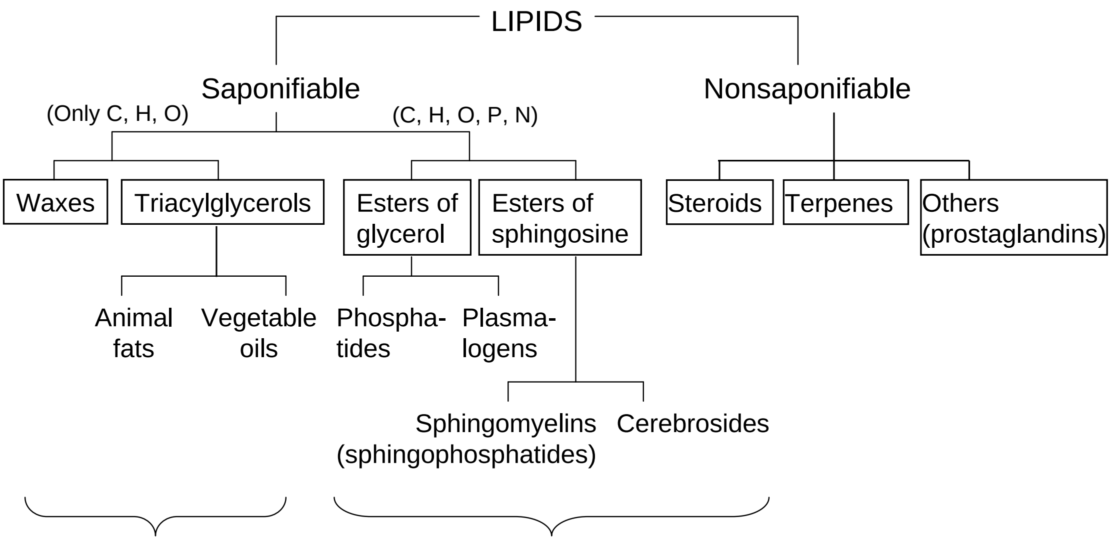
№ 44. LIPIDS – CLASSIFICATION, FATTY ACIDS. SIMPLE LIPIDS. FATS – STRUCTURE AND PROPERTIES.

Characteristics of lipids. **Lipids** are a diverse group of compounds that are broadly defined as any fat-soluble (lipophilic), naturally-occurring molecule, such as fats, oils, waxes, cholesterol, sterols, fat-soluble vitamins (such as vitamins A, D, E and K), monoacylglycerols, diacylglycerols, phospholipids, and others. They can be separated from polar (water soluble) naturally occurring molecules using their solubility in nonpolar solvents such as ether, chloroform, benzene etc. Although the term lipid is sometimes used as a synonym for fats, fats are a subgroup of lipids called triacylglycerols (the old term is triglycerides). Lipids also encompass molecules such as fatty acids and their derivatives (including tri-, di-, and monoacylglycerols and phospholipids), as well as other steroid skeleton-containing metabolites such as cholesterol and bile acids.

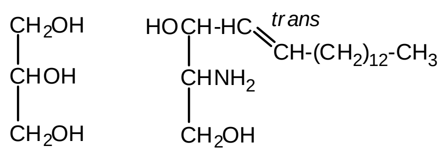
Functions of lipids. The main biological functions of lipids include energy storage, acting as structural components of cell membranes (as phospholipids), and participating as important signaling molecules. Some lipids function as protective coating of cell walls of bacteria, the leaves of higher plants, the cuticle of insects and the skin of vertebrates; some other lipids are starting materials for the synthesis of vitamins, prostaglandins, and hormones.

