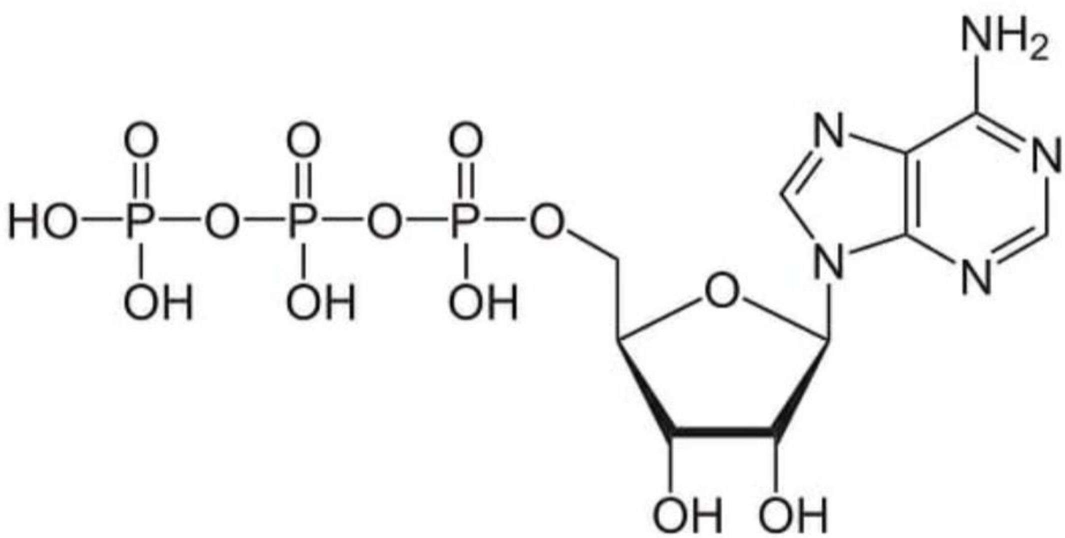
Adenosine Triphosphate (ATP)

Adenosine Triphosphate Definition

Adenosine triphosphate, also known as ATP, is a molecule that carries energy within cells. It is the main energy currency of the cell, and it is an end product of the processes of photophosphorylation (adding a phosphate group to a molecule using energy from light), cellular respiration, and fermentation. All living things use ATP. In addition to being used as an energy source, it is also used in signal transduction pathways for cell communication and is incorporated into deoxyribonucleic acid (DNA) during DNA synthesis.

Structure of ATP



This is a structural diagram of ATP. It is made up of the molecule adenosine (which itself is made up of adenine and a ribose sugar) and three phosphate groups. It is soluble in water and has a high energy content due to having two phosphoanhydride bonds connecting the three phosphate groups.

Functions of ATP

Energy Source

ATP is the main carrier of energy that is used for all cellular activities. When ATP is hydrolyzed and converted to adenosine diphosphate (ADP), energy is released. The removal of one phosphate group releases 7.3 kilocalories per mole, or 30.6 kilojoules per mole, under standard conditions. This energy powers all reactions that take place inside the cell. ADP can also be converted back into ATP so that the energy is available for other cellular reactions.

ATP is produced through several different methods. Photophosphorylation is a method specific to plants and cyanobacteria. It is the creation of ATP from ADP using energy from sunlight, and occurs during photosynthesis. ATP is also formed from the process of cellular respiration in the mitochondria of a cell. This can be through aerobic respiration, which requires oxygen, or anaerobic respiration, which does not. Aerobic respiration produces ATP (along with carbon dioxide and water) from glucose and oxygen. Anaerobic respiration uses chemicals other than oxygen, and this process is primarily used by archaea and bacteria that live in anaerobic environments. Fermentation is another way of producing ATP that does not require oxygen; it is different from anaerobic respiration because it does not use an electron transport chain. Yeast and bacteria are examples of organisms that use fermentation to generate ATP.

Signal Transduction

ATP is a signaling molecule used for cell communication. Kinases, which are enzymes that phosphorylate molecules, use ATP as a source of phosphate groups. Kinases are important for signal transduction, which is how a physical or chemical signal is transmitted from receptors on the outside of the cell to the inside of the cell. Once the signal is inside the cell, the cell can respond appropriately. Cells may be given signals to grow, metabolize, differentiate into specific types, or even die.

DNA Synthesis

The nucleobase adenine is part of adenosine, a molecule that is formed from ATP and put directly into RNA. The other nucleobases in RNA, cytosine, guanine, and uracil, are similarly formed from CTP, GTP, and UTP. Adenine is also found in DNA, and its incorporation is very similar, except ATP is converted into the form deoxyadenosine triphosphate (dATP) before becoming part of a DNA strand.

What is biology?

Biology is a branch of science that deals with living organisms and their vital processes. Biology encompasses diverse fields, including botany, conservation, ecology, evolution, genetics, marine biology, medicine, microbiology, molecular biology, physiology, and zoology.

Why is biology important?

As a field of science, biology helps us understand the living world and the ways its many species (including humans) function, evolve, and interact. Advances in medicine, agriculture, biotechnology, and many other areas of biology have brought improvements in the quality of life. Fields such as genetics and evolution give insight into the past and can help shape the future, and research in ecology and conservation inform how we can protect this planet's precious biodiversity.

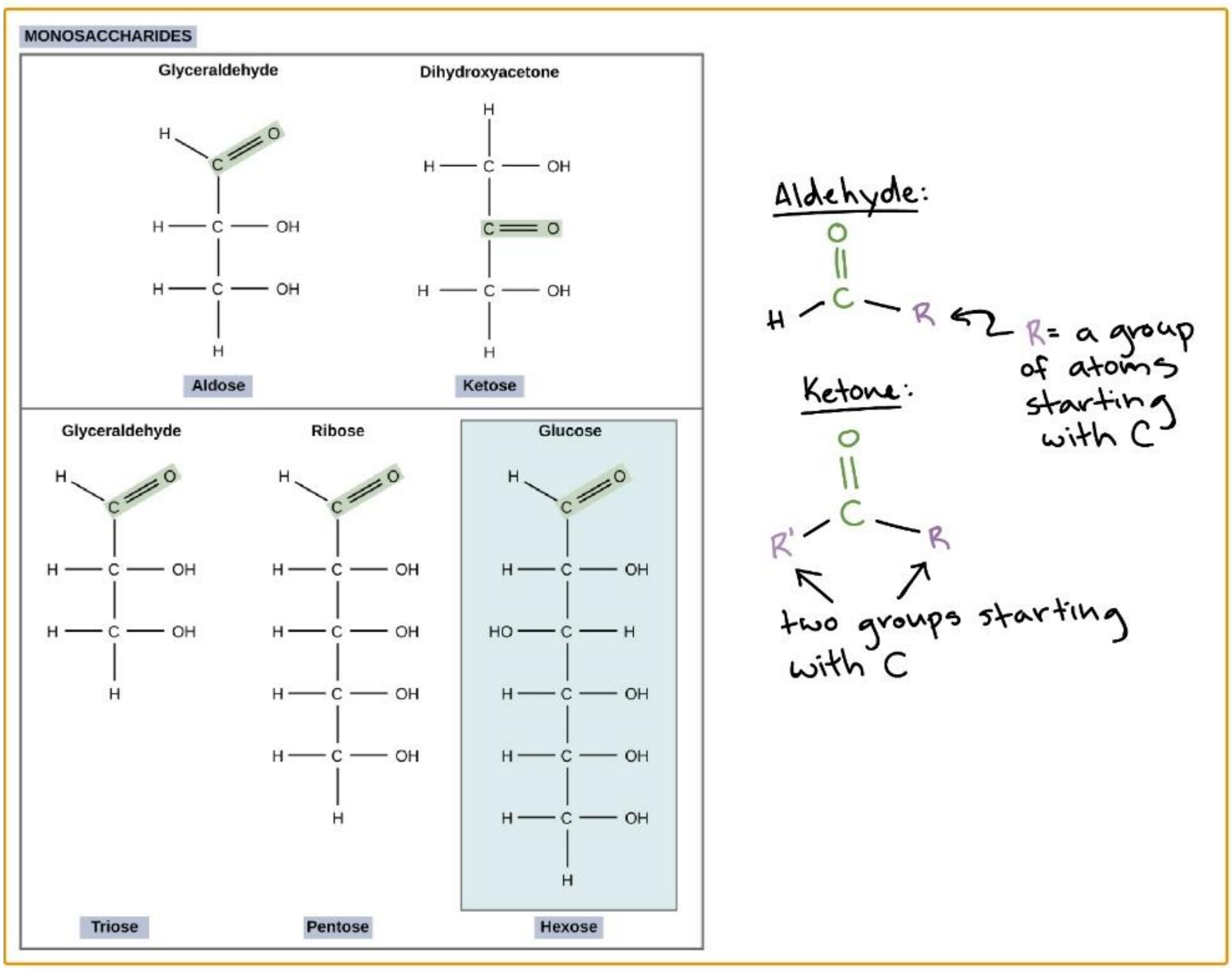
Significance of biology

Biology, study of living things and their vital processes. The field deals with all the physicochemical aspects of life. The modern tendency toward cross-disciplinary research and the unification of scientific knowledge and investigation from different fields has resulted in significant overlap of the field of biology with other scientific disciplines. Modern principles of other fields—chemistry, medicine, and physics, for example—are integrated with those of biology in areas such as biochemistry, biomedicine, and biophysics Biology is subdivided into separate branches for convenience of study, though all the subdivisions are interrelated by basic principles. Thus, while it is custom to separate the study of plants (botany) from that of animals (zoology), and the study of the structure of organisms (morphology) from that of function (physiology), all living things share in common certain biological phenomena—for example, various means of reproduction, cell division, and the transmission of genetic material. Biology is often approached on the basis of levels that deal with fundamental units of life. At the level of molecular biology, for example, life is regarded as a manifestation of chemical and energy transformations that occur among the many chemical constituents that compose an organism. As a result of the development of increasingly powerful and precise laboratory instruments and techniques, it is possible to understand and define with high precision and accuracy not only the ultimate physiochemical organization (ultrastructure) of the molecules in living matter but also the way living matter reproduces at the molecular level. Especially crucial to those advances was the rise of genomics in the late 20th and early 21st centuries. Cell biology is the study of cells—the fundamental units of structure and function in living organisms. Cells were first observed in the 17th century, when the compound microscope was invented. Before that time, the individual organism was studied as a whole in a field known as organismic biology; that area of research remains an important component of the biological sciences. Population biology deals with groups or populations of organisms that inhabit a given area or region. Included at that level are studies of the roles that specific kinds of plants and animals play in the complex and self-perpetuating interrelationships that exist between the living and the nonliving world, as well as studies of the built-in controls that maintain those relationships naturally. Those broadly based levels—molecules, cells, whole organisms, and populations—may be further subdivided for study, giving rise to specializations such as morphology, taxonomy, biophysics, biochemistry, genetics, epigenetics, and ecology. A field of biology may be especially concerned with the investigation of one kind of living thing—for example, the study of birds in ornithology, the study of fishes in ichthyology, or the study of microorganisms in microbiology.

Monosaccharides OR MONOMERS

Monosaccharides (mono- = “one”; sacchar- = “sugar”) are simple sugars, the most common of which is glucose. Monosaccharides have a formula of (\text {CH}_2\text O)_n(CH2O)nleft parenthesis, start text, C, H, end text, start subscript, 2, end subscript, start text, O, end text, right parenthesis, start subscript, n, end subscript, and they typically contain three to seven carbon atoms

- If the sugar has an aldehyde group, meaning that the carbonyl C is the last one in the chain, it is known as an aldose.
- If the carbonyl C is internal to the chain, so that there are other carbons on both sides of it, it forms a ketone group and the sugar is called a ketose.
- Sugars are also named according to their number of carbons: some of the most common types are trioses (three carbons), pentoses (five carbons), and hexoses (six carbons).



Polysaccharides or polymers

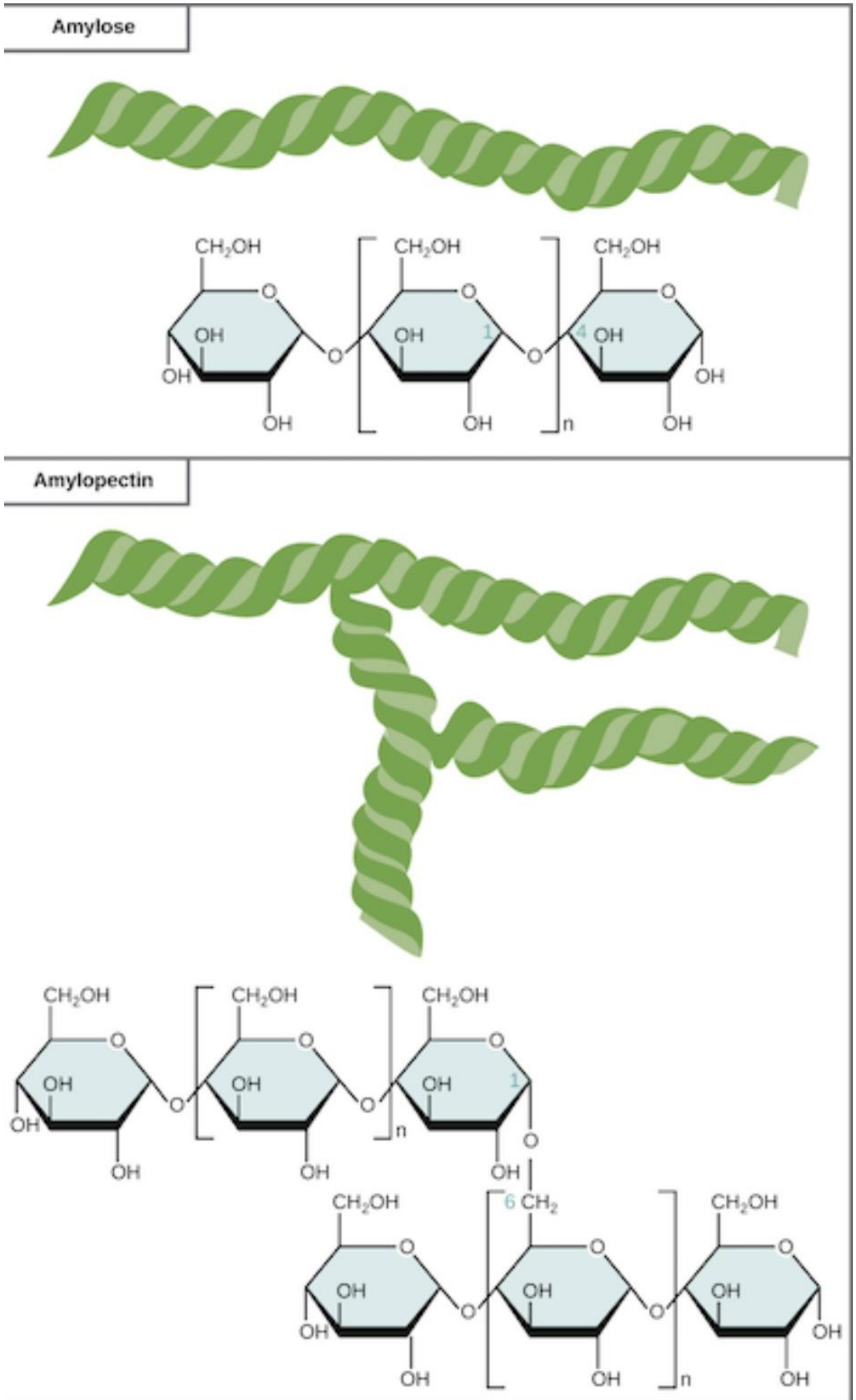
A long chain of monosaccharides linked by glycosidic bonds is known as a polysaccharide (poly- = "many"). The chain may be branched or unbranched and may contain different types of monosaccharides. The molecular weight of a polysaccharide can be quite high, reaching 100,000 daltons or more if enough monomers are joined. Starch, glycogen, cellulose, and chitin are some major examples of polysaccharides important in living organisms.

Starch is the stored form of sugars in plants and is made up of a mixture of two polysaccharides, amylose and amylopectin (both polymers of glucose). Plants are able to synthesize glucose using light energy gathered in photosynthesis, and the excess glucose, beyond the plant's immediate energy needs, is stored as starch in different plant parts, including roots and seeds. The starch in the seeds provides food for the embryo as it germinates and can also serve as a food source for humans and animals, who will break it down into glucose monomers using digestive enzymes.

In starch, the glucose monomers are in the α form (with the hydroxyl group of carbon 1 sticking down below the ring), and they are connected primarily by 1-4 glycosidic linkages (i.e., linkages in which carbon atoms 1 and 4 of the two monomers form a glycosidic bond).

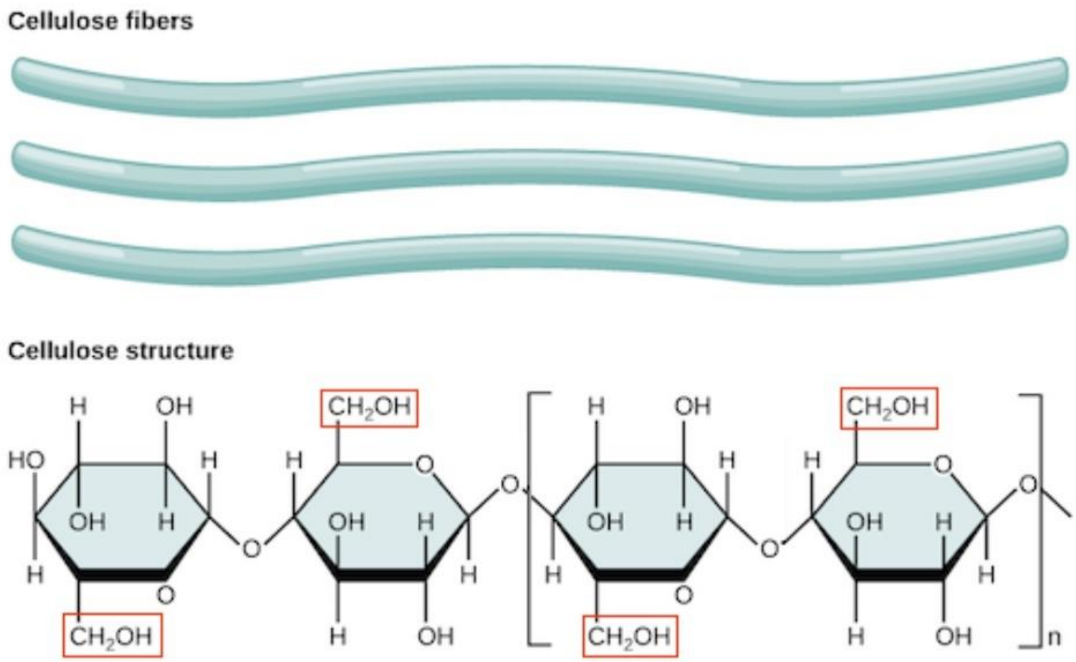
- **Amylose** consists entirely of unbranched chains of glucose monomers connected by 1-4 linkages.
- **Amylopectin** is a branched polysaccharide. Although most of its monomers are connected by 1-4 linkages, additional 1-6 linkages occur periodically and result in branch points.

Because of the way the subunits are joined, the glucose chains in amylose and amylopectin typically have a helical structure, as shown in the diagram below.



Amylose
CH2OH
OH
OH
O
1
4
n
Amylopectin
6 CH2

Cellulose, for example, is a major component of plant cell walls, which are rigid structures that enclose the cells (and help make lettuce and other veggies crunchy). Wood and paper are mostly made of cellulose, and cellulose itself is made up of unbranched chains of glucose monomers linked by 1-4 glycosidic bonds.



Lipids

Fats and oils

A fat molecule consists of two kinds of parts: a glycerol backbone and three fatty acid tails. Glycerol is a small organic molecule with three hydroxyl (OH) groups, while a fatty acid consists of a long hydrocarbon chain attached to a carboxyl group. A typical fatty acid contains 12–18 carbons, though some may have as few as 4 or as many as 36.

Saturated and unsaturated fatty acids

If there are only single bonds between neighboring carbons in the hydrocarbon chain, a fatty acid is said to be **saturated**. (The thing that fatty acids are saturated with is hydrogen; in a saturated fat, as many hydrogen atoms as possible are attached to the carbon skeleton.)

When the hydrocarbon chain has a double bond, the fatty acid is said to be **unsaturated**, as it now has fewer hydrogens. If there is just one double bond in a fatty acid, it's monounsaturated, while if there are multiple double bonds, it's polyunsaturated.

Unicellular or Single celled Organisms

As the name implies, unicellular organisms are made up of a single cell. They are the oldest form of life, with fossil records dating back to about 3.8 million years ago. Bacteria, amoeba, Paramecium, archaea, protozoa, unicellular **algae**, and unicellular fungi are examples of unicellular organisms. These unicellular organisms are mostly invisible to the naked eye, hence, they are also referred to as microscopic organisms. Most of the unicellular organisms are also prokaryotes.

Examples of Unicellular Organisms

Some of the examples of unicellular organisms are:

- Amoeba
- Euglena
- Paramecium
- Plasmodium
- Nostoc, Salmonella (Prokaryotic unicellular organisms)
- Protozoans, Fungi, Algae (Eukaryotic unicellular organisms)

Multicellular Organisms

Organisms that are composed of more than one cell are called multicellular organisms. **Multicellular organisms** are almost always eukaryotes. However, bacteria can form large interlinked strcutures such as colonies or biofilms but these can’t be classified as multicellular organisms.

Multicellular Organisms Examples

Some of the examples of multicellular organisms are listed below:

- All vertebrates and invertebrates
- All angiosperms, gymnosperms and higher land plants

Sr. no.	**Unicellular Organisms**	**Multicellular Organisms**
1	Unicellular organisms are composed of a single cell	Multicellular organisms are composed of more than one cell
2	Irregular in shape	Have a definite shape
3	Simple body organization	Complex body organization
4	A single cell carries out all necessary life processes	Multiple cells perform different functions
5	The total cell body is exposed to the environment	Only the outer cells are exposed to the environment
6	Division of labour is at the organelle level	Division of labour is at cellular, tissue, organs and organ system level
7	Includes both eukaryotes and prokaryotes	Includes only eukaryotes
8	A lifespan of a unicellular organism is usually short	Multicellular organisms have a comparitively longer lifespan
9	Injury to the cell leads to the death of the organism	Injury to a cell does not cause death of the multicellular organism
10	Reproduce by asexual reproduction	Reproduction happens sexually as well as asexually
11	Cell differentiation is absent	Cell differentiation is obvious
12	They can be autotrophs or heterotrophs	They include both autotrophs and heterotrophs
13	They are microscopic in nature	They are macroscopic in nature
14	Bacteria, amoeba, paramecium, and yeast are examples of unicellular organisms	Humans, animals, plants, birds and insects, are examples of multicellular organisms

Prokaryotic Cell

The term “**prokaryote**” is derived from the Greek word “*pro*“, (meaning: before) and “*karyon*” (meaning: kernel). It translates to “***before nuclei.***“

Prokaryotic cells are comparatively smaller and much simpler than eukaryotic cells. The other defining characteristic of prokaryotic cells is that it does not possess membrane-bound cell organelles such as a nucleus. Reproduction happens through the process of binary fission.

Structurally, prokaryotes have a capsule enveloping its entire body, and it functions as a protective coat. This is crucial for preventing the process of phagocytosis (where the bacteria gets engulfed by other eukaryotic cells such as macrophages.) The pilus is a hair-like appendage found on the external surface of most prokaryotes and it helps the organism to attach itself to various environments. The pilus essentially resists being flushed, hence, it is also called attachment pili. It is commonly observed in bacteria.

Eukaryotic Cell

The term “**Eukaryotes**” is derived from the Greek word “*eu*“, (meaning: good) and “*karyon*” (meaning: kernel), therefore, translating to “***good or true nuclei***.” Eukaryotes are more complex and much larger than the prokaryotes. They include almost all the major kingdoms except kingdom monera.

Structurally, eukaryotes possess a cell wall, which supports and protects the plasma membrane. The cell is surrounded by the plasma membrane and it controls the entry and exit of certain substances.

The nucleus contains DNA, which is responsible for storing all genetic information. The nucleus is surrounded by the nuclear membrane. Within the nucleus exists the nucleolus, and it plays a crucial role in synthesising proteins. Eukaryotic cells also contain mitochondria, which are responsible for the creation of energy, which is then utilized by the cell.

Present in only plant cells, chloroplasts are the subcellular sites of photosynthesis. Endoplasmic reticulum helps in the transportation of materials. Besides these, there are also other **cell organelles** that perform various other functions and these include ribosomes, lysosomes, Golgi bodies, cytoplasm, chromosomes, vacuoles, and centrosomes.

Examples of eukaryotes include almost every unicellular organism with a nucleus and all multicellular organisms.

1		**Prokaryotes**	**Eukaryotes**
2	**Type of Cell**	Always unicellular	Unicellular and multi-cellular
3	**Cell size**	Ranges in size from 0.2 μm – 2.0 μm in diameter	Size ranges from 10 μm – 100 μm in diameter
4	**Cell wall**	Usually present; chemically complex in nature	When present, chemically simple in nature
5	**Nucleus**	Absent	Present
6	**Ribosomes**	Present. Smaller in size and spherical in shape	Present. Comparatively larger in size and linear in shape
7	**DNA arrangement**	Circular	Linear
8	**Mitochondria**	Absent	Present
9	**Cytoplasm**	Present, but cell organelles absent	Present, cell organelles present
10	**Endoplasmic reticulum**	Absent	Present
11	**Plasmids**	Present	Very rarely found in eukaryotes
12	**Ribosome**	Small ribosomes	Large ribosomes
13	**Lysosome**	Lysosomes and centrosomes are absent	Lysosomes and centrosomes are present
14	**Cell division**	Through binary fission	Through mitosis
15	**Flagella**	The flagella are smaller in	The flagella are larger in size
16	**Reproduction**	Asexual	Both asexual and sexual
17	**Example**	Bacteria and Archaea	Plant and Animal cell

Autotroph

An autotroph or producer, is an organism that produces complex organic compounds (such as carbohydrates, fats, and proteins) from simple substances present in its surroundings, generally using energy from light (photosynthesis) or inorganic chemical reactions (chemosynthesis). They are the producers in a food chain, such as plants on land or algae in water (in contrast to heterotrophs as consumers of autotrophs). They do not need a living source of energy or organic carbon. Autotrophs can reduce carbon dioxide to make organic compounds for biosynthesis and also create a store of chemical energy. Most autotrophs use water as the reducing agent, but some can use other hydrogen compounds such as hydrogen sulfide. Some autotrophs, such as green plants and algae, are phototrophs, meaning that they convert electromagnetic energy from sunlight into chemical energy in the form of reduced carbon.

Autotrophs can be photoautotrophs or chemoautotrophs. Phototrophs use light as an energy source, while chemotrophs use electron donors as a source of energy, whether from organic or inorganic sources; however in the case of autotrophs, these electron donors come from inorganic chemical sources. Such chemotrophs are lithotrophs. Lithotrophs use inorganic compounds, such as hydrogen sulfide, elemental sulfur, ammonium and ferrous iron, as reducing agents for biosynthesis and chemical energy storage. Photoautotrophs and lithoautotrophs use a portion of the ATP produced during photosynthesis or the oxidation of inorganic compounds to reduce NADP+ to NADPH to form organic compounds.

Lithotroph

Lithotrophs are a diverse group of organisms using inorganic substrate (usually of mineral origin) to obtain reducing equivalents for use in biosynthesis (e.g., carbon dioxide fixation) or energy conservation (i.e., ATP production) via aerobic or anaerobic respiration. Known chemolithotrophs are exclusively microorganisms; no known macrofauna possesses the ability to use inorganic compounds as energy sources. Macrofauna and lithotrophs can form symbiotic relationships, in which case the lithotrophs are called "prokaryotic symbionts". An example of this is chemolithotrophic bacteria in giant tube worms or plastids, which are organelles within plant cells that may have evolved from photolithotrophic cyanobacteria-like organisms. Lithotrophs belong to either the domain Bacteria or the domain Archaea. The term "lithotroph" was created from the Greek terms 'lithos' (rock) and 'troph' (consumer), meaning "eaters of rock". Many lithoautotrophs are extremophiles, but this is not universally so.

Different from a lithotroph is an organotroph, an organism which obtains its reducing agents from the catabolism of organic compounds.

Main Difference

The main difference between Autotroph and Lithotroph is that the Autotroph is a organism that produces complex organic compounds (such as carbohydrates, fats, and proteins) from simple substances present in its surroundings, generally using energy from light (photosynthesis) or inorganic chemical reactions (chemosynthesis) and Lithotroph is a organism using inorganic substrate (usually of mineral origin) to obtain reducing equivalents for use in biosynthesis (e.g., carbon dioxide fixation) or energy conservation (i.e., ATP production) via aerobic or anaerobic respiration.

Aminotelic and Ureotelic

Aminotelic organisms are the organisms that excrete nitrogenous wastes in the form of ammonia. Most aquatic animals generally excrete ammonia. Ammonia is a highly toxic product. It also requires sufficient water to excrete. Therefore, aquatic organisms, including most fish species, protozoans, crustaceans, platyhelminths are ammonotelic.

Ureotelic organisms are the organisms that excrete nitrogenous waste in the form of urea. All terrestrial species mainly produce urea.Urea is less toxic. It also needs less water, unlike ammonia excretion. Cartilaginous fish, few bony fishes, adult amphibians and mammals including humans, are ureotelic animals.

Main Difference

Ammonotelic organisms are organisms that excrete ammonia while ureotelic organisms are the organisms that excrete urea.. Ammonia is highly toxic for cells and body tissues, but urea is less toxic. Moreover, ammonia excretion needs sufficient water while urea excretion needs less water.

Identification and classification of microorganisms

Microorganisms are very diverse. They include bacteria, fungi, algae, and protozoa; microscopic plants (green algae); and animals such as rotifers and planarians. Most microorganisms are unicellular (single-celled), but this is not universal.

Phenotypic Methods of Classifying and Identifying Microorganisms

Classification seeks to describe the diversity of bacterial species by naming and grouping organisms based on similarities. Microorganisms can be classified on the basis of cell structure, cellular metabolism, or on differences in cell components such as DNA, fatty acids, pigments, antigens, and quinones.

- Bacteria: lack membrane -bound organelles and can function and reproduce as individual cells, but often aggregate in multicellular colonies. Their genome is usually a single loop of DNA, although they can also harbor small pieces of DNA called plasmids. These plasmids can be transferred between cells through bacterial conjugation. Bacteria are surrounded by a cell wall, which provides strength and rigidity to their cells.

- Archaea: In the past, the differences between bacteria and archaea were not recognized and archaea were classified with bacteria as part of the kingdom Monera. Archaea are also single-celled organisms that lack nuclei. Archaea in fact differ from bacteria in both their genetics and biochemistry. While bacterial cell membranes are made from phosphoglycerides with ester bonds, archaean membranes are made of ether lipids.
- Eukaryotes: Unlike bacteria and archaea, eukaryotes contain organelles such as the cell nucleus, the Golgi apparatus, and mitochondria in their cells. Like bacteria, plant cells have cell walls and contain organelles such as chloroplasts in addition to the organelles in other eukaryotes.

Classification of Prokaryotes

- All living things can be classified into three main groups called domains; these include the Archaea, the Bacteria, and the Eukarya.
- Prokaryotes arose during the Precambrian Period 3.5 to 3.8 billion years ago.
- Prokaryotic organisms can live in every type of environment on Earth, from very hot, to very cold, to super haline, to very acidic.
- The domains Bacteria and Archaea are the ones containing prokaryotic organisms.
- The Archaea are prokaryotes that inhabit extreme environments, such as inside of volcanoes, while Bacteria are more common organisms, such as E. coli.

Key Terms

- prokaryote: an organism whose cell (or cells) are characterized by the absence of a nucleus or any other membrane-bound organelles
- domain: in the three-domain system, the highest rank in the classification of organisms, above kingdom: Bacteria, Archaea, and Eukarya
- archaea: a taxonomic domain of single-celled organisms lacking nuclei, formerly called archaebacteria, but now known to differ fundamentally from bacteria

Ecological aspects of microorganisms

Animals are only one small part of an ecosystem. For an ecosystem to work, it has to have many organisms that all work together in a continuous cycle. Microorganisms form part of that cycle, and because of their huge numbers, the part they play is an important one. Microorganisms have several vital roles in ecosystems: decomposition, oxygen production, evolution, and symbiotic relationships.

Decomposition is where dead animal or plant matter is broken down into more basic molecules. This process only happens because of the microorganisms that find their way into the dead matter. The process of decomposition provides nutrients that future plants and animals will be able to reuse, making soil more fertile. Plants would not continue to grow without it - not to mention the world be really cluttered with dead animals and plants without it.

The Genetic Material

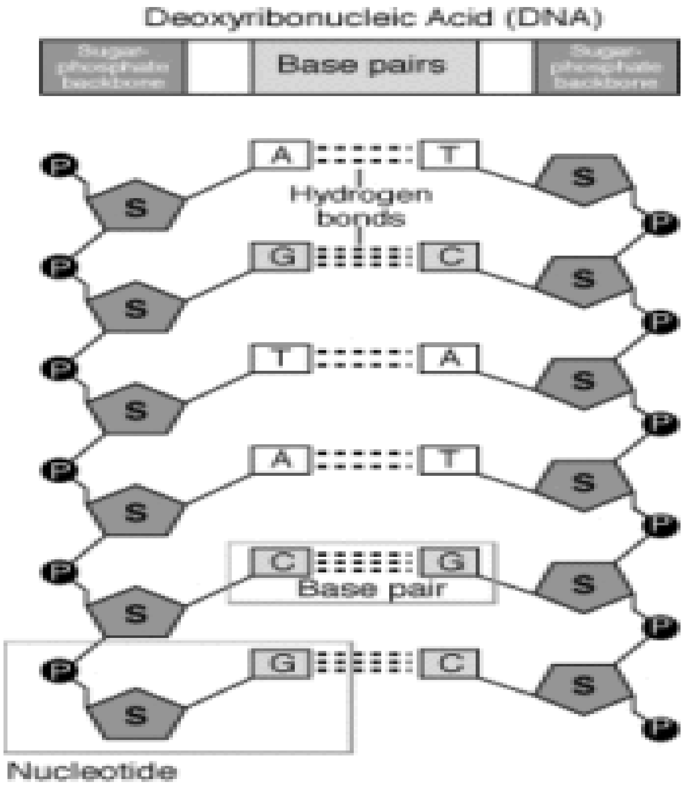
DNA is the genetic material that carries information from generation to generation.

Structure of DNA

The genetic material in most organisms is DNA or Deoxyribonucleic acid; whereas in some viruses, it is RNA or Ribonucleic acid. A DNA molecule consists of two polynucleotide chains i.e. chains with multiple nucleotides. Let's understand the structure of this chain in detail.

Structure Of Polynucleotide Chain

1. A nucleotide is made of the following components:
2. Pentose sugar – A pentose sugar is a 5-carbon sugar. In case of DNA, this sugar is deoxyribose whereas, in RNA, it is ribose.
3. Phosphate group
4. Nitrogenous base – These can be of two types – Purines and Pyrimidines. Purines include Adenine and Guanine whereas pyrimidines include Cytosine and Thymine. In RNA, thymine is replaced by Uracil.
5. Nitrogenous base + pentose sugar (via N-glycosidic linkage) = Nucleoside.
6. Nucleoside + phosphate group (via phosphoester linkage) = Nucleotide.
7. Nucleotide + Nucleotide (via 3'-5' phosphodiester linkage) = Dinucleotide.
8. Many nucleotides linked together = Polynucleotide.
9. A polynucleotide has a free phosphate group at the 5' end of the sugar and this is called the 5' end. Similarly, the sugar also has a free 3'-OH group at the other end of the polynucleotide which is called the 3' end. The backbone of a polynucleotide chain consists of pentose sugars and phosphate groups; whereas the nitrogenous bases project out of this backbone.



Polynucleotide chains of DNA and its components

Double Helix Structure

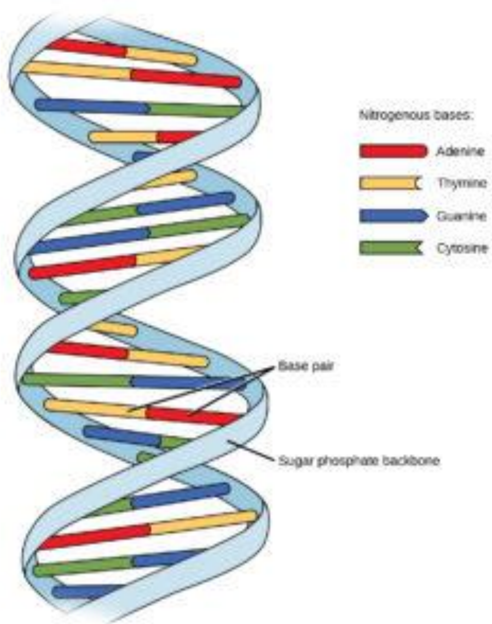
DNA is a long polymer and therefore, difficult to isolate from cells in an intact form. This is why it is difficult to study its structure. However, in 1953, James Watson and Francis revealed the 'double helix' model of the structure of DNA, based on X-ray diffraction data from Maurice Wilkins and Rosalind Franklin.

This model also reveals a unique property of polynucleotide chains – Base pairing. It refers to the hydrogen bonds that connect the nitrogen bases on opposite DNA strands. This pairing gives rise to complementary strands i.e. if you know the sequence of bases on one strand, you can predict the bases on the other strand. Additionally, if each DNA strand acts as a template for synthesis (parent) of a new strand, then the new double-stranded DNA (daughters) produced are identical to the parental DNA strand.

Salient Features of DNA Double-Helix

1. It consists of two polynucleotide chains where the sugar and phosphate group form the backbone and the nitrogenous bases project inside the helix.
2. The two polynucleotide chains have anti-parallel polarity i.e. if one strand has 5′ → 3′ polarity, the other strand has 3′ → 5′ polarity.

3. The bases on the opposite strands are connected through hydrogen bonds forming base pairs (bp). Adenine always forms two hydrogen bonds with thymine from the opposite strand and vice-versa. Guanine forms three hydrogen bonds with cytosine from the opposite strand and vice-versa. Therefore, a purine always pairs with a pyrimidine on the other strand, giving rise to a uniform distance between the two strands of the helix.
4. The two strands coil in a right-handed fashion. Each turn of the helix is 3.4nm (or 34 Angstrom units) consisting of 10 nucleotides. These nucleotides are at a distance of 0.34nm (or 3.4 Angstrom units).
5. The helix is stable because of the base pairs that stack over one another and hydrogen bonds that hold the bases together.

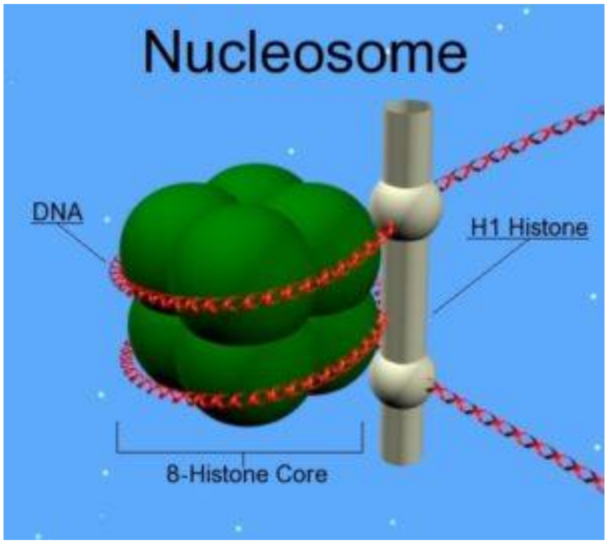


DNA double helix

Packaging of DNA Helix

1) If you calculate the length of DNA in a typical mammalian cell, it is approximately 2.2 meters. The dimension of a typical nucleus is only about 10-6 meters! Then, how does such a long polymer fit in the nucleus of a cell?
2) Prokaryotes like E. coli, do not have a defined nucleus. Here, the negatively-charged DNA is held together in large loops by positively-charged proteins in a structure called 'nucleoid'. In Eukaryotes, however, the organization of DNA in the nucleus is much more complex and is as follows:
3) The negatively-charged DNA is wrapped around a positively-charged histone octamer i.e. a unit of 8 histone molecules. This forms a 'Nucleosome'. Histones are positively-charged proteins that are rich in basic amino acids – arginines and lysines. A typical nucleosome has 200bp of DNA helix.

4) Many nucleosomes join together to form a thread-like structure – Chromatin in the nucleus. The nucleosomes in chromatin appear as 'beads-on-string' under the electron microscope.
5) The chromatin is packaged to form chromatin fibres which are further coiled and condensed to form chromosomes. The higher level packaging of chromatin requires another set of proteins – Non-histone Chromosomal (NHC) proteins.



Nucleosome Structure

Note: Euchromatin is the region of chromatin that is loosely packed and therefore stains lightly; whereas Heterochromatin is the densely packed region and therefore stains dark.

Meaning of Enzymes:

Enzymes are proteinaceous (and even nucleic acids) biocatalyst which alter (generally enhance) the rate of a reaction.

Classification of Enzymes:

Classification of enzymes are based upon:

(1) The reaction catalysed,
(2) The presence or absence at a given time,
(3) The regulation of action,
(4) The place of action and
(5) Their clinical importance.

1. Classification Based upon the Reaction Catalysed:

Enzymes are broadly divided into six groups based on the type of reaction catalysed.

They are:

(1) Oxidoreductases
(2) Transferases
(3) Hydrolases
(4) Lyases
(5) Isomerases and
(6) Ligases.

(a) Oxidoreductases:

Enzymes which bring about oxidation and reduction reactions.

(b) Transferases:

Enzymes which catalyze transfer of groups from one substrate to another, other than hydrogen. Ex. Transaminase catalyses transfer of amino group from amino acid to a keto acid to form a new keto acid and a new amino acid.

(c) Hydrolases:

Those enzymes which catalyse the breakage of bonds with addition of water (hydrolysis). All the digestive enzymes are hydrolases. Ex. Pepsin, trypsin, amylase, maltase.

(d) Lyases:

Those enzymes which catalyse the breakage of a compound into two substances by mechanism other than addition of water. The resulting product always has a double bond.

(e) Isomerases:

Those enzymes which catalyse the inter-conversion of optical and geometric isomers.

Ex. Glyceraldehyde-3-phosphate—ISOMERASE → Dihydroxyacetone phosphate

(f) Ligases:

These enzymes catalyse union of two compounds. This is always an energy requiring process (active process).

2. Classification Based upon the Presence or Absence at a Given Time:

Two types are identified:

(a) Inducible enzymes:

Those enzymes that are synthesized by the cell whenever they are required. Synthesis of these enzymes usually requires an inducer.

Ex. Invertase, HMG-CoA reductase, p-galactosidase and enzymes involved in urea cycle.

(b) Constitutive enzymes:

Enzymes which are constantly present in normal amounts in the body, irrespective of inducers.

Ex. Enzymes of glycolysis.

3. Classification Based upon the Regulation of Enzyme Action:

They are of two types:

(a) Regulatory enzymes:

The action of these enzymes is regulated depending upon the status of the cell. The action of regulatory enzymes is either increased or decreased by a modulator at a site other than the active site called the "allosteric site".

Ex. Phosphofructokinase (PFK) and glutamate dehydrogenase.

(b) Non-regulatory enzymes:

The action of these enzymes is not regulated.

Ex. Succinate dehydrogenase.

4. Classification Based upon the Place of Action:

Depending upon the two sites of action, they are divided into—

(a) Intracellular enzymes:

Enzymes that are produced by the cell and act inside the same cell are known as intracellular enzymes.

Ex. All the enzymes of glycolysis and TCA cycle.

(b) Extracellular enzymes:
Enzymes produced by a cell but act outside that cell independent of it. Ex, All the digestive enzymes viz. trypsin, pancreatic lipase etc.

5. Classification Based upon their Clinical Importance:
(a) Functional plasma enzymes:
Enzymes present in the plasma in considerably high concentration and are functional in the plasma due to the presence of their substrate it plasma.

Ex. Serum lipase, blood clotting enzymes.

(b) Non-functional plasma enzymes:
Enzymes present in the plasma in negligible concentration and have no function in the plasma due to the absence of their substrate in it. Non-functional plasma enzymes are of diagnostic importance.

Mechanism of Enzyme Action:
An enzyme (or protein) should be in its native conformation to be biologically active. The three dimensional conformation of enzymes have a particular site where the substrate binds and is acted upon, this site is called the active site.

The active site is earmarked into two specific areas:
(1) Binding site—where the substrate binds and

(2) Catalytic site—where the enzyme catalysis takes place.

The amino acids present at the active site are tyrosine, histidine, cysteine, glutamic acid, aspartic acid, lysine and serine. In aldolase, lysine is present at the active site. In carboxypeptidase, two tyrosine residues are present at the active site. Ribonuclease has two histidines at the active site. Michaelis and Menten established the theory of combination of enzyme with substrate to form the enzyme-substrate complex. According to this, the enzyme combines with the substrate on which it acts to form an enzyme-substrate complex. Then, this enzyme is liberated and the substrate is broken down into the product of the reaction.

E [Enzyme] + S [Substrate] → ES [Enzyme-Substrate complex] → E + Product

The ES complex is also called as 'Michaelis Menten complex'.

Enzymes accelerate the rate of chemical reaction by four major mechanisms viz.

1. Proximity and Orientation:
The enzyme binds to the substrate in such a way that the susceptible bond is in close proximity to the catalytic group and also precisely oriented to it resulting in the catalysis.

2. Strain and Distortion or Induced Fit Model:
Binding of the substrate induces a conformational change in the enzyme molecule which strains the shape of the active site and also distorts the bounded substrate, thus bringing about the catalysis. The binding of the substrate to the enzyme will bring about a change in the tertiary or quaternary structure of enzyme molecule, which destabilizes the enzyme. In order to attain stability, the enzyme distorts the substrate thereby forming the reaction product.

3. General Acid-Base Catalysis:
The active site of the enzyme has amino acids that are good proton donors or proton acceptors, this result in acid-base catalysis of the substrate.

4. Covalent Catalysis:
Some enzymes react with their substrates to form very unstable, covalently joined enzyme-substrate complexes, which undergo further reaction to form the products.

Factors Affecting Enzyme Action:

The factors influencing the rate of the enzyme catalysed reaction are:

1. Temperature
2. pH
4. Enzyme concentration
5. Concentration of products
6. Light
7. Ions

1. Effect of Temperature:

When all the other parameters are kept constant (i.e. at their optimum level), then the rate of enzyme reaction increases slowly with increase of temperature till it reaches a maximum. Further increase in temperature denatures the protein resulting in decrease in the enzyme action and a further increase in temperature may totally destroy the protein.

2. Effect of pH:

When all the other parameters are kept constant, the velocity of an enzyme catalysed reaction increases till it reaches the optimum pH and then decreases with further increase/decrease in pH. The activity is maximum for most of the enzymes at the biological pH of 7.4. Optimum pH for pepsin is 1.5, acid phosphatase is 4.5 and for alkaline phosphatase it is 9.8.

4. Effect of Enzyme Concentration:

As the enzyme concentration increases, the rate of reaction increases steadily in presence of an excess amount of substrate, the other factors being kept constant. A linear curve is produced.

5. Effect of Products:

When the product is more in the reaction mixture, then the rate of reaction decreases due to feedback inhibition.

6. Effect of Light:

The speed of activity of various enzymes changes in different wavelength of light ex. blue light enhances the activity of salivary amylase whereas, U.V. light decreases the velocity.

7. Effect of Ions:

Presence or absence of particular ions enhances or reduces the activity of enzymes ex. Pepsinogen is converted to pepsin in presence of H^+ ions. Kinases act in presence of Mg^{+2} ions.

Definition of Endothermic Reaction

As the name suggests, '**endo**' means 'to absorb' while '**thermic**' refers to 'heat'. So we can define the endothermic reactions as such chemical reaction where the **energy is absorbed** during the conversion of reactant into the product. This happens because of the dissociation of the bonds between the molecules. Later on, the energy is released, when the new bonds are formed.

In the endothermic reaction, the products contain more energy than the reactants. In these reactions, the heat is taken up from the surroundings, due to which the temperature of the system where the reaction is going remains cooler. Even the enthalpy (ΔH) which is defined as the change in heat energy during the conversion of reactants to the products becomes **higher** at the end of the reaction.

The value of ΔH or DH or DE is always **positive**.

$$H \text{ reactants} < H \text{ products}$$

$$\Delta H = H \text{ products} - H \text{ reactants} = \text{positive value for } \Delta H$$

Few common examples of endothermic reactions are:
1. Photosynthesis – The process where chlorophyll present in green plants in converted the water and carbon dioxide into the glucose and oxygen, in the presence of sunlight, which works as the energy provider.

Definition of Exothermic Reaction

Here '**exo**' refers 'to release or to evolve', and **'thermic**' refers to 'heat'. Hence exothermic reaction can be defined as such chemical reaction where the energy is **released or evolved**. These types of reactions are warmer, and sometimes they are dangerous feel if the reaction is at the higher rate.

In an exothermic reaction, the amount of energy released during the formation of new bonds (product) is higher than the total amount of energy needed while breaking up the bonds (reactants). This is the reason for heating of the system or reactions. Even the enthalpy change becomes lower at the end of the reaction.

The value of ΔH or DH or DE is always **negative**.

H products < H reactants

$$\Delta H = H\ products - H\ reactants = negative\ value\ for\ \Delta H$$

Few common examples of endothermic reactions are:
1. Combustion – Burning of coal, a candle, sugar.
2. When laundry detergent is dissolved in water, or when water is added to the quicklime while preparing whitewash. In such reaction, there is the production of the ample of heat, which warms up the water.
3. Formation of ice from water.
4. Respiration, digestion of food.

1	**BASIS FOR COMPARISON**	**ENDOTHERMIC REACTIONS**	**EXOTHERMIC REACTIONS**
2	Meaning	Chemical reactions involving the use of energy at the time of dissociation to form a new chemical bond is known as the endothermic reaction.	Chemical reactions where the energy is released or evolved in the form of heat is known as the exothermic reaction.
3	Energy	The endothermic process requires energy in the form of heat.	The exothermic process evolves or releases in the form of heat.
4	Enthalpy (ΔH)	ΔH is positive, as heat is absorbed.	ΔH is negative, as heat is evolved.
5	Examples	1. Conversion of ice into water vapour through boiling, melting or evaporation.	1. Formation of ice from water.
6		molecules.	2. Burning of coal (combustion).
7		3. Production of anhydrous salt from hydrate.	3. The reaction between water and the strong acid.

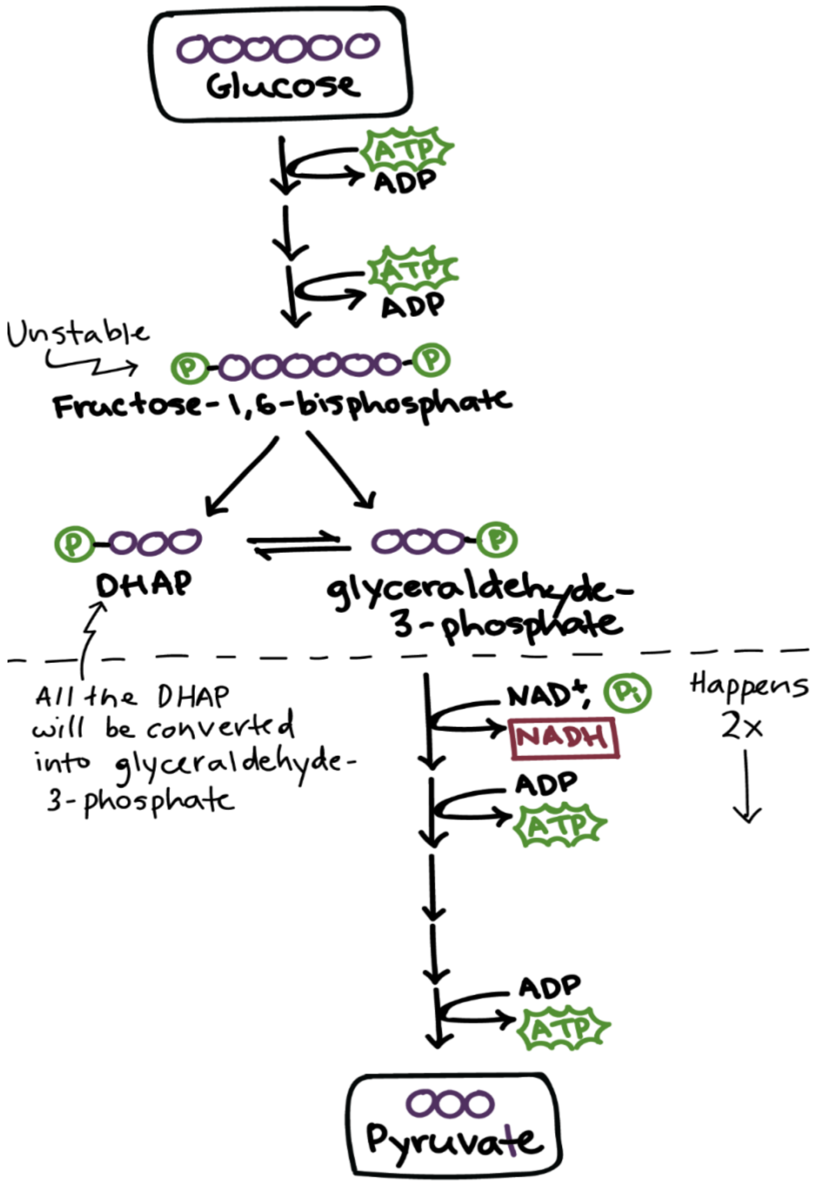
What is glycolysis?

Glycolysis is a series of reactions that extract energy from glucose by splitting it into two three-carbon molecules called pyruvates. Glycolysis is an ancient metabolic pathway, meaning that it evolved long ago, and it is found in the great majority of organisms alive today.

In organisms that perform cellular respiration, glycolysis is the first stage of this process. However, glycolysis doesn’t require oxygen, and many anaerobic organisms—organisms that do not use oxygen—also have this pathway.

Glycolysis takes place in the cytosol of a cell, and it can be broken down into two main phases: the energy-requiring phase, above the dotted line in the image below, and the energy-releasing phase, below the dotted line.

Energy-requiring phase. In this phase, the starting molecule of glucose gets rearranged, and two phosphate groups are attached to it. The phosphate groups make the modified sugar—now called fructose-1,6-bisphosphate—unstable, allowing it to split in half and form two phosphate-bearing three-carbon sugars. Because the phosphates used in these steps come from, ATP two ATP, end text molecules get used up.



Simplified diagram of glycolysis.

Energy investment phase. Glucose is first converted to fructose-1,6-bisphosphate in a series of steps that use up two ATP. Then, unstable fructose-1,6-bisphosphate splits in two, forming two three-carbon molecules called DHAP and glyceraldehyde-3-phosphae. Glyceraldehyde-3-phosphate can continue with the next steps of the pathway, and DHAP can be readily converted into glyceraldehyde-3-phosphate.

Energy payoff phase. In a series of steps that produce one NADH and two ATP, a glyceraldehyde-3-phosphate molecule is converted into a pyruvate molecule. This happens twice for each molecule of glucose since glucose is split into two three-carbon molecules, both of which will go through the final steps of the pathway.

The three-carbon sugars formed when the unstable sugar breaks down are different from each other. Only one—glyceraldehyde-3-phosphate—can enter the following step. However, the unfavorable sugar, DHAP end text, can be easily converted into the favorable one, so both finish the pathway in the end

Energy-releasing phase. In this phase, each three-carbon sugar is converted into another three-carbon molecule, pyruvate, through a series of reactions. In these reactions, two ATP end text molecules and one NADH molecule are made. Because this phase takes place twice, once for each of the two three-carbon sugars, it makes four ATP and two NADH, overall.

Each reaction in glycolysis is catalyzed by its own enzyme. The most important enzyme for regulation of glycolysis is phosphofructokinase, which catalyzes formation of the unstable, two-phosphate sugar molecule, fructose-1,6-bisphosphate^44start superscript, 4, end superscript. Phosphofructokinase speeds up or slows down glycolysis in response to the energy needs of the cell.

Overall, glycolysis converts one six-carbon molecule of glucose into two three-carbon molecules of pyruvate. The net products of this process are two molecules of ATP. 4 ATP produced -–minus 2 ATP used up) and two molecules of NADH

Detailed steps: Energy-requiring phase

Step 1. A phosphate group is transferred from ATP to glucose, making glucose-6-phosphate. Glucose-6-phosphate is more reactive than glucose, and the addition of the phosphate also traps glucose inside the cell since glucose with a phosphate can't readily cross the membrane.

Step 2. Glucose-6-phosphate is converted into its isomer, fructose-6-phosphate.

Step 3. A phosphate group is transferred from ATP to fructose-6-phosphate, producing fructose-1,6-bisphosphate. This step is catalyzed by the enzyme phosphofructokinase, which can be regulated to speed up or slow down the glycolysis pathway.

Step 4. Fructose-1,6-bisphosphate splits to form two three-carbon sugars: dihydroxyacetone phosphate DHAP and glyceraldehyde-3-phosphate. They are isomers of each other, but only one—glyceraldehyde-3-phosphate—can directly continue through the next steps of glycolysis.

Step 5. DHAP is converted into glyceraldehyde-3-phosphate. The two molecules exist in equilibrium, but the equilibrium is "pulled" strongly downward, in the scheme of the diagram above, as glyceraldehyde-3-phosphate is used up. Thus, all of the DHAP is eventually converted.

Detailed steps: Energy-releasing phase

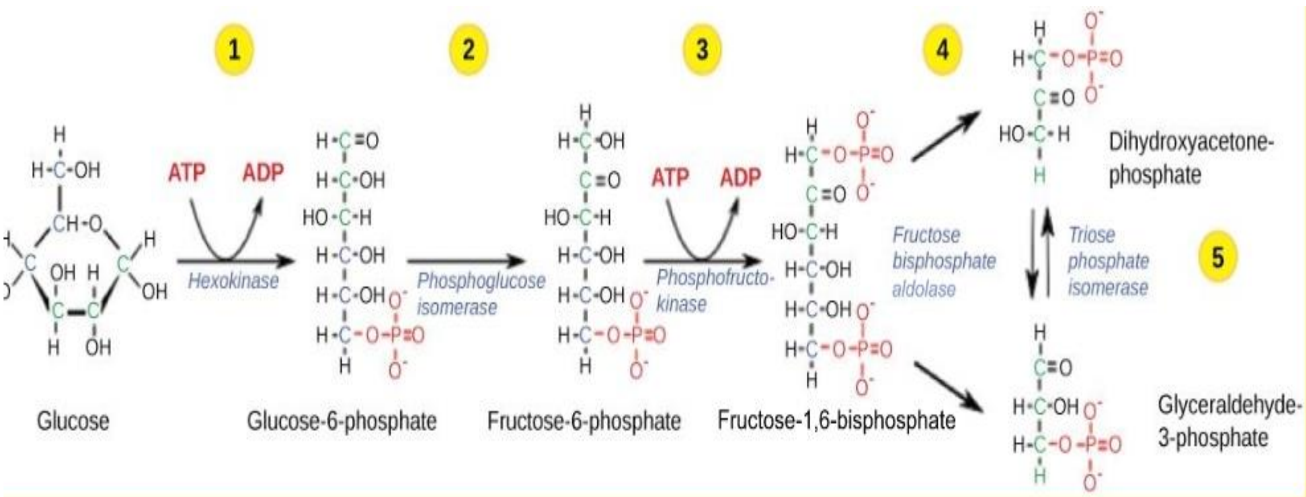
Step 6. Two half reactions occur simultaneously: 1) Glyceraldehyde-3-phosphate (one of the three-carbon sugars formed in the initial phase) is oxidized, and 2) NAD+, start superscript, plus, end superscript is reduced to NADH and H+start superscript, plus, end superscript. The overall reaction is exergonic, releasing energy that is then used to phosphorylate the molecule, forming 1,3-bisphosphoglycerate.

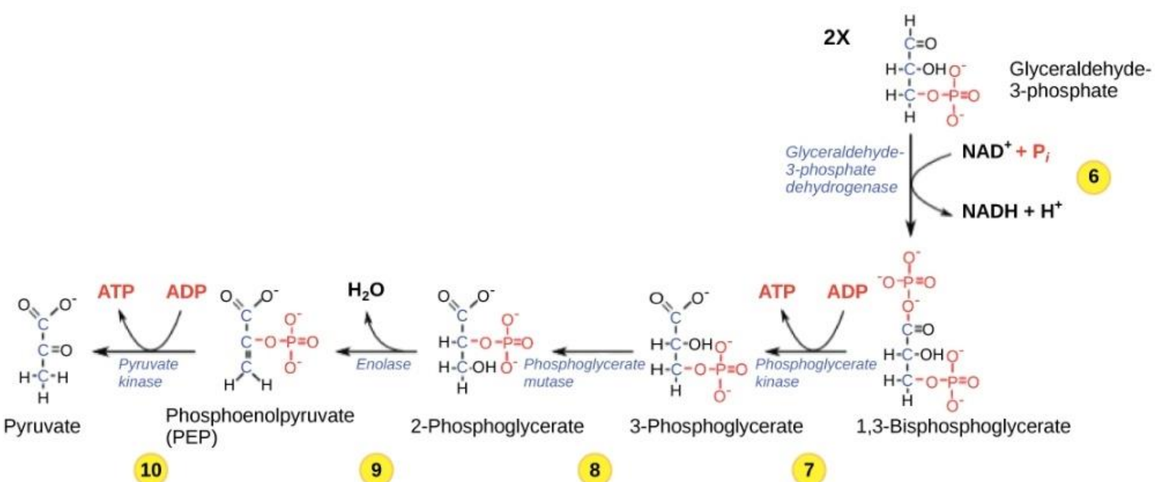
Step 7. 1,3-bisphosphoglycerate donates one of its phosphate groups to ADP making a molecule of ATP and turning into 3-phosphoglycerate in the process.

Step 8. 3-phosphoglycerate is converted into its isomer, 2-phosphoglycerate.

Step 9. 2-phosphoglycerate loses a molecule of water, becoming phosphoenolpyruvate PEP. PEP is an unstable molecule, poised to lose its phosphate group in the final step of glycolysis.

Step 10. PEP readily donates its phosphate group to ADPmaking a second molecule of ATP As it loses its phosphate, PEP is converted to pyruvate, the end product of glycolysis.





Photosynthesis (Photon = Light, Synthesis = Putting together) is an anabolic, endergonic process by which green plant synthesize carbohydrates (initially glucose) requiring carbon dioxide, water, pigments and sunlight. In other words, we can say that photosynthesis is transformation of solar energy/radiant energy/light energy (ultimate source of energy for all living organisms) into chemical energy.

Simple general equation of photo synthesis is as follows:

$$6CO_2 + 6H_2O \xrightarrow[\text{Chlorophyll}]{\text{Light}} C_6H_{12}O_6 + 6O_2$$

Thus, the overall correct biochemical reaction for photosynthesis can be written as:

$$6CO_2 + 12H_2O \xrightarrow[\text{Chlorophyll}]{\text{Sun Light}} C_6H_{12}O_6 + 6O_2 \uparrow + 6H_2O$$

Significance of Photosynthesis:

1. Photosynthesis is the most important natural process which sustains life on earth.

2. The process of photosynthesis is unique to green and other autotrophic plants. It synthesizes organic food from inorganic raw materials.

3. All animals and heterotrophic plants depend upon the green plants for their organic food, and therefore, the green plants are called producers, while all other organisms are known as consumers.

4. Photosynthesis converts radiant or solar energy into chemical energy. The same gets stored in the organic food as bonds between different atoms. Photosynthetic products provide energy to all organisms to carry out their life activities (all life is bottled sunshine).

5. Coal, petroleum and natural gas are fossil fuels which have been produced by the application of heat and compression on the past plant and animal parts (all formed by photosynthesis) in the deeper layers of the earth. These are extremely important source of energy.

6. All useful plant products are derived from the process of photosynthesis, e.g., timber, rubber, resins, drugs, oils, fibers, etc.

7. It is the only known method by which oxygen is added to the atmosphere to compensate for oxygen being used in the respiration of organisms and burning of organic fuels. Oxygen is important in (a) efficient utilization and complete breakdown of respiratory substrate and (b) formation of ozone in stratosphere that filters out and stops harmful UV radiations in reaching earth.

8. Photosynthesis decreases the concentration of carbon dioxide which is being added to the atmosphere by the respiration of organisms and burning of organic fuels. Higher concentration of carbon dioxide is poisonous to living beings.

9. Productivity of agricultural crops depends upon the rate of photosynthesis. Therefore, scientists are busy in genetically manipulating the crops.

Proteins: Large molecules composed of one or more chains of amino acids in a specific order determined by the base sequence of nucleotides in the DNA coding for the protein.

Proteins are required for the structure, function, and regulation of the body's cells, tissues, and organs. Each protein has unique functions. Proteins are essential components of muscles, skin, bones and the body as a whole.

Examples of proteins include whole classes of important molecules, among them enzymes, hormones, and antibodies.

Proteins are one of the three types of nutrients used as energy sources by the body, the other two being carbohydrate and fat. Proteins and carbohydrates each provide 4 calories of energy per gram, while fats produce 9 calories per gram.

Primary structure

The simplest level of protein structure, primary structure, is simply the sequence of amino acids in a polypeptide chain. For example, the hormone insulin has two polypeptide chains, A and B, shown in diagram below. (The insulin molecule shown here is cow insulin, although its structure is similar to that of human insulin.) Each chain has its own set of amino acids, assembled in a particular order. For instance, the sequence of the A chain starts with glycine at the N-terminus and ends with asparagine at the C-terminus, and is different from the sequence of the B chain.

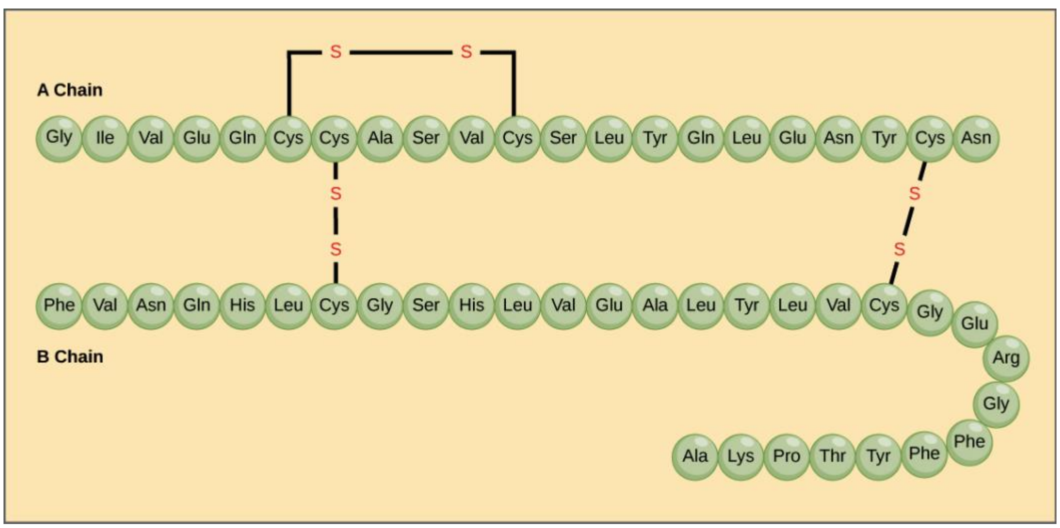


Image of insulin. Insulin consists of an A chain and a B chain. They are connected to one another by disulfide bonds (sulfur-sulfur bonds between cysteines). The A chain also contains an internal disulfide bond. The amino acids that make up each chain of insulin are represented as connected circles, each with the three-letter abbreviation of the amino acid's name.

The sequence of a protein is determined by the DNA of the gene that encodes the protein (or that encodes a portion of the protein, for multi-subunit proteins). A change in the gene's DNA sequence may lead to a change in the amino acid sequence of the protein. Even changing just one amino acid in a protein's sequence can affect the protein's overall structure and function.

For instance, a single amino acid change is associated with sickle cell anemia, an inherited disease that affects red blood cells. In sickle cell anemia, one of the polypeptide chains that make up hemoglobin, the protein that carries oxygen in the blood, has a slight sequence change. The glutamic acid that is normally the sixth amino acid of the hemoglobin β chain (one of two types of protein chains that make up hemoglobin) is replaced by a valine. This substitution is shown for a fragment of the β chain in the diagram below.

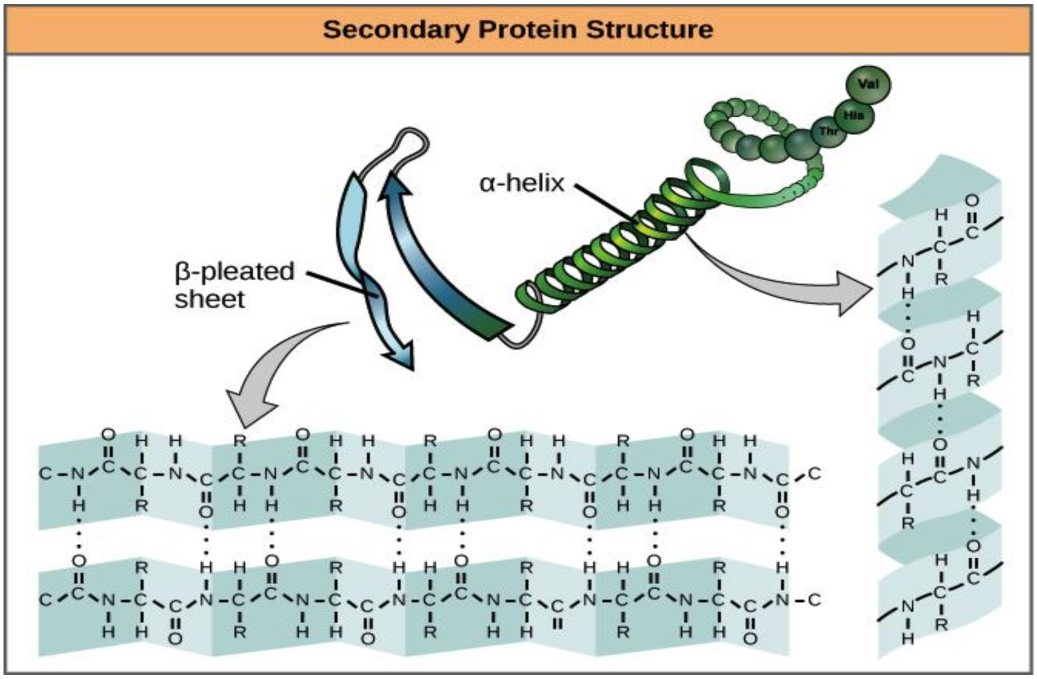
What is most remarkable to consider is that a hemoglobin molecule is made up of two α chains and two β chains, each consisting of about 150 amino acids, for a total of about 600 amino acids in the whole protein. The difference between a normal hemoglobin molecule and a sickle cell molecule is just 2 amino acids out of the approximately 600.

A person whose body makes only sickle cell hemoglobin will suffer symptoms of sickle cell anemia. These occur because the glutamic acid-to-valine amino acid change makes the hemoglobin molecules assemble into long fibers. The fibers distort disc-shaped red blood cells into crescent shapes. Examples of "sickled" cells can be seen mixed with normal, disc-like cells in the blood sample bel

kled cells get stuck as they try to pass through blood vessels. The stuck cells impair blood flow and can cause serious health problems for people with sickle cell anemia, including breathlessness, dizziness, headaches, and abdominal pain.

Secondary structure

The next level of protein structure, secondary structure, refers to local folded structures that form within a polypeptide due to interactions between atoms of the backbone. (The backbone just refers to the polypeptide chain apart from the R groups – so all we mean here is that secondary structure does not involve R group atoms.) The most common types of secondary structures are the α helix and the β pleated sheet. Both structures are held in shape by hydrogen bonds, which form between the carbonyl O of one amino acid and the amino H of another.



Images showing hydrogen bonding patterns in beta pleated sheets and alpha helices.

In an α helix, the carbonyl (C=O) of one amino acid is hydrogen bonded to the amino H (N-H) of an amino acid that is four down the chain. (E.g., the carbonyl of amino acid 1 would form a hydrogen bond to the N-H of amino acid 5.) This pattern of bonding pulls the polypeptide chain into a helical structure that resembles a curled ribbon, with each turn of the helix containing 3.6 amino acids. The R groups of the amino acids stick outward from the α helix, where they are free to interact^33cubed.

In a β pleated sheet, two or more segments of a polypeptide chain line up next to each other, forming a sheet-like structure held together by hydrogen bonds. The hydrogen bonds form between carbonyl and amino groups of backbone, while the R groups extend above and below the plane of the sheet^33cubed. The strands of a β pleated sheet may be parallel, pointing in the same direction (meaning that their N- and C-termini match up), or antiparallel, pointing in opposite directions (meaning that the N-terminus of one strand is positioned next to the C-terminus of the other).

Certain amino acids are more or less likely to be found in α-helices or β pleated sheets. For instance, the amino acid proline is sometimes called a “helix breaker” because its unusual R group (which bonds to the amino group to form a ring) creates a bend in the chain and is not compatible with helix formation^44start superscript, 4, end superscript. Proline is typically found in bends, unstructured regions between secondary structures. Similarly, amino acids such as tryptophan, tyrosine, and phenylalanine, which have large ring structures in their R groups, are often found in β pleated sheets, perhaps because the β pleated sheet structure provides plenty of space for the side chains^44start superscript, 4, end superscript.

Many proteins contain both α helices and β pleated sheets, though some contain just one type of secondary structure (or do not form either type).

Tertiary structure

The overall three-dimensional structure of a polypeptide is called its tertiary structure. The tertiary structure is primarily due to interactions between the R groups of the amino acids that make up the protein.

R group interactions that contribute to tertiary structure include hydrogen bonding, ionic bonding, dipole-dipole interactions, and London dispersion forces – basically, the whole gamut of non-covalent bonds. For example, R groups with like charges repel one another, while those with opposite charges can form an ionic bond. Similarly, polar R groups can form hydrogen bonds and other dipole-dipole interactions. Also important to tertiary structure are hydrophobic interactions, in which amino acids with nonpolar, hydrophobic R groups cluster together on the inside of the protein, leaving hydrophilic amino acids on the outside to interact with surrounding water molecules.

Finally, there's one special type of covalent bond that can contribute to tertiary structure: the disulfide bond. Disulfide bonds, covalent linkages between the sulfur-containing side chains of cysteines, are much stronger than the other types of bonds that contribute to tertiary structure. They act like molecular "safety pins," keeping parts of the polypeptide firmly attached to one another.

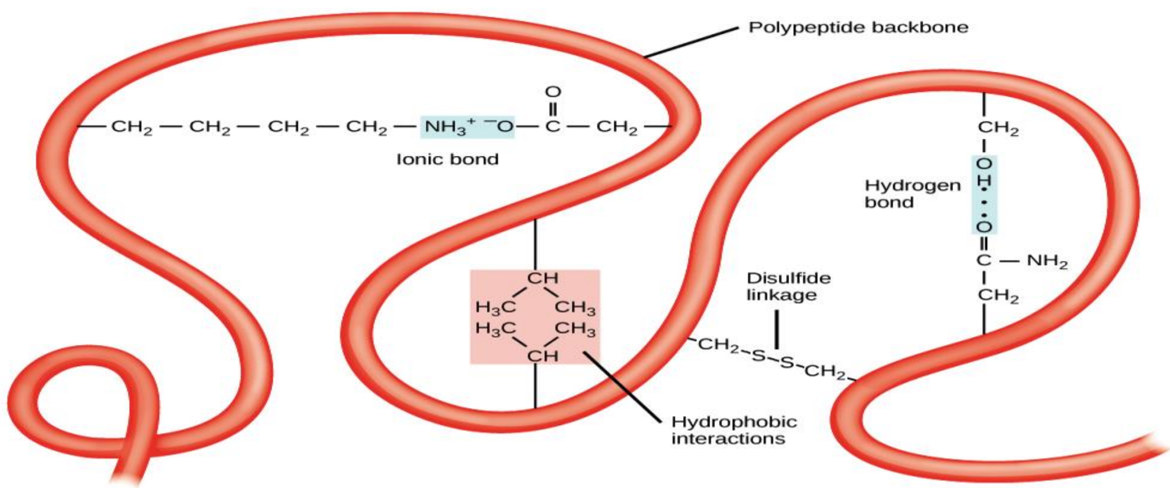


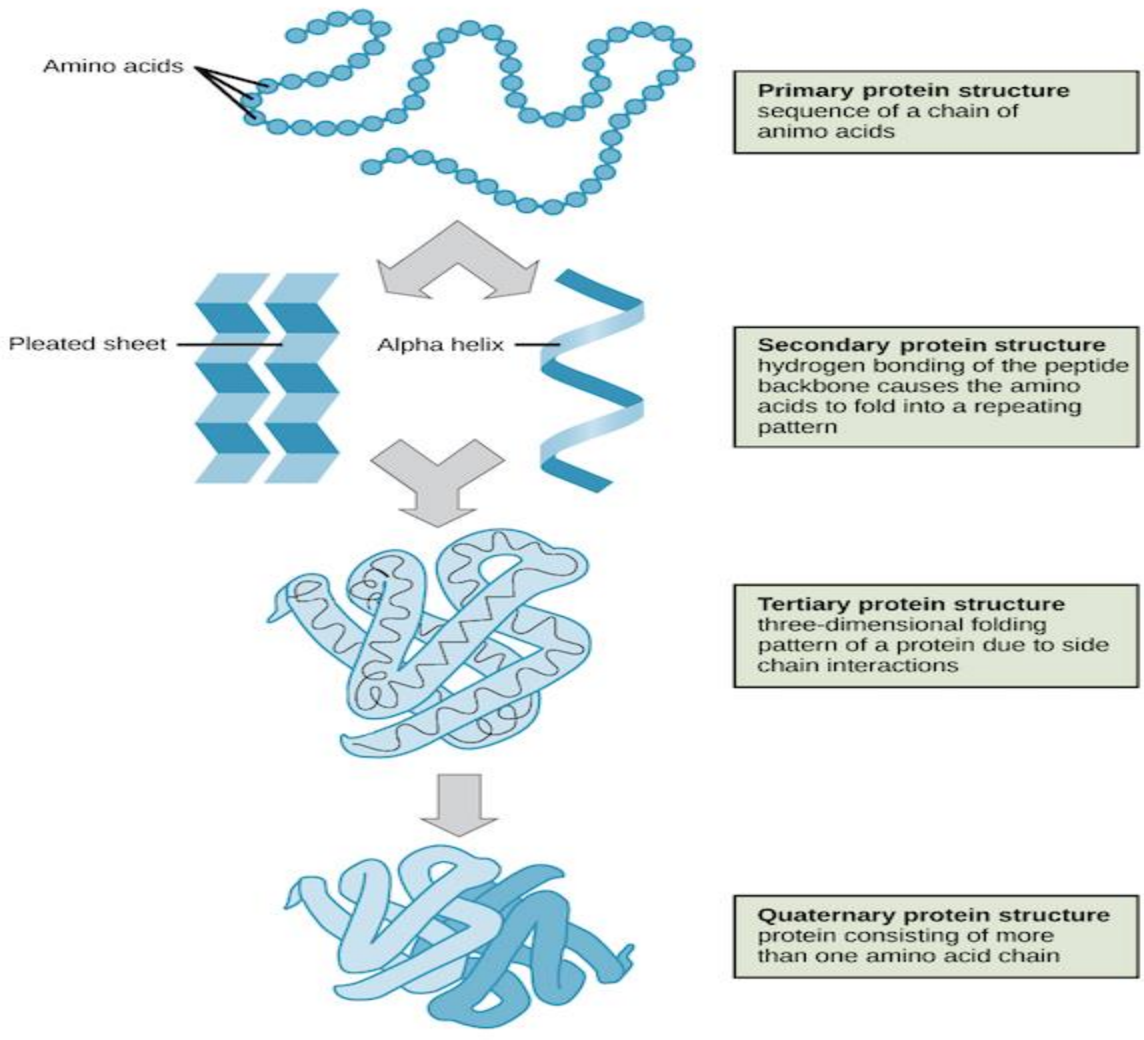
Image of a hypothetical polypeptide chain, depicting different types of side chain interactions that can contribute to tertiary structure. These include hydrophobic interactions, ionic bonds, hydrogen bonds, and disulfide bridge formation.

Quaternary structure

Many proteins are made up of a single polypeptide chain and have only three levels of structure (the ones we've just discussed). However, some proteins are made up of multiple polypeptide chains, also known as subunits. When these subunits come together, they give the protein its quaternary structure.

We've already encountered one example of a protein with quaternary structure: hemoglobin. As mentioned earlier, hemoglobin carries oxygen in the blood and is made up of four subunits, two each of the α and β types. Another example is DNA polymerase, an enzyme that synthesizes new strands of DNA and is composed of ten subunits^55start superscript, 5, end superscript.

In general, the same types of interactions that contribute to tertiary structure (mostly weak interactions, such as hydrogen bonding and London dispersion forces) also hold the subunits together to give quaternary structure.



Flowchart depicting the four orders of protein structure.