Introduction to Astrobiology

Meaning of the term "astrobiology"

Astrobiology

- Used in space missions of the National Aereonautics & Space Administration (NASA)
- Adopted by the community of biologists and chemists interested in the study of the origin of life
- Now commonly adopted in all studies of life in the universe
  - Study of the living universe
  - Origin, distribution, evolution and destiny of life in the universe
    - Includes terrestrial life by definition

Other terms used to design studies of life in the Universe

Bioastronomy

- Adopted by the International Astronomical Union (IAU)
- Mostly used inside the astronomical community
  - Search for planets around other stars
  - Search for interstellar molecules of biological interest
  - Detection of possible signatures of biological activity
  - …

Exobiology

- Used in space missions of the European Space Agency (ESA)
  - Search for life ouside Earth
    - This definition does not include terrestrial life and can be criticized since there is no evidence for life outside Earth so far

Terrestrial Life

What is life ?

The definition of life is still the subject of ongoing scientific debate

The problem of life definition

- There is no single property that is intrinsic and unique to life
  - Life properties, if considered one by one, can be present also in the non biological world
- There is no sharp separation between living and non-living systems

The difficulty of defining life makes hard to define astrobiology in a rigorous way

- Leaves the door open to the following criticism:
  - Does it make sense to search for something in the universe that we are not even able to define on earth?

The definition of life

Life is usually defined by listing a <u>set of properties shared by living systems</u>

Here is an example of set of properties used to define life

Metabolism

Reproduction

Genetic information

Adaptment to the environment

Other sets of properties can be used
The choice of the set of properties varies according to different authors
and tends to change in the course of time
following the progress in our understanding of the biological world

Properties of life

Metabolism

Living organisms use and transform energy by means of a network of chemical reactions called metabolism

- Examples of metabolism
  - Photosynthesis (carbon fixation)
  - Catabolism (digestion)
  - Anabolism (synthesis of organic molecules)
  - Respiration (extraction of chemical energy)
- The energy is extracted through electron transfer and stored in molecules that are later used to exchange energy

In the non-biological world there are examples of chemical reactions with transfer of electrons and storage of energy, similar to the ones that take place in the biological world

- This makes hard to define life using only metabolic properties

Properties of life

Reproduction

Most living organisms have the capability of reproduction, that is to generate new organisms of the same species

However, there are examples of organisms lacking the capability of reproduction

- Red globules, mules
- Therefore, the capability of reproduction does not allow us to discriminate the biological world from the non-biological world in all cases

Properties of life

Genetic information

- Living organisms carry the instructions used to drive their metabolism and reproduction
  - Such instructions constitute the genetic information of life
- The presence of genetic information is one of the most characteristic features of life
  - However, the presence of genetic information is not sufficient, by itself, for identifying living organisms
    - As an example, viruses carry their own genetic information, but do not have an internal metabolism and can reproduce only in a host organism

Properties of life

Adaptation to the environment

- Physiological adaptation
  - Feedback mechanisms that allow organisms to tune their metabolic functions in response to changes of physical/chemical conditions of the environment
- Genetic adaptation
  - Natural selection of genetic properties of individual organisms that provide adaptation to long term changes of the environmental conditions
  - This form of adaptation takes place in the course of many generations of organisms of the same species, leading to the evolution of the species, as proposed by Darwin
  - The evolution of the species results from the accumulation of changes of the genetic pool induced by natural selection

Properties of life

Self organization

Living organisms organize themselves spontaneously, creating a network of substructures which cooperate to carry out the metabolic, genetic and reproduction functions

The cell

The minimum structural unit which has the properties of life is called "cell"

Organisms can be unicellular, if they are composed of a single cell, or multicellular, if they are composed of many cells that work in cooperation

Cells are delimited by a border that provides a separation from the external environment

- The border allows for selective exchanges of energy and matter with the environment
- The border is, in practice, a membrane

Life definitions in astrobiology (1)

Operational definition adopted by NASA
Joyce (1994)

"Life is a self-sustained chemical system
capable of Darwinian evolution"

The chemical properties

The search for chemical disequilibrium offers a way to search for traces of life,
but care should be taken since chemical traces may lead to ambiguous results

Darwinian evolution

Is one of the most characteristic features of life,
but not very useful to identify traces of extraterrestrial life

Life definitions in astrobiology (2)

Example of definition based on thermodynamical concepts
Schulze-Makuch et al. (2002)

"Life is
(1) composed of bounded microenvironments in thermodynamic disequilibrium with the external environment,
(2) capable of transforming energy and the environment to maintain a low-entropy state and
(3) capable of information encoding and transmission."