Classification of lipids Lipids are classified depending on their chemical behaviour towards aqueous base in a hydrolysis reaction into **saponifiable** and **nonsaponifiable** lipids. According to their biosynthesis and function, lipids can be classified also into originating entirely or in part from two distinct types of biochemical subunits or "building blocks": ketoacyl and isoprene groups. Using this approach, lipids may be divided into eight categories: fatty acyls, glycerolipids, glycerophospholipids, sphingolipids, saccharolipids and polyketides (derived from condensation of ketoacyl subunits); and sterol lipids and prenol lipids (derived from condensation of isoprene subunits).



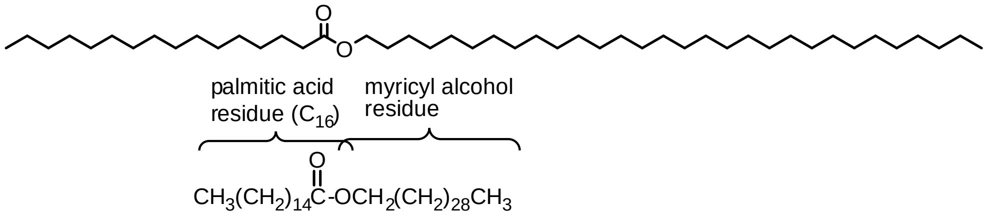
Lipids that are not hydrolyzed by a base are called **nonsaponifiable** lipids. They include steroids which have three cyclohexane and one cyclopentane condensed rings. Steroid nucleous is found in the structure of several vitamins, hormones, drugs, poisons, bile acids, and sterols. Terpenes are produced in plants. Prostaglandins are also considered nonsaponifiable lipids. A prostaglandin is any member of a group of lipid compounds that are derived enzymatically from fatty acids and have hormonal (mediating) functions in the animal body.

Lipids that are hydrolyzed by a base are called **saponifiable** lipids. When the hydrolysis products are only glycerol and fatty acids, the lipids belong to the class of simple lipids. When the hydrolysis products include besides glycerol and fatty acids also other compounds such as sphingosine, amino alcohol, amino acid, carbohydrate, phosphoric acid etc, they belong to the class of complex lipids.



glycerol sphingosine

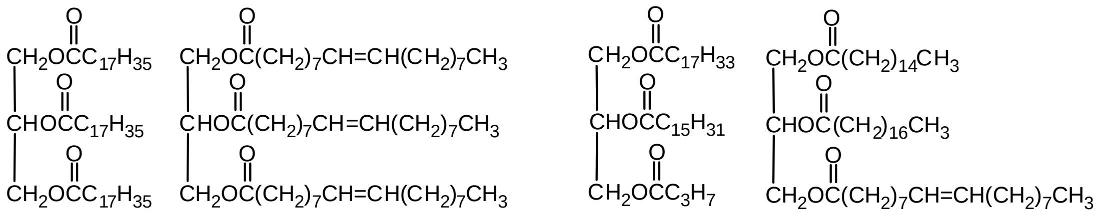
Plant and animal waxes. Waxes are esters of fatty acid (FA with C_{16} or longer) and long-chain alcohol (C_{16} or longer), both containing even number of carbon atoms.



beeswax

For example, beeswax is largely an ester of myricyl alcohol and palmitic acid and is secreted by bees to be used in honeycombs building. Because of their long hydrocarbon chains, waxes are completely insoluble in water and are non-reactive. They are excellent protective and water-repellant coatings on skin, feathers, leaves, and fruits. Carnauba wax coat the leaves of palm tree (component is $C_{25}H_{51}COOC_{30}H_{61}$). Whale oil contains actually a wax - $C_{15}H_{31}COOC_{16}H_{33}$. Natural waxes are used in cosmetics, floor waxes, furniture and car polishes, ointments and crèmes, and waterproof materials.

Triacylglycerols (fats and **oils).** The most abundant lipids are neutral fats, called triacylglycerols. The old name triglycerides has been rejected by UIPAC. The triacylglycerols are esters of glycerol (a triprotic alcohol) with three FA which can be saturated (giving solids, fats) or unsaturated (giving liquids, oils). The FAs can be identical - then the lipids are called simple triacylglycerols, or they can be different - then the lipids are mixed triacylglycerols. These compounds are the main form of fat storage in plants and in adipose tissue cells (fat cells, adipocytes) of animals. Average man's body is 21% fat, enough to supply energy for 2-3 months.



tristearin (solid, in tallow); triolein (liquid, in olive oil) — simple triacylglycerols

oleopalmitobutyrin (in butter); oleopalmitostearin (in lard) — mixed triacylglycerol

Natural fats and oils are mixtures of compounds with varying FA chain length and degree of unsaturation.

All simple lipids are rich in C-H bonds (low degree of oxidation). Therefore, they are good storehouses of chemical energy. Both fats and oils, at energy contents of 9.0 kcal per gram, make the highest calorie components of food ingredients, which can be compared to 4.0 kcal per gram for proteins and carbohydrates.

The liquid neutral lipids are usually from plant sources such as olives, corn, soybeans and so are called vegetable oils. They contain mostly unsaturated fatty acids. Due to geometrical reasons their molecules do not pack well together to form a solid. In contrast, the solid neutral lipids contain mostly saturated fatty acids and are obtained from animals. Therefore they are named animal fats which include butterfat, lard (pork fat), tallow (beef fat)

Fatty acids. The term **fat** should not be confused with the term **fatty acid**. In chemistry, especially biochemistry, a **fatty acid** is a carboxylic acid often with a long unbranched aliphatic chain (tail), which is either saturated or unsaturated. Short carboxylic acids such as butyric acid (4 carbon atoms) are considered to be fatty acids, whereas fatty acids derived from natural fats and oils may be assumed to have at least 8 carbon atoms, e.g., caprylic acid (octanoic acid). Most of the natural fatty acids have an even number of carbon atoms because their biosynthesis involves acetyl-CoA, a coenzyme carrying two carbon atom group.

The homologous series of saturated monocarboxylic acids is:

Acid		Name	Number of C atoms
$HCOOH$		**Formic** (methanoic)	1
CH_3COOH		**Acetic** (ethanoic)	2
CH_3CH_2COOH	C_2H_5COOH	**Propionic** (propanoic)	3
$CH_3(CH_2)_2COOH$	C_3H_7COOH	**Butyric** (butanoic)	4
$CH_3(CH_2)_3COOH$	C_4H_9COOH	**Valeric** (pentanoic)	5

$CH_3(CH_2)_4COOH$	$C_5H_{11}COOH$	**Caproic** (hexanoic)	6
			With even number of C atoms
$CH_3(CH_2)_6COOH$	$C_7H_{15}COOH$	**Caprylic** (octanoic)	8
$CH_3(CH_2)_8COOH$	$C_9H_{19}COOH$	**Capric** (decanoic)	10
$CH_3(CH_2)_{10}COOH$	$C_{11}H_{23}COOH$	**Lauric** (dodecanoic)	12
$CH_3(CH_2)_{12}COOH$	$C_{13}H_{27}COOH$	**Myristic** (tetradecanoic)	14
$CH_3(CH_2)_{14}COOH$	$C_{15}H_{31}COOH$	**Palmitic** (hexadecanoic)	16
$CH_3(CH_2)_{16}COOH$	$C_{17}H_{35}COOH$	**Stearic** (octadecanoic)	18
$CH_3(CH_2)_{18}COOH$	$C_{19}H_{39}COOH$	**Arachidic** (eicosanoic)	20

Note on nomenclature: The trivial and more common names above are given in bold. When using them and the chain has substituents, their position is shown by Greek letters, α, β, γ, etc., excluding the carbon of COOH group. Thus, the α-carbon is adjacent to the carboxyl group, as illustrated with γ-aminobutyric acid. If the IUPAC name is used, then the carboxyl carbon is always numbered 1, and the adjacent to it is 2. The IUPAC nomenclature for carboxylic acids uses the alkane name that corresponds to the longest carbon chain in the acid. The ending –e in the alkane name is replaced by suffix –ioc acid.

Fatty acids are produced by the hydrolysis of the ester linkages in a fat or biological oil (both of which are triacylglycerols), with the removal of glycerol. **Common unsaturated fatty acids** found in liquid oils are:

oleic acid: *cis* $CH_3(CH_2)_7CH{=}CH(CH_2)_7COOH$, symbol 18:1$\omega$-9

linoleic acid: *cis,cis* $CH_3(CH_2)_4CH{=}CHCH_2CH{=}CH(CH_2)_7COOH$, symbol 18:2$\omega$-6

and **linolenic acid**: *cis, cis, cis* $CH_3CH_2CH{=}CHCH_2CH{=}CHCH_2CH{=}CH(CH_2)_7COOH$, symbol 18:3$\omega$-3.

The symbol (A:B ω-C) indicates: A=number of carbon atoms; B=number of double bonds; and C=position of the first double bond counting from the methyl end of the molecule. For instance, docosahexaenoic acid (DHA) is a 22:6ω-3 FA: $CH_3CH_2(CH{=}CHCH_2)_6CH_2COOH$ and eicosapentaenoic acid (EPA) is a 20:5ω-3 FA: $CH_3CH_2(CH{=}CHCH_2)_5(CH_2)_2COOH$. Fish oil contains a high concentration of polyunsaturated fatty acids (PUFA), but these FA belong to the omega-3 (or ω-3) family which has been connected to beneficial effects in lowering risk of atherosclerosis or heart disease.

The most common FA from animal fat are myristic acid, symbol 14:0, $CH_3(CH_2)_{12}COOH$ (tetradecanoic acid), palmitic acid, symbol 16:0, $CH_3(CH_2)_{14}COOH$ (hexadecanoic acid), stearic acid symbol 18:0, $CH_3(CH_2)_{16}COOH$ (octadecanoic acid), and arachidic acid, symbol 20:0, $CH_3(CH_2)_{18}COOH$ (eicosanoic acid). Animal fats contain relatively more saturated FA than unsaturated FA and therefore are usually low melting solids at room temperature.

Fat stored in animal **adipose tissue** (beneath the skin and around internal organs; the human fat cells are called **adipocytes**) serves also a structural purpose, providing insulation against cold and padding to protect internal organs. The higher melting saturated fats of animals are better suited to these purposes than liquid oils.

Physical properties

Fats can be in liquid or solid state. The solid fats are mainly esters of long chain saturated fatty acids and their origin is from animals (with exception of fish oil). The liquid fats are mainly esters of polyunsaturated fatty acids (PUFA), and their origin is in oils of plants. Liquid fats can polymerize and can be converted to solid fats by hydrogenation. Fats are nonpolar, hydrophobic compounds. They do not contain charged functional group. The only functional group is the ester group but it has little effect on the molecule's polarity.

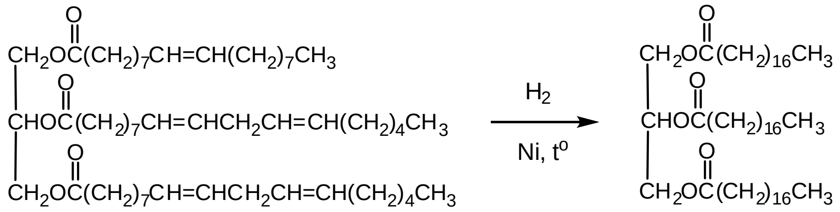
The solubility of fats in water is very low. The solubility in nonpolar organic solvents, like ether, chloroform, benzene, is higher.

The physical separation from natural sources can be achieved by simple pressing of vegetables such as olives, corn, and peanuts or when from animal origin - by melting the fat and removing the liquid.

Chemical properties of triacylglycerols

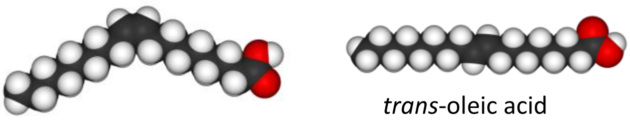
- **Iodine number**: The unsaturated bonds in a fatty acid component of a natural lipid react with iodine in an addition reaction (similar to the practical lab-work with bromine). Chemists have defined iodine number as a measure of the degree of unsaturation of a lipid. The higher the iodine number, the more unsaturated the fat.

- **Hydrogenation**: Addition of hydrogen to a double bond of a lipid in the presence of catalyst (Ni) at elevated temperature (e.g. 180^oC) causes liquid fats to convert into solid fats. For example, vegetable margarines and shortenings are commercially produced by the partial hydrogenation of soybean, corn, or cottonseed oil. The complete hydrogenation of these oils would result in a hard, brittle product. Addition of butyraldehyde to margarine imparts taste like that of natural butter.



typical vegetable oil (a liquid) tristearin (a solid fat)

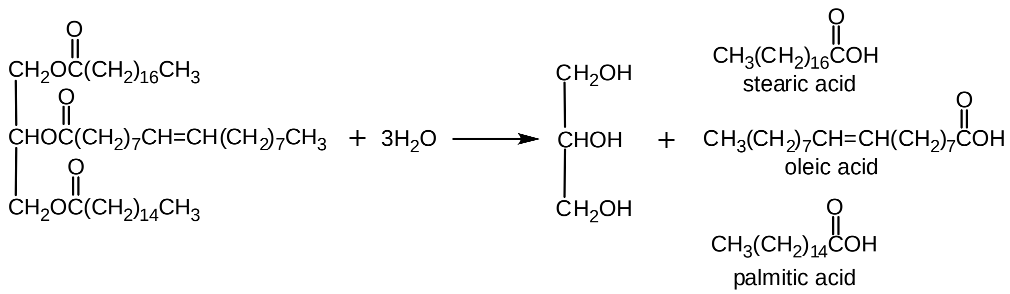
The process of hydrogenation frequently has a side reaction that turns some ***cis***-isomers into ***trans*-unsaturated** fats instead of hydrogenating them completely. Unlike other dietary fats, trans fats are not essential, and they do not promote good health. The consumption of trans fats increases one's risk of coronary heart disease by raising levels of "bad" LDL cholesterol and lowering levels of "good" HDL cholesterol. Health authorities worldwide recommend that consumption of trans fat be reduced to trace amounts.


trans-oleic acid

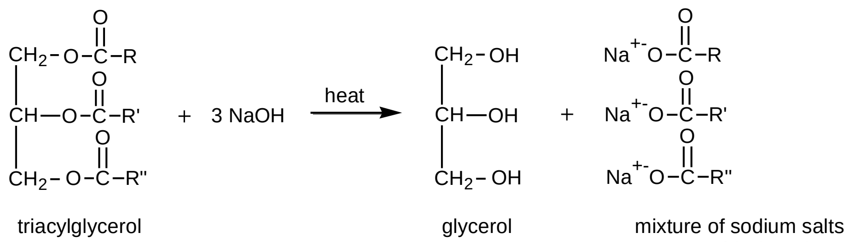
- **Rancidity**: When fats and oils develop a disagreeable (foul, bad) odor and taste, they are then said to be rancid. There are two causes of rancidity: hydrolysis and oxidation. For example: butter becomes rancid when left too long at room temperature. This occurs because some of the fat in butter undergoes hydrolysis, which is accelerated by enzymes produced in microorganisms in the air. This hydrolysis produces fatty acid – butyric acid and higher FAs which cause the odor of rancid butter.

Oxygen in the air reacts with unsaturated chains of triacylglycerols, breaking them apart and converting them into a variety of smaller foul-smelling and foul-tasting acids and aldehydes. In order to slow down such oxidation in commercial cooking oils and food products, such as bread and crackers, manufacturers add chemicals called antioxidants (synthetic or natural vitamin E). Antioxidants added to foods may decrease the rate of oxidation and preserve the food for longer time.

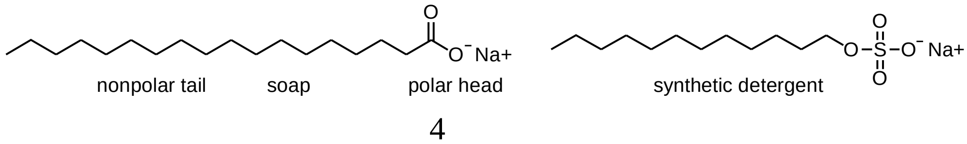
- **Hydrolysis**: The reaction of fats with water which cleaves the ester linkage is named hydrolysis. This chemical interaction occurs under the action of superheated steam (also under pressure, catalysts ZnO, MgO), hot mineral acids or specific enzymes (lipases). Hydrolysis under such conditions produces glycerol and three fatty acids.



- **Saponification**: Saponification is also hydrolysis carried out in the presence of strong base such as sodium hydroxide or potassium hydroxide. The products are glycerol and sodium salts of the fatty acids which are called soaps.

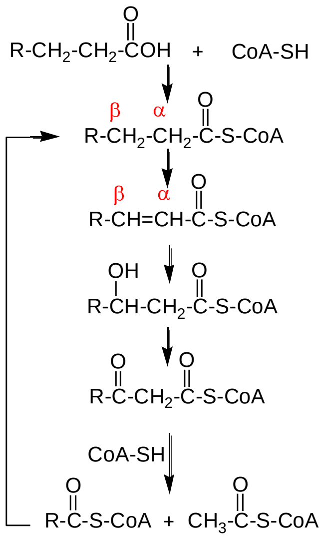


Soaps are useful for cleaning because soap molecules have both a hydrophilic end (charged polar head), which prefers contact with water, as well as a hydrophobic end (hydrocarbon nonpolar tail), which is able to adhere (dissolve) to nonpolar grease molecules. Although grease will normally adhere to skin or clothing, the soap molecules can form micelles which surround the grease particles and allow them to be dissolved in water.



Sodium salts of FA are used in bar soaps and potassium salts are used in liquid soaps. Both commercial preparations of soaps contain also additives to give them color and scents. Many cleaning agents today are technically not soaps, but synthetic detergents which are less expensive and easier to manufacture. Their cleaning action is based on the same principle.

- **β-Oxidation**: In vertebrates, oxidation of fatty acids provides at least half the energy needed by the liver, kidneys, heart, and the skeletal muscles at rest.



The fat oxidation begins with hydrolysis to glycerol and fatty acids. They are then oxidized mainly in the mitochondria of the liver, heart and skeletal muscles through a repeating series of reactions called the fatty acid cycle, or β-oxidation. These reactions are:

- joining the coenzyme A (CoA) to the acid
- dehydrogenation reaction that produces α–β double bond (the removal of hydrogens = oxidation)
- water is added to the double bond forming an alcohol at β-carbon
- the alcohol group is oxidized, producing NADH and H+ (hence β-oxidation)
- in the last step, CoA breaks the α–β bond, which produces one acetyl-CoA and a new fatty acid (having 2 fewer carbon atoms) joined to CoA.
- the new fatty acid again enters the cycle.

The cycle continues to remove two-carbon units from the fatty acid until it has been completely oxidized. Each turn of the cycle produces $FADH_2$ and NADH that can enter the respiratory chain, one molecule acetyl-CoA that participate in the citric acid cycle for production of ATP.

Overall, about 50% of the energy released in the complete oxidation of a fatty acid is trapped in molecules of ATP.