond between two monosaccharides is called a *glycosidic bond*; more specifically, one may also specify the carbon atoms at each side of the bond and the isomer of the left glucose fragment (α or β). Accordingly, the bonds between maltose and cellobiose are α -1,4-glycosidic and β -1,4-glycosidic bonds, respectively.



maltose

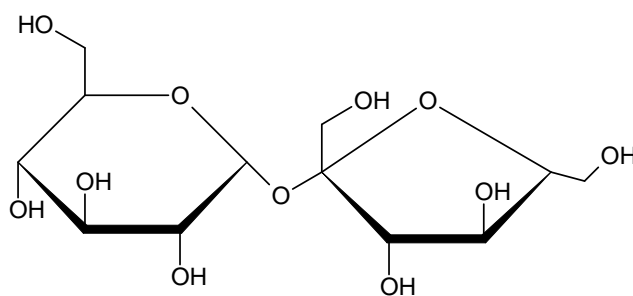


cellobiose

Glucose (in a water solution) is a reducing agent, as the aldehyde group easily can oxidize to a carboxylic group. Carbon atoms 1 in the right glucose fragments of maltose and cellobiose being intact and being able to open and form aldehyde groups, maltose and cellobiose are reducing agents as well.

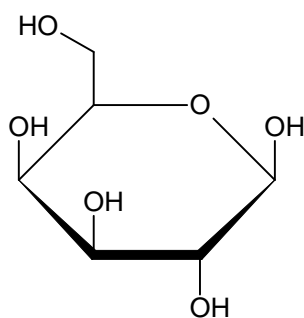
Sucrose (*saccharose* or *table sugar*) is a disaccharide of one glucose fragment and one fructose fragment. Carbon atom 1 from the glucose fragment forms a bond to carbon atom 2 of the fructose fragment; thus, no aldehyde group can form, and sucrose is *not* a reducing agent. Sucrose is a white solid, exceedingly frequently used within the food industry and at meals,

making the food taste sweeter. Having several hydroxyl groups (able to form hydrogen bonds), sucrose is highly water-soluble.



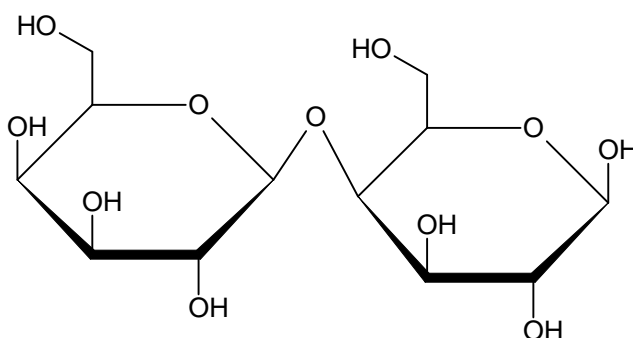
sucrose

Another very important monosaccharide is galactose, an aldohexose. Galactose occurs chiefly in dairy product. Studying the structural formula below, we realize that galactose is an enantiomer of glucose.



galactose

Lactose is a disaccharide consisting of one glucose fragment and one galactose fragment. Lactose occurs mainly in milk; thus the name (Latin: lac=milk). The mass percentage of lactose is 6-7 % in human breast milk and 4-5 % in cow milk. Lactose is also used as filling substance in drugs.



lactose

More than two monosaccharides can be bonded, forming an *oligosaccharide*. If several monosaccharides are bonded, a *polysaccharide* is formed; hundreds or even thousands of monosaccharide fragments can be bonded.

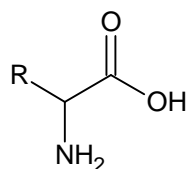
The polysaccharide *starch* is made up of two polysaccharides *amylose* and *amylopectin*. Amylose is a straight chain of glucose fragments connected via α -1,4-glycosidic bonds. As a consequence, the amylose molecule is curved, prohibiting starch from forming long fibres; instead, starch forms small particles. Amylopectin is a branched chain of glucose fragments; almost at every 30th fragment, a branch sticks out. When starch is being broken down, for instance during human digestion, maltose is formed, which later is broken down to glucose. Starch is the most common carbohydrate in human food, making it the most important human source of energy. Starch is found in bread, potato, pasta and rice. Starch is also synthesized by plants, using it as an energy store. Starch is insoluble in water, and also used within the paper- and textile industries.

Glycogen is another polysaccharide, similar in structure to the amylopectin molecule, but the branches protrude at every 10th glucose fragment. Glycogen constitutes the chemical energy store in animals; having more glucose available than necessary, the human body can convert glucose molecules into glycogen, later on being able to convert the glycogen back into glucose. In human beings, glycogen is stored in skeletal muscles and in the liver (approx. 10 % of the liver's mass is due to glycogen).

Being the major component of the primary cell wall of green plants, the polysaccharide *cellulose* is the most abundant organic compound on earth. (Actually, it is fair to say, that plants primarily are made up of cellulose.) Cellulose is built up of glucose fragments bond with β -1,4-glycosidic bonds, making the polysaccharide fibrous. Sometimes, cellulose is referred to as simply "fibre". The human gastrointestinal tract, however, is unable to break down the bonds of cellulose, making the human body unable to obtain any energy from it. Furthermore, cellulose is the main component of paper.

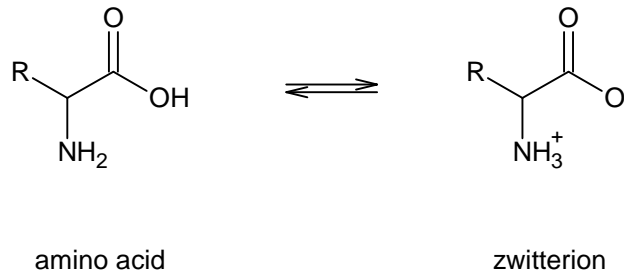
Amino acids

An amino acid is an organic compound containing both a carboxylic group and an amino group. The amino acids being of highest biochemical interest are the α amino acids, having the general formula shown below.



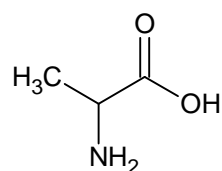
α amino acid

A water solution of an amino acid contains quite few amino acids not having reacted either as acids or as bases; instead, most amino acids are zwitterions, forming when the carboxyl group has reacted as an acid *and* the amino group has reacted as a base, according to the following formula.

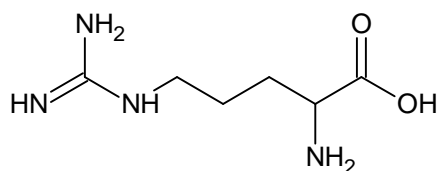


There are also electrically charged forms of amino acids, having only one of the two functional groups charged; the dominant form of an amino acid in a solution is both a function of the amino acid itself, and the current pH.

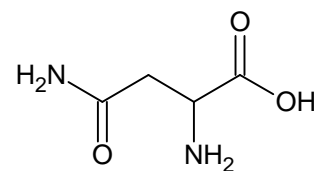
20 amino acids are necessary in the human body. Amino acids necessary for life, but not being bodily synthesisable, are called *essential amino acids* and must be included in (the every day) food. The essential amino acids are coloured red in the table on the next page.



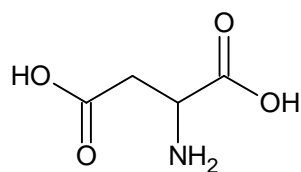
Alanine (Ala, A)



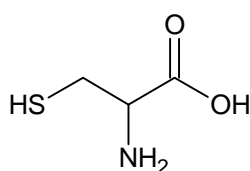
Arginine (Arg, R)



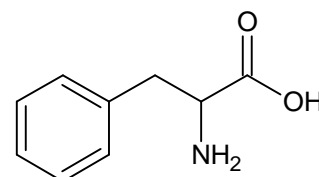
Asparagine (Asn, N)



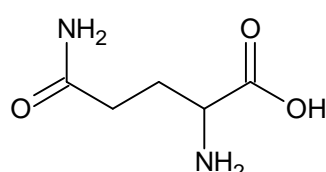
Aspartic acid (Asp, D)



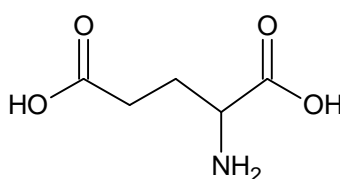
Cysteine (Cys, C)



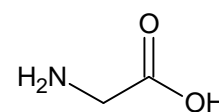
Phenylalanine (Phe, F)



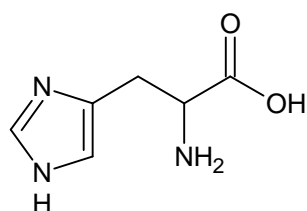
Glutamine (Gln, Q)



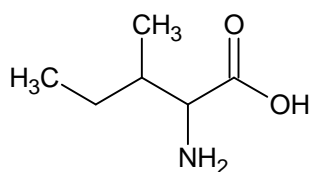
Glutamic acid (Glu, E)



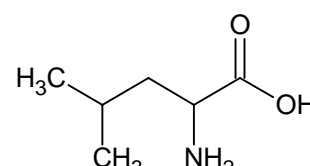
Glycine (Gly, G)



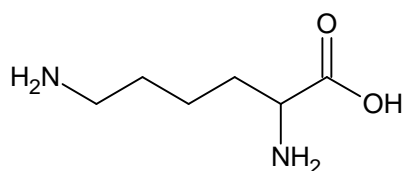
Histidine (His, H)



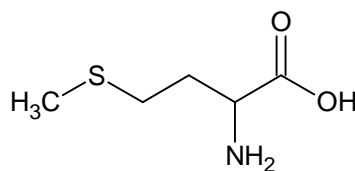
Isoleucine (Ile, I)



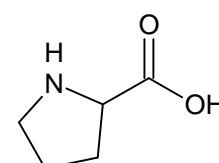
Leucine (Leu, L)



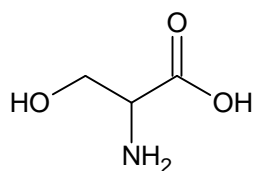
Lysine (Lys, K)



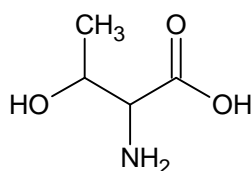
Methionine (Met, M)



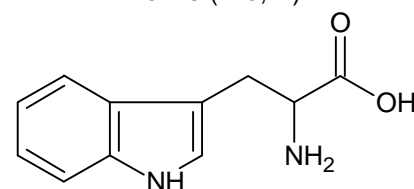
Proline (Pro, P)



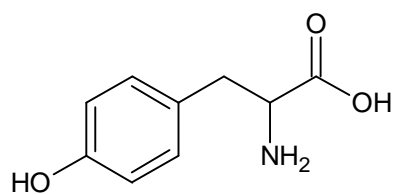
Serine (Ser, S)



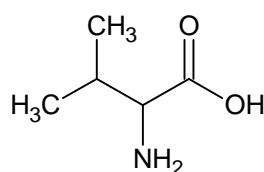
Threonine (Thr, T)



Tryptophan (Trp, W)



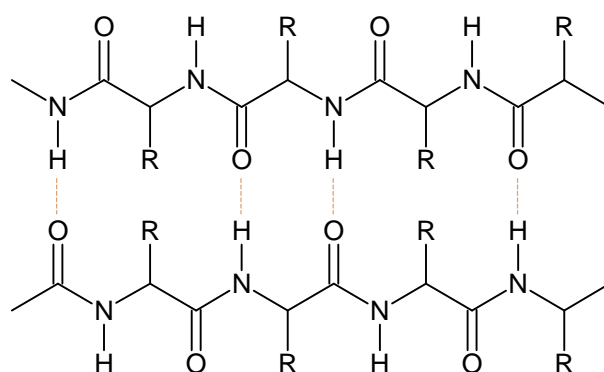
Tyrosine (Tyr, Y)



Valine (Val, V)

The 20 amino acids necessary in the human being: structural formulas, names and codes.

Essential amino acids are coloured red.

 β sheets

The (fibrous) connective tissue in a human being contains water and fibrous proteins; the most important proteins here are *collagen* and *elastin*. Skin, gastrointestinal mucous membranes, tendons, ligaments and the tissues surrounding internal organs and muscles exemplify fibrous connective tissues. Collagen constitutes approximately one third of all protein mass of an adult; all-in-all, there are some 25 types of collagens. Elastin, the other major protein, makes the tissues elastic. Cartilage tissue consists of collagen and elastin. Containing additional elastin, elastic cartilage is found in the epiglottis and the inner ear. Containing additional collagen, fibrous cartilage is for instance found in the temporomandibular (jaw) joints.

Skin consists of two layers, one thin, outer layer (epidermis, 0.05-1mm)⁸ and one inner layer (dermis, 0.5-3 mm). Epidermis is divided into several minor layers (outermost to innermost): *Stratum corneum* (“the horny layer”), *Stratum lucidum*, *Stratum granulosum*, *Stratum spinosum* and *Stratum germinativum/basale*. Normally, the innermost layer consists of a layer of special cells, *keratinocytes* that are constantly undergoing cell division. These cells move out and replace the old cells in the outer layers. When the cells have reached *stratum spinosum*, the fibrous protein *keratin* is formed within the cells. The keratin stabilizes the cells, and the keratin skeleton in near-by cells form bonds to each other, forming a stable structure throughout the layer. In *Stratum lucidum*, most cells have died (due to lack of energy and nutrition; there are no blood vessels in epidermis – nutrition diffuses here from dermis). The final destination of the cells is the outermost layer. The cells contain keratin (almost 50 % of their mass), making the skin hard and preventing it from drying out. Epidermis also protects the body from pathogens and alien chemicals. The journey of the cells, from the moment they are formed to the moment they are torn away from the skin, occupies somewhat more than a month.

Mainly, dermis is build up of fibrous connecting tissue and contains blood vessels, nerve endings associated with the senses of touch and heat, sweat glands and hair follicles. The connecting tissue is made of collagen (90 %) elastin (5 %) and liquids. The fibres are produced by the cells located as “isles” in the matrix (main substance). Chiefly, it is the skin’s content of elastin that allows the skin to regain its original state after being dragged or pushed on.

Muscles are made of the fibrous proteins *actin* and *myosin*, which also are responsible for the contraction of the muscle cells. The human skeleton is composed of inorganic calcium phosphate, although some organic material, chiefly collagen, occurs as well. Moreover, elastic

⁸ The thickness of epidermis varies throughout the body; the layer is very thin on the eyelids and quite thick on the sole of the foot. Mainly, it is the outermost layer of the epidermis that varies in thickness.

blood vessels are composed of elastin, the hardness of nails comes from keratin and hair is 90 % composed of α -keratin and 10 % water.

Globular proteins

Globular proteins are often approximately spherical proteins, controlling chemical processes in the body. Most chemical reactions in the body are catalyzed by enzymes (biocatalysts), which (usually) are proteins. Moreover, antibodies, binding to and neutralizing hazardous micro-organisms are proteins. Neurotransmitters and hormones, sending information between different parts of the body (via the nervous system or the circulatory system, respective), are often proteins. All cell receptors that receive information (e.g. from neurons and hormones) are proteins. In addition, proteins also transport other substances in blood vessels, by forming bonds to them, offering them a hydrophilic “freighter”. Globular proteins are often folded in such a way, that their inside becomes chiefly hydrophobic whereas their outside becomes chiefly hydrophilic; this makes most globular proteins water-soluble.

The structure of a globular protein can be described using four properties or “levels of structure”. The primary structure describes the sequence of amino acids of the peptide chain(s). The secondary structure describes how different parts of the chain(s) are shaped in three-dimensional space: as α helices or β sheets (by hydrogen bonds). The tertiary structure describes the shape of the entire chain(s), mostly due to weak forces and the hydrophobic effect. Finally, the quaternary structure describes the shape of the entire protein molecule (consisting of multiple subunits having their own chains). We shall now study some very well-known globular proteins that exist in the human body.

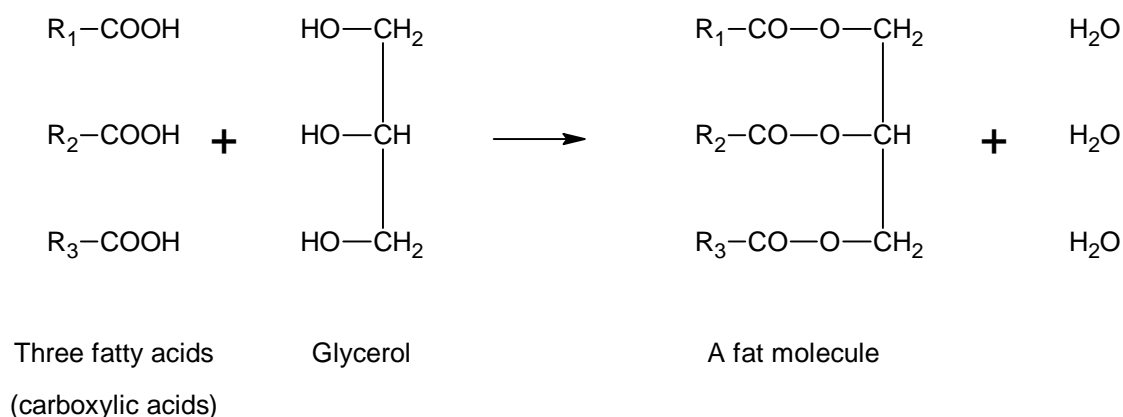
Haemoglobin (Hb) is a globular protein in the erythrocytes (red blood cells) which transport oxygen in the blood, from the pulmonary alveoli of the lungs to the oxygen requiring tissues of the body (such as the muscles). Even though the major part of the carbon dioxide produced in the body are transported to the lungs directly solved in the blood (as hydrogen carbonate ions), a small fraction is transported bonded to haemoglobin. Usually, the haemoglobin molecule consists of four subunits (polypeptide chains) bonded to each other. The subunits contain parts of α structure. Furthermore, every subunit contains another, non-protein molecule, the *haem prosthetic group*. In the centre of every haem group, there is an iron atom, which bonds to the oxygen. Thus, a haemoglobin molecule can bind four oxygen molecules. The carbon monoxide (CO) molecule, however, is able to form even stronger bonds to haemoglobin than oxygen, making inhalation of carbon monoxide lethal due to “internal asphyxia”. Another very important transportation protein is *albumin*, transporting hydrophobic substances, chiefly fatty acids and steroid hormones in the blood.

Myoglobin is also a globular protein – a storage protein. Myoglobin consists of only one polypeptide chain and this contains, as with the chains of haemoglobin, a haem group. Myoglobin is present in muscles and is used to store oxygen. Mainly, the red colour of meat comes from myoglobin.

Lipids

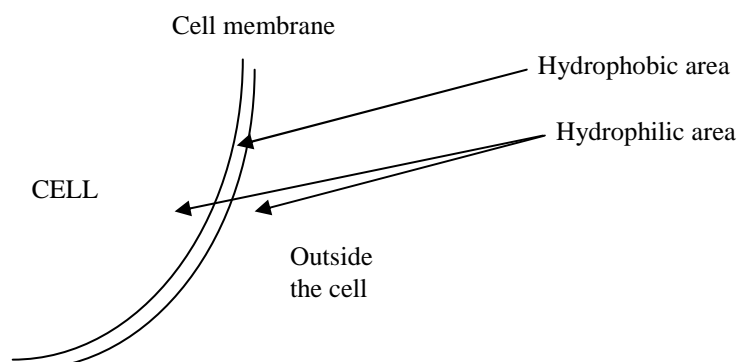
Lipids are organic compounds that are insoluble in water⁹ due to their not being polar. Particularly, all fats are lipids. A fat molecule is a triester of the alcohol glycerol (propanetriol) and three carboxylic acids, often high-molecular ones (16-18 carbon atoms), which in this position are referred to as fatty acids. Thus, fats are triglycerides. The general formula showing the formation of a fat molecule is shown below.

⁹ There is no perfect definition of a lipid, but the one used here is quite describing.



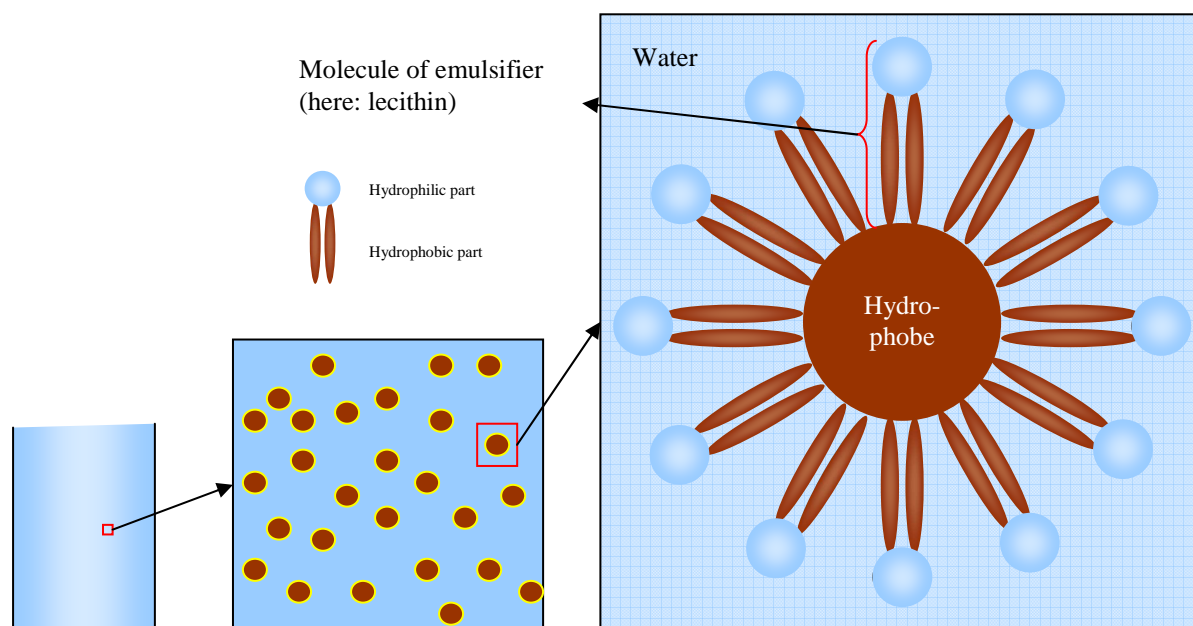
Usually, fats are solids or liquids and are said to be saturated or unsaturated depending on the number of double and triple bonds of the fatty acids; in general, saturated fats are solids, whereas unsaturated fats are liquids (at room temperature). Humans are able to obtain energy from fat in food and fats are also a “storage form” of chemical energy; this is appropriate, as the value of useable energy per unit of mass of fats is approximately twice as high as the corresponding value of carbohydrates. The subdermal fat also serves as a thermal insulation. Moreover, body fat has a shock absorbing effect, protecting the internal organs from damage. Some life-essential fatty acids, belonging to the ω -3 and ω -6 groups, cannot be produced by the human body; these *essential fatty acids* must be included in food. ω -3 fatty acids can be found in some fishes. In addition, some vitamins, such as vitamin A, D, E and K are fat-soluble, and in order for the body to utilize these vitamins, one should also make sure to eat food rich in fats.

A triglyceride of *two* fatty acids *and one phosphoric acid*, which is also bond to a (often nitrogenous) alcohol, is called a *phospholipid*. A typical group of phospholipids is the one containing the nitrogenous alcohol *choline*. These molecules are called *lecithins* and may be found in egg and can be obtained from soy oil. Phospholipids have one hydrophilic (water-soluble) end (at the alcohol) and one hydrophobic (water-insoluble) end. Being the building blocks of cell membranes, phospholipids are very biologically common molecules. The membranes are designed as a dual layer of phospholipids; the hydrophobic ends are turned to each other, to the inside of the two layers, whereas the hydrophilic ends are turned to the cell and out to the intercellular medium.

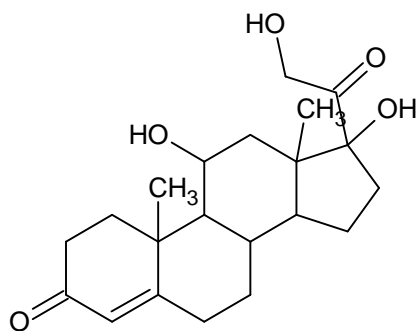


However, there is a way on which a hydrophobic compound actually can be homogeneously mixed with a hydrophilic one (e.g. water). Such a compound is called an *emulsion*, and is possible because the areas of the hydrophobic molecules are surrounded by molecules that – as phospholipids – both have a hydrophobic and a hydrophilic end. The hydrophobic ends are turned to the hydrophobic molecules whereas the hydrophilic ends are turned outwards, to the

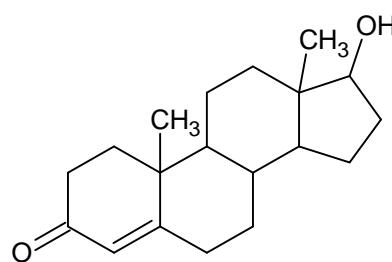
water (for instance). The substance surrounding the hydrophobic molecules is called an *emulsifier*. A common example of an emulsion is *milk*, an aquatic solution containing fats. Often, lecithins are industrially used (e.g. within the food industry) as emulsifiers. A hydrophobic-in-water emulsion is shown below.



Steroids are lipids sharing the basic structure of four connected carbon rings; today, hundreds of steroids have been found in living plants and animals. Their major biological role might be as hormones, so-called *steroid hormones*. Among these, *cortisol* and other corticosteroids from the adrenal cortex and “sex hormones” (gonadal steroids) such as testosterone can be named.

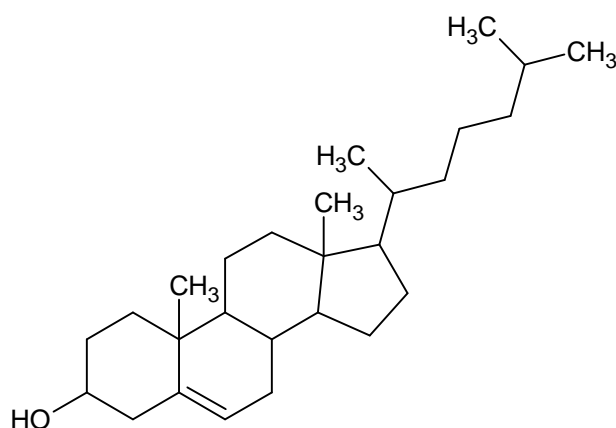


cortisol



testosterone

Being a key stabilizing component in cell membranes, *cholesterol* is a biologically very important steroid. Moreover, cholesterol is the precursor for steroid hormones during the body's own synthesis.

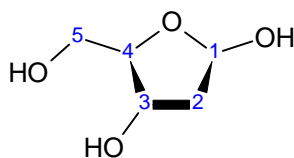


cholesterol

Nucleic acids

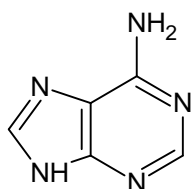
Nucleic acids constitute the *genes*, i.e. the information describing how the organism is to look and function. We shall now only quite quickly study nucleic acids.

There are two main types of nucleic acids, *deoxyribonucleic acid* (DNA) and *ribonucleic acid* (RNA). DNA is the nucleic acid being present in all cell nuclei in a human being. All DNA molecules in a particular individual are identical to each other, but they differ between different individuals (that are not identical (one-egg) twins). The DNA molecule is built as a double helix; one can think of the DNA molecule as two long chains (strings) with bars between them – and this “rope ladder” is twisted, forming a double helix. Every chain in DNA consists of every two fragment sugar and phosphate group; the sugar is always the monosaccharide *deoxyribose*, an aldopentose.

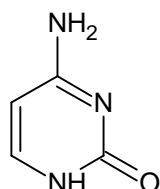


deoxyribose

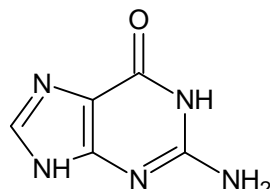
The bars between the chains are made up of pairs of *nitrogenous bases*, bond to every deoxyribose fragment. DNA uses the four nitrogenous bases *adenine*, *cytosine*, *guanine* and *thymine*, often abbreviated A, C, G and T, respectively.



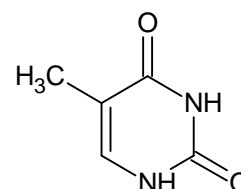
adenine



cytosine



guanine

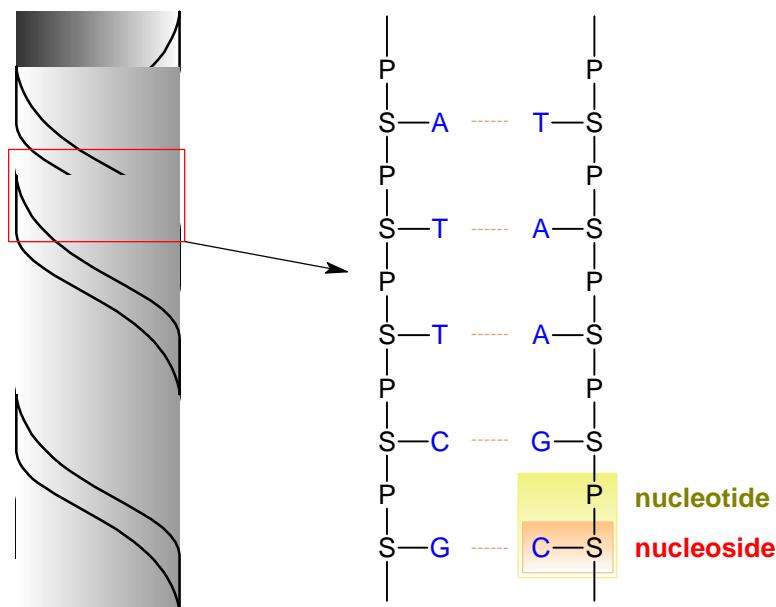


thymine

The two surrounding phosphate groups of a deoxyribose fragment in a DNA string are bonded to carbon atoms 3 and 5 in the deoxyribose fragment, whereas the nitrogenous base is bonded to carbon atom 1. The “bars” between the two chains are always consisting of either the A-T

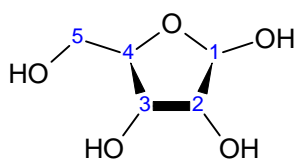
or the C-G pair of bases, making all bars having the same width (three rings). In a pair of nitrogenous bases, a single base belongs to only one of the two chains.

A typical DNA segment is shown below. P represents a phosphate group and S a deoxyribose fragment. A, T, G and C are nitrogenous bases.

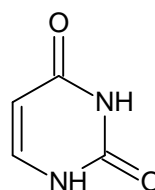


Every sugar-base segment is called a *nucleoside* and every phosphate-sugar-base segment is called a *nucleotide*. Thus, a nucleotide is a nucleoside and a phosphate group, and a complete DNA molecule can be considered a polynucleotide. In a nucleotide, the nitrogenous base, the deoxyribose fragment and the phosphate group are covalently bond to each other. The two strings of a DNA molecule are – via their nitrogenous bases – bond to each other by hydrogen bonds.

RNA resembles DNA, but consists of only one string, contains the monosaccharide *ribose* instead of *deoxyribose* and the nitrogenous base *uracil* instead of thymine.



ribose



uracil

In human cells, new proteins are constantly produced, and DNA constitutes the “recipe” of the proteins. A fragment of a DNA molecule, consisting of some thousand nitrogenous bases, is called a *gene* if it contains information about the *amino acid sequence* of a certain protein; every sequence of three nitrogenous bases codes for a certain amino acid, and the amino acids of the protein will get exactly the order of these base triplets in the DNA. Every DNA molecule consists of thousands of such genes. The human being’s being controlled by proteins, and DNA being the “recipe” of the proteins, one can say that DNA controls exactly how a human will look like and function. When a protein is to be synthesized, the base sequence in the appropriate gene is copied to a certain form of RNA; the RNA molecule leaves the cell nucleus and moves to one of the *ribosomes* of the cell. (A ribosome is a cell organelle producing pro-

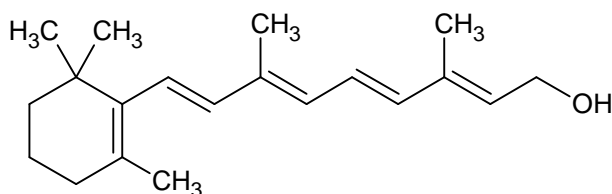
teins.) The ribosome synthesizes a new protein molecule with the amino acid sequence described by the sequences of the RNA bases.

Vitamins

We are now to study a group of molecules called *vitamins*. In contrast to the groups of chemicals we have seen this far, vitamins constitute a very heterogeneous group, containing molecules sharing very few similarities. Organic molecules that must be part of food, as they are needed for individual processes in the body, but really cannot be sorted into any of the previous categories, are called “vitamins”¹⁰. If one does not get sufficient amounts of a vitamin, in general, a deficiency disease specific to that vitamin will develop. Of course, vitamins have rational chemical names, but also designations *as vitamins*. We are now to study some of the most important vitamins.

Vitamin A

A fat-soluble vitamin, *retinol* is designated vitamin A. Retinol is not always directly available in food; instead retinyl esters (e.g. in egg and milk) are intaken, which later on in the human body are converted to retinol; carrots and spinach contains *carotene*, which also may be converted. Carotene is an orange pigment, for instance colouring carrots. Retinol is used in the body to produce *retinal* used in the *retina* of the eye (thus its name). Retinal is crucial for human night vision; lack of vitamin A may imply night blindness. Severe lack of vitamin A, predominantly occurring in developing countries, might even result in permanent (total) blindness.



retinol

B vitamins

There are eight human vitamins referred to as B vitamins; all of them are water-soluble. The table below shows their names.

Designation	Chemical name
B ₁	Thiamine
B ₂ (G)	Riboflavin
B ₃	Niacin
B ₅	Pantothenic acid
B ₆	Pyridoxine
B ₇ (H)	Biotin
B ₉	Folic acid
B ₁₂	Cobalamin

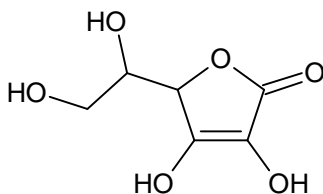
Table 8 B vitamins

¹⁰ The word “vitamin” comes from “vital amines”; when the “vitamin” concept was coined (1912), it was thought that all vitamins were chemical amines, which was shown to be a false presumption.

We are very briefly to study the roles of the B vitamins inside the human body. *Thiamine* is an important coenzyme during metabolism of carbohydrates. *Riboflavin* (which has a yellowish green colour and is used within the pharmaceutical and food industries as a colouring agent) is used by the body for metabolic processes. *Niacin* may give the derivative NAD^+ , a very important metabolic molecule. *Pantothenic acid* is a component of coenzyme A.¹¹ *Pyridoxine* is used for synthesis of erythrocytes. *Folic acid* has several important functions in the body, for instance concerning production of new cells. *Cobalamin* is a very complex molecule (to be a vitamin) and is used in the synthesis of erythrocytes.

Vitamin C

Vitamin C, or *ascorbic acid*, is a water-soluble vitamin and a common antioxidant. The corresponding anion of the acid is called *ascorbate ion*. Most animals – but not humans – are able to produce ascorbic acid in the body, and thus, for them, ascorbic acid is not a “true” vitamin. For instance, vitamin C is used for production of collagen in connective tissues and for synthesis of some hormones. A deficiency of vitamin C leads to a condition called *scurvy*, characterized by superficial bleedings (skin and gingiva), deteriorative healing from wounds and periodontitis. There have also been speculations about whether excessive doses of ascorbic acid during a common cold might accelerate the healing from it.



ascorbic acid

D vitamins

D vitamins are a group of steroids, e.g. *ergocalciferol* (D_2) and *cholecalciferol* (D_3). Vitamin D_3 , the human natural form of the vitamin, is actually produced from cholesterol by the skin when affected by ultraviolet radiation. D_3 is a hormone; it is not active, but it might be converted by the liver to *calcidiol*, 25-hydroxyl-cholecalciferol. Calcidiol is then converted by the kidneys to *calcitriol*, 1,25-dihydroxyl-cholecalciferol. Calcitriol increase the intestine and the kidney absorption of calcium and phosphate, and stimulates the growth of bone matrix. Vitamin D deficiency might lead to *osteomalacia* (instable skeleton) and *osteoporosis*.

Other vitamins

Vitamin E, or *tocopherol*, is a fat-soluble vitamin and an important antioxidant. Vitamin E is also believed to accelerate healing from wounds, and is therefore used in pharmaceutical creams. K vitamins are required for proper coagulation (clotting) of blood.

Dietary minerals

Chemical elements (other than carbon, hydrogen, oxygen and nitrogen) that must be included in food in order for the body to function properly are called *dietary minerals*¹². Thus, minerals are very simple, *inorganic* compounds. These might be intaken as atoms or in salts. Calcium, chloride, magnesium, phosphor, potassium, sodium and sulphur should be intaken in quite high doses, whereas chromium, cobalt, copper, fluorine, iodine, iron, manganese, molybde-

¹¹ NAD^+ and coenzyme A will be discussed in the catabolism chapter.

¹² Compare with *geological* minerals

num, selenium and zinc are only required in quite low doses (< 200 mg/day). There are also theories about use of other elements, such as silicon and nickel, in the body.

Calcium plays an important role for many organisms, e.g. for development of bone matrix and teeth; an overdose of calcium might however result in kidney stones. Dairy products are a major food source of calcium. Phosphorus atoms are included in DNA, ATP, phospholipids and in bone matrix (as calcium phosphate). Iodine is used in the thyroid hormones and iron is used in haem groups (e.g. in haemoglobin and myoglobin).

Part 3: Physiological processes

We shall now study some important physiological processes taking place in the human body, particularly digestion and catabolism, i.e. how the chemical compounds of the food are used by the body to obtain energy and synthesis new body structures (for growth of children or to replace old structures in adults).

Digestion

The food we eat consists of carbohydrates, proteins, fats, vitamins, dietary minerals, water and minor amounts of other compounds. We eat to obtain energy, which is possible from the first three groups of compounds – for instance, we need to be able to obtain kinetic energy in our muscles, thermal energy in the entire body, electric energy in the nervous system and energy to the synthesis of new chemical compounds. We also eat to get the molecular building blocks used by the body for that synthesis. However, in order to obtain energy and these building-blocks from the food, the molecules of the food must be broken down – or slit apart to their small building blocks; proteins are broken down to amino acids, carbohydrates to monosaccharides (e.g. glucose) and fats to glycerol and fatty acids. The digestion is begun as soon as the food is laid in one's mouth. After the digestion is completed, the useful molecules are absorbed by the circulatory and lymphatic systems from the intestines; the remains of the food are excreted mainly via urethra and anus. This entire process is called *digestion* and is performed in the *gastrointestinal tract*, extending between mouth and anus. Thus, the gastrointestinal tract may be considered to be part of the *outside* of the organism.

We can separate between mechanical and chemical digestion. Throughout the entire gastrointestinal tract, there are muscular contractions, the so-called *peristalsis*, “pushing” the food in the right direction and also (macroscopically) splitting it apart. The chewing of food together with the peristalsis constitutes the mechanical digestion. The enzymes (biocatalysts) in the gastrointestinal tract, chemically splitting molecules apart, constitute the chemical digestion. We are now to study the mechanical and chemical digestion taking place in the different parts of the gastrointestinal tract.

The food enters the tract via the mouth, where it is chewed by the teeth. The saliva in the mouth, excreted by six salivary glands, contains an enzyme called *amylase*, splitting starch to maltose molecules. After being swallowed, the food “glides” down to the *stomach* (via its topmost opening, the *cardia*). Even if one is standing upside-down, the food will reach the stomach thanks to the peristalsis, pushing the food in the direction towards the stomach. The amylase continues to function in the stomach until the pH has fallen below the lower functional limit of the enzyme. In the stomach, pH is very low (approximately 1), protecting from pathogens¹³. The low pH is an implication of the stomach cells' producing *gastric acid* containing hydrochloric acid, after endocrine secretion of the peptide hormone *gastrin* (which happens instantly after food intake). The gastric acid also contains *pepsinogen*, which later on converts to *pepsin*, splitting proteins into shorter polypeptide chains. In order for the stomach walls (consisting of proteins) not to be affected by the enzyme, they are covered with a mucus rich in hydrogen carbonate. Pepsin works optimally at the low pH of the stomach. The bottommost opening (the ending) of the stomach, the *pylorus*, leads the food to the *duodenum*. Pylorus is opened and closed using *feedback*; it is opened, letting food out from the stomach and into the duodenum, when the pH of the duodenum is increased, and it is closed when the

¹³ However, some pathogens, such as *Helicobacter pylori* (the “peptic ulcer bacterium”), can live in this environment, thanks to its producing neutralizing ammonia. The risk of getting peptic ulcer also increases if one eats (drinks) acetylsalicylic acid or ethanol.

pH is decreased. Because pH is low in the stomach, this makes sure that duodenum is not loaded with more food until the previously loaded food has been properly processed.

The *liver* produces *bile* (*gall*), which is secreted into the duodenum. Additional bile is stored in the *gallbladder* (*cholecyst*), just below the liver. Bile contains *bile salts* (from *bile acids* formed from cholesterol), which act as emulsifiers for the fats of the food (the bile salts has one hydrophobic end and one, negatively charged, hydrophilic end). The motion of the intestine makes the “drops of fats” smaller and smaller. Moreover, these “drops” cannot fuse with each other, because of repulsion due to their all having negatively charged surfaces. Furthermore, the *pancreas* secretes pancreatic juice after endocrine secretion of the peptide hormone *secretin*; the pancreatic juice contains hydrogen carbonate ions increasing pH to about 8. After endocrine secretion of another peptide hormone, *CKK*, pancreas also secretes some important enzymes: *lipase* splits every fat molecule (triglyceride) into one 2-monoglyceride and two free fatty acids, and *trypsinogen* and *chymotrypsinogen* are converted into *trypsin* and *chymotrypsin* (respectively), splitting proteins into shorter polypeptides.

Eventually, duodenum is replaced by the *small intestine*. Here, enzymes such as *maltase* (splits maltose to 2×glucose), *lactase*¹⁴ (splits lactose to glucose and galactose), *sucrase* (splits sucrose to glucose and fructose) and *proteases* (break peptide bonds) are active. The internal walls of the small intestine are filled with *villi* (sing. villus; small hairs) and on the villi, there are microvilli (even smaller hairs), extending the internal wall area from 0.3 m² (without villi) to approximately 200 m². Here, blood capillaries take up glucose, amino acids, smaller fatty acids, and some other nutritional, whereas lymph capillaries take up larger fatty acids (which first form lipoproteins, so-called *chylomicrons*). Molecules absorbed to the circulatory system are transported to the liver via the portal vein, whereas fatty acids absorbed by the lymphatic system are released to the circulatory system via the left subclavian vein.

The remains of the food are transported to *colon*. Here, the last water absorption takes place¹⁵ and symbiotic bacteria produce vitamin K for us; approximately two kilogram of the mass inside colon comes from bacteria as well as 1/3 of the (dry) faeces. The colon bacteria and their possible toxins constitutes a threat to us, only if they are able to come *inside* the body, i.e. into the circulatory system. Normally, the bacteria produce some two litres gas per day, most of which is absorbed by colon. Eventually, the remains of the food reaches *rectum*, ending with two sphincters (one of which is consciously controllable) and a body opening, *anus*. The remains passing through anus are called *faeces*.

The total time occupied by the food's being in the gastrointestinal tract approximately equals four hours.

Absorption phase

The time directly after an intake of food (a meal) is called the *absorption phase*; this is the phase when the digested molecules are utilized. In the liver, all galactose and most of the fructose are converted to glucose, making glucose constitute almost all monosaccharides. Then, glucose is transported via the blood to all body cells, so they at need can “burn” the glucose to obtain useful energy. In fatty tissues, glucose may also be converted into glycerol, which then binds to fatty acids forming fat molecules (triglycerides), constituting energy “stores”. In the liver and in skeletal muscles, the “surplus” of glucose is converted to glycogen for storage. After a high intake of glucose, glucose may also (in the liver) be converted to fatty acids.

¹⁴ Often, humans living outside of Europe do not synthesize lactase as adults, making them intolerant of dairy products; it is likely that adult Europeans' producing lactase is due to a mutation.

¹⁵ If this water absorption does not function properly, one may get *diarrhoea*.

After being absorbed by the lymphatic system as chylomicrons, the triglycerides are transported through the circulatory system and will eventually be located at the body's fatty tissues. The amino acids are transported via the blood to all body cells, using the amino acids for their own synthesis of proteins. Some of the amino acids are used for protein synthesis already in the liver; for instance, the liver produces somewhat more than 10 grams of albumin per day. Amino acids may also be converted to carbohydrates and fatty acids, if a surplus of amino acids is present. When amino acids are converted to carbohydrates, at first, the nitrogen atom of the amino group is removed, forming ammonia (NH₃), a toxic. Thus, as soon as possible, the ammonia is converted to *urea* (*carbamide*, diaminomethanal), which is excreted in the urine. (In fact, urea is a major component of urine, only succeeded by water.)

Post absorption phase

During the period – normally occurring once a day – when the body does not receive any new molecules from the intestinal absorption, the body uses its “energy stores” instead of “fresh” (recently digested) glucose. The liver produces glucose from the glycogen, in order to keep the blood's glucose concentration as stable as possible, even though the blood does not get any “new” glucose from the intestines. In fact, this is necessary because the brain normally cannot use any other source of energy than glucose. In addition, the liver is able to synthesize glucose from (for instance) glycerol; such processes are called *gluconeogeneses*. However, most body cells – for instance muscle cells – will now start to use fats as energy source, not to tear at the now fragile glucose concentration of the blood.

These actions allow a human, well-fed adult to survive as long as two months without eating anything (one must drink water, though). The cause of death at starving might be that the protein stores get so small, that the normal cell processes cannot be upheld anymore.

Hormones play a major role in the metabolism in both phases. At stable availability of glucose (in the absorption phase), pancreas will produce the hormone *insulin*, which increases the cells' intake of glucose, acts towards increased conversion of glucose to glycogen, increased built-up of “fat stores” and decreased gluconeogenesis. In the post absorption phase, when the glucose availability has decreased, pancreas will instead produce *glucagon*. Glucagon acts towards increased fatty metabolism, conversion of glycogen to glucose and gluconeogenesis¹⁶.

Digestion of alcohols

In some cultures, ethanol is used as a beverage, i.e. some kind of relaxing substance, even though ethanol is a toxic and also, temporarily, changes the personality of the drinker. Liquid products such as *beer* and *wine* contain ethanol and are supposed to be drunk. In the body (the stomach and the liver), ethanol is digested to ethanal (acetaldehyde) via the enzyme *alcohol dehydrogenase*¹⁷. Thus, alcohol dehydrogenase occurs naturally in the human body, probably to digest the alcohol that is naturally occurring in (normal) food. Then, the ethanal is converted to ethanoic acid (acetic acid) by the enzyme *acetaldehyde dehydrogenase*; this final product is not severely toxic.

Methanol (wood alcohol) is (to humans) an even more toxic substance than ethanol. Methanol is digested in analogy to how ethanol is digested: first to methanal (formaldehyde; also using

¹⁶ For more information about how insulin and glucagon control the metabolism, see Rejbrand, Andreas. *Endokrinologi – en kort introduction*. Katrineholm 2006.

¹⁷ Sometimes, alcohol dehydrogenase is abbreviated ADH, which also may be an abbreviation for antidiuretic hormone (vasopressin), a hormone stimulating the water absorption in the kidneys.

alcohol dehydrogenase) and then to methanoic acid (formic acid). However, the pure methanol is not toxic; instead, it is its metabolites, methanal and methanoic acid, that are the real toxics. Very small quantities of methanol (perhaps as little as a teaspoonful of it) may destroy the optic nerve, causing blindness. Larger quantities may cause death (100 ml might be sufficient). The cause of death is likely acidosis (decline of blood pH), caused by the formic acid. If an individual has been intoxicated by methanol, then the toxic effects may be reduced by drinking ethanol, because ethanol competes with methanol about the alcohol dehydrogenase, making the toxic metabolites of methanol form more slowly. (Hopefully, no metabolites at all will be formed from the methanol.) Thus, methanol intoxication may be “reduced” to ethanol intoxication.

Quite often, methanol intoxication is caused by humans’ drinking it as if were ethanol; both smell and taste are identical.

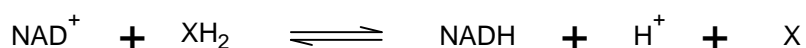
Catabolism of digested molecules

We are now to study what happens with the digested carbohydrates, proteins and fats (the glucose, amino acids and fatty acids, respectively), and how the body is able to utilize the chemical energy of these molecules.

Transportation molecules

Molecules binding to and transporting energy or other particles are called *transportation molecules*. We shall now study some of the most important transportation molecules.

NAD^+ (*Nicotinamide Adenine Dinucleotide*) is a hydrogen transporter. NAD^+ is a dinucleotide with the nitrogenous bases adenine and *nicotinamide*. One NAD^+ molecule can transport one hydrogen atom. The reaction when NAD^+ bonds to one hydrogen atom from an arbitrary compound X is shown below.



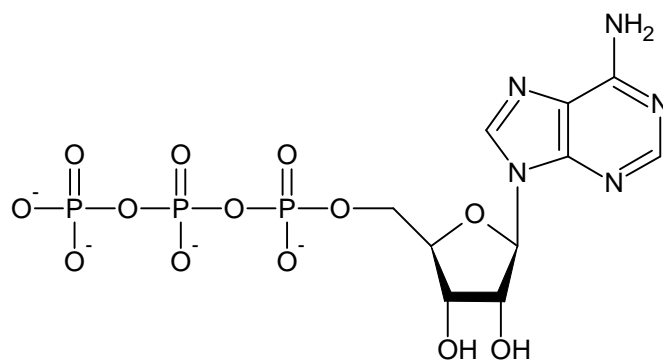
Another important hydrogen transporter is *FAD* (*Flavin Adenine Dinucleotide*), able to transport two hydrogen atoms; the reaction when FAD is “loaded” with two atoms from an arbitrary molecule is shown below.



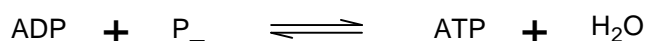
Besides hydrogen atoms, the *acetyl group* CH_3CO- is an important catabolic group. The transporter of acetyl groups is *coenzyme A* (CoA), a thiol. CoA is able to form a *thioester* with the acetyl group.



Moreover, the phosphate group is relevant. The molecules *AMP* (*Adenosine MonoPhosphate*), *ADP* (*Adenosine DiPhosphate*) and *ATP* (*Adenosine TriPhosphate*) are nucleosides with ribose and the nitrogenous base adenine bond to one, two or three phosphate groups, respectively. Thus, ATP – the most “interesting” of these – can be considered to be a phosphate group transporter.



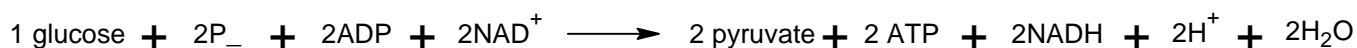
ATP



In the above formula, P_- represents a phosphor group, i.e. HPO_4^{2-} or H_2PO_4^- depending on the cell's pH. The reaction to the right is very endothermic, and the left reaction is (needless to say) exothermic. Thus, ATP is not only a carrier of phosphate groups, but an energy transmitter as well. ATP can be compared to a loaded (charged) battery and ADP to an uncharged battery. ATP is the body's main energy transmitter, and the molecule that the cell uses when it is about to perform an action that requires energy. At rest, a human being uses approximately ten millions of ATP molecules per second. In general, ATP molecules are consumed quite rapidly (within minutes) after their synthesis. Thus, ATP is rather the "last carrier" of energy, than any "long term storage" of it; "storage" of energy is performed by fat and glycogen. As we will see, it is ATP molecules that are synthesized during catabolism of glucose and fatty acids.

Glycolysis

The *glycolysis* is a series of reactions taken place in the cell cytoplasm, converting every molecule of glucose into two *pyruvate* ions (see *Ketone* above). Furthermore, for every glucose molecule, two ATP are loaded from ADP, and two NADH are loaded from NAD^+ . Thus, the net result may be written as below.



Below, a more detailed description of the glycolysis is shown. Please notice, that the molecule fructose-1,6-diphosphate (6 C) is broken down to two molecules, dihydroxyacetonephosphate (3 C) and glyceraldehyde-3-phosphate (3 C). A dynamic equilibrium between these two molecules is formed, and only the later continues to react. But as this process goes on, the equilibrium will be "pushed" to the right, to the reacting molecule, so that (optimally) all dihydroxyacetonephosphate will be converted to glyceraldehyde-3-phosphate. Also observe that the reactions following glyceraldehyde-3-phosphate therefore are performed *twice* for every molecule of glucose.

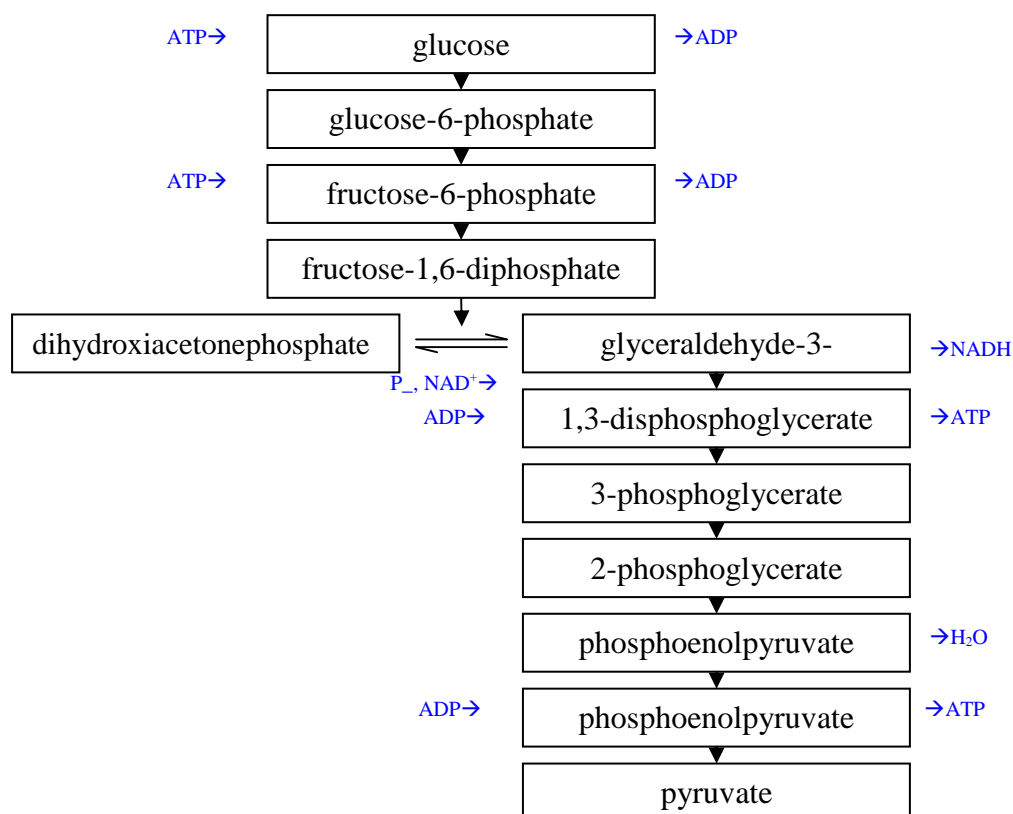


Illustration 1 The Glycolysis

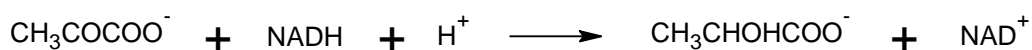
However, in order for the cell to be able to obtain any energy from the pyruvate ions, these must be transported into the cell mitochondria. This transportation requires one ATP per pyruvate ion.

Pyruvate ions are converted to acetyl-CoA

In the mitochondria, pyruvate ions are converted to acetyl-CoA, forming one NADH per ion, according to the following formula.



The cell might easily run out of NAD^+ needed in the glycolysis; if the processes does not propagate at a reasonable rate – e.g. during a lack of oxygen in a muscle cell – NADH may be converted into NAD^+ simply by pyruvate ions' adding hydrogen atoms and forming lactate ions. This results in a temporary pain in the muscle.



Beta oxidation

In the mitochondria, fatty acids are broken down to acetyl-CoA. This process involves several steps; in each step, one acetyl-CoA molecule is produced, as well as one NADH and one FADH_2 . This process has obtained its name from the fact, that one of the main steps in it involves the oxidation of the β carbon of the fatty acid. If a saturated fatty acid with an even number of carbon atoms is oxidized, an fatty acid with n carbon atoms will give $n/2 - 1$ cycles and thus $n/2$ acetyl Co-A, $n/2 - 1$ NADH and $n/2 - 1$ FADH_2 . Below, a more detailed descrip-

tion is given. The fact that n carbon atoms, resulting in $n/2$ acetyl-CoA, only requires $n/2 - 1$ cycles is due to the fact that $R = H$ after the last cycle; thus, then we instantly obtain *two* acetyl-CoA molecules.

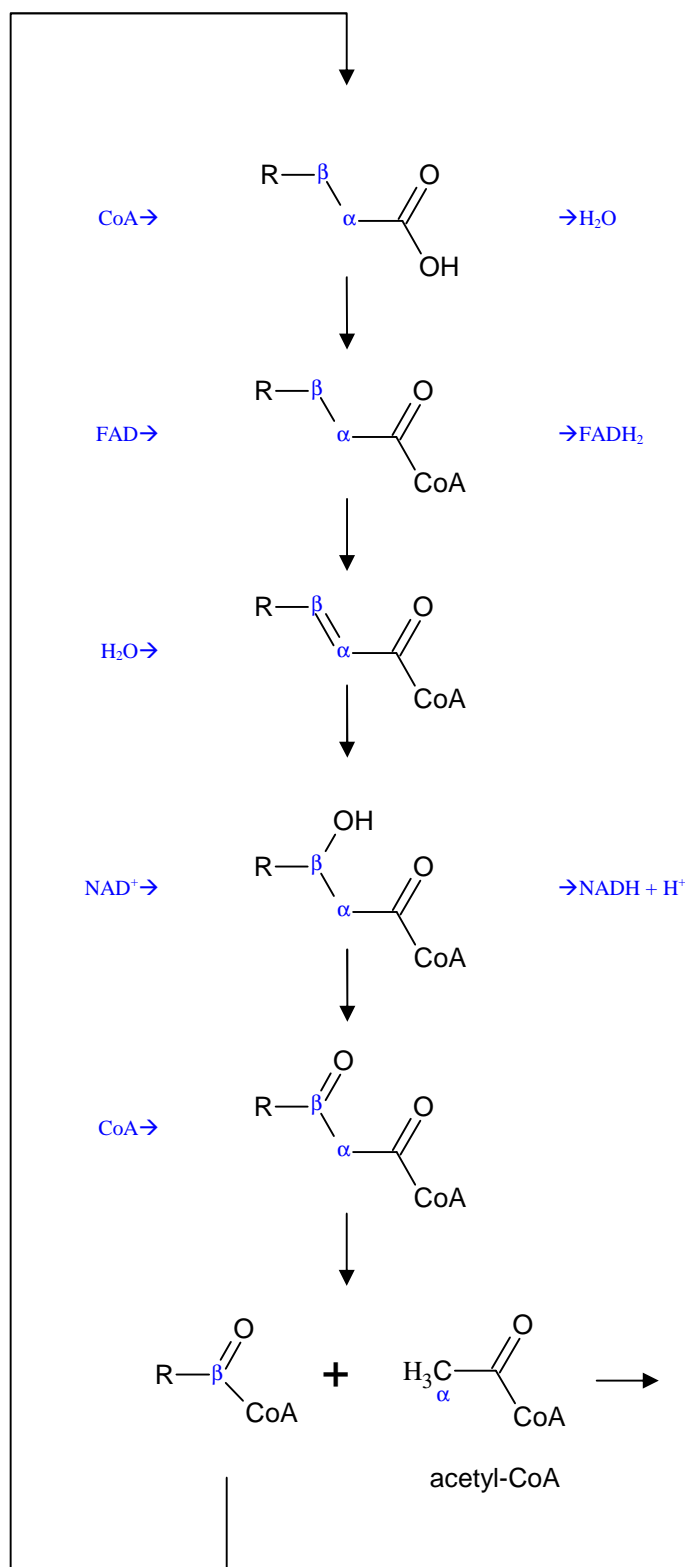
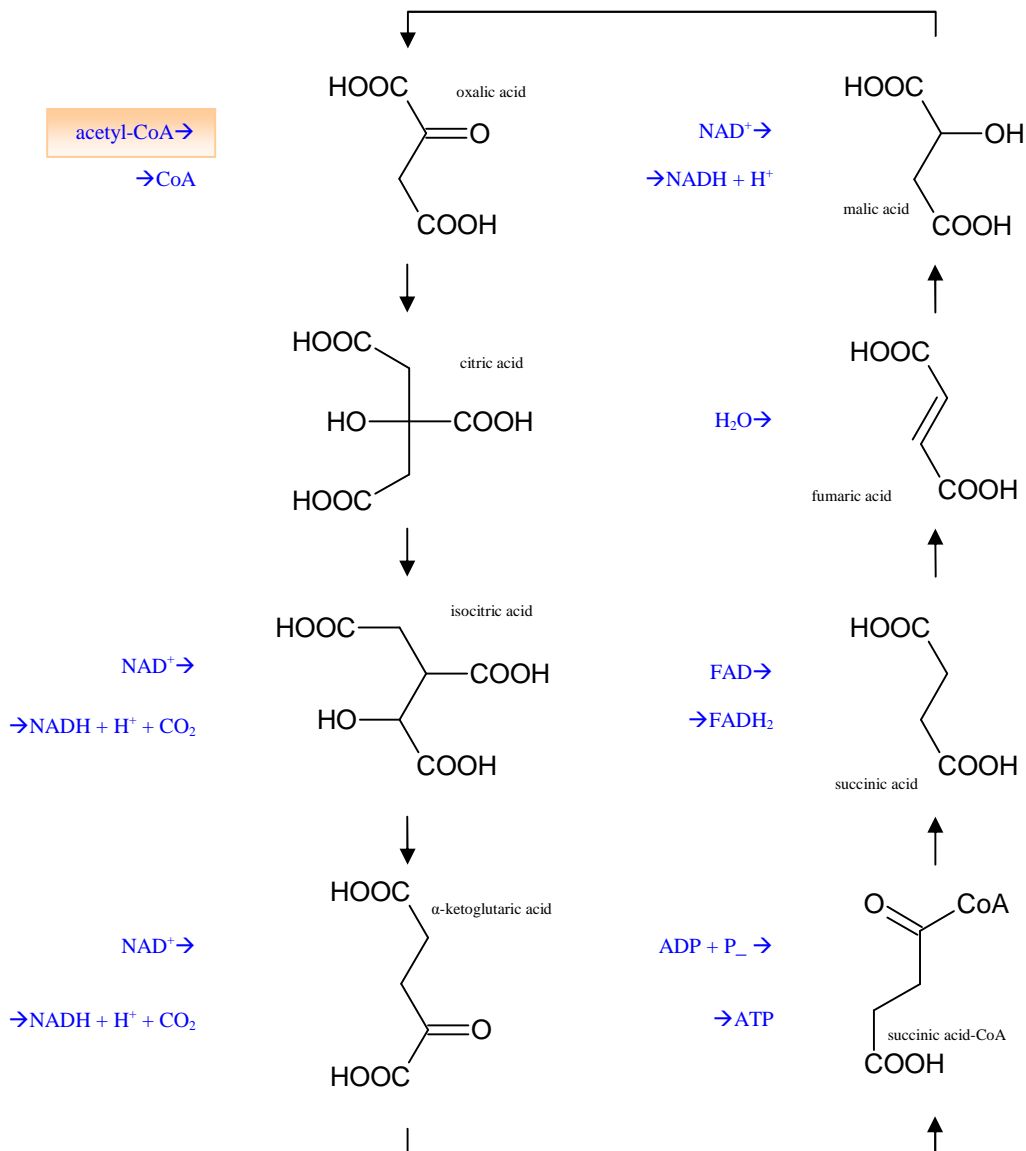


Illustration 2 The Beta oxidation

Citric acid cycle

One of the most central processes in catabolism is the *citric acid cycle*. This cycle begins with the combination (in a 1:1 proportion) of oxalic acid (4 C) and acetyl-CoA originating from pyruvate ions and fatty acids, forming citric acid (6 C). Later, during a series of reactions, two carbon atoms will escape from the cycle in the shape of two molecules of carbon dioxide; the CO_2 that a human exhales is believed to largely originate from this very cycle. Eventually, the cycle is back at its original state (oxalic acid), ready to start over. During each cycle – except for the two molecules CO_2 – three NADH, one FADH_2 and one ATP are formed.

**Illustration 3** The citric acid cycle**Cellular respiration**

The final stage in catabolism is the *cellular respiration*, taking place inside of the outer membrane of mitochondria (an organelle having dual membranes). Here, NADH and FADH_2 leave their hydrogen atoms; these atoms are oxidized to water with oxygen from the lungs. The energy released is used to “charge” ATP molecules. One NADH results in three ATP, whereas one FADH_2 results in two ATP.

Final words

In this document, we have studied the chemical compounds that can be formed from hydrocarbons; we have realized that these compounds build up all plants and animals in the earth's biosphere and also that many modern materials consist of these molecules.

Concerning the human physiology, we have presented several models, and these models are – of course – meant to reflect reality. However, in an every-day environment, it may be difficult to study e.g. the glycolysis, beta oxidation, citric acid cycle and the respiration; moreover, biochemical structures and processes are often quite complex. For the most part, however, the contents of this document are correct, but some details in the current knowledge may very well be reviewed in the future. Should you – the reader of this document – find any error in this document, you are more than welcome to send your comments to the author via email at andreas@rejbrand.se. Also notice, that this document is an English translation of the original Swedish version. Should you find any incorrect use of the English language, I would appreciate if you did inform me about it (using my address shown above). Thank you.

Finally, the author want to deduce the conclusion that the organic chemistry and biochemistry are very interesting fields, describing the human being and the nature, as well as the modern society – biochemistry is the “technical documentation” of the biosphere.

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Only minor changes have been implemented during the English translation. The translation was completed 2006-06-22 by Andreas Rejbrand.