Concluding remarks on the definition of life

Our difficulty to define life may reflect the lack of a proper scientific theory of life processes

- Analogy:
  - It would not possible to provide a simple definition of “water” such as “H_2O”, without a scientific theory of atoms and molecules
  - Before we understood the nature of atoms and molecules, water was defined making use of a list of its properties

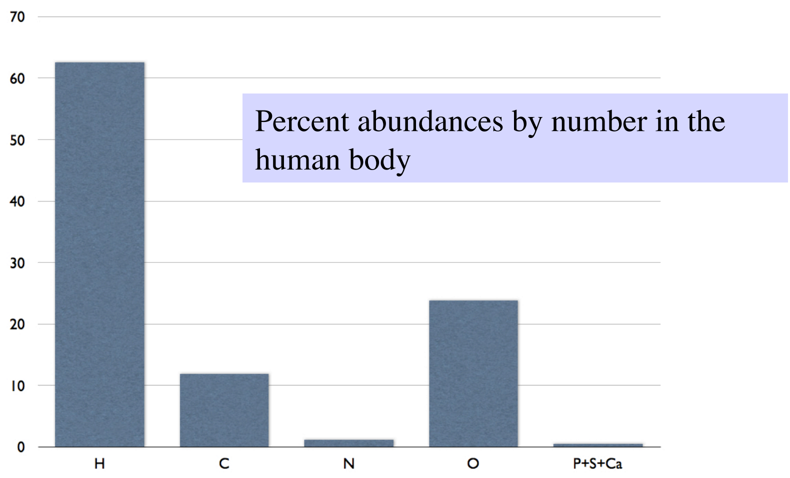
Chemical properties of life

Chemical elements of life

Biological molecules and macromolecules

The chemical elements of life (1)

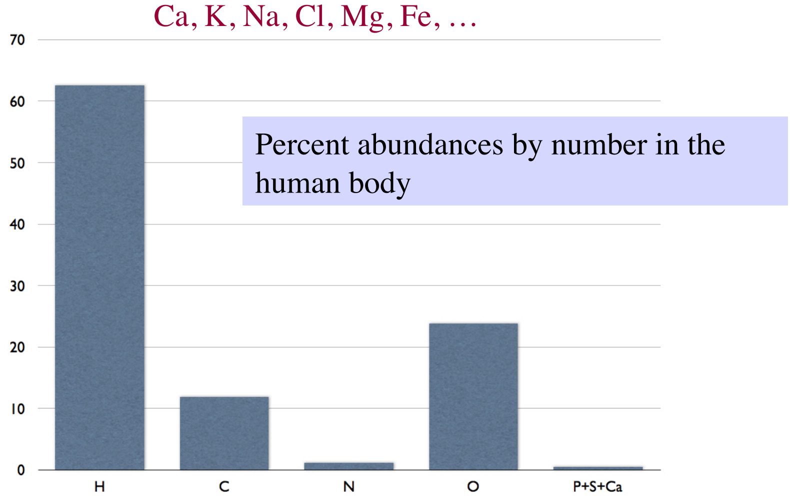
Most abundant elements in living systems:
H, C, N, O



The high abundance of H and O and their ratio approximately 2:1 is due to the fact that water is the substrate of life

The chemical elements of life (2)

Other essential elements in living systems:
S, P
Ca, K, Na, Cl, Mg, Fe, …

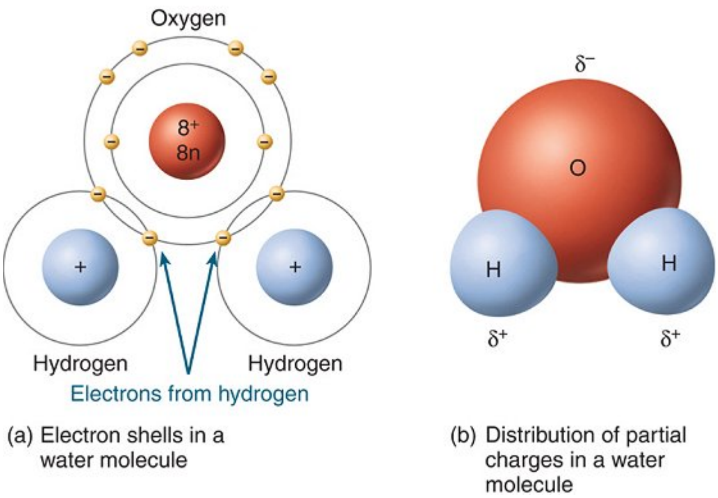


In spite of their lower abundance, also S and P are extremely important
Also other elements, present in trace quantities, play a fundamental role

The water molecule

Most abundant molecule in living organisms

The water molecule is polar

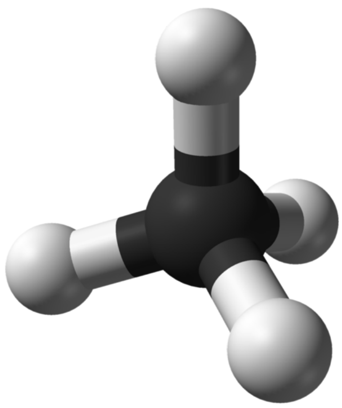


(a) Electron shells in a water molecule

(b) Distribution of partial charges in a water molecule

Chemical properties of molecules relevant to life (1)

- Polar and non polar molecules
  - The polar character depends on the geometrical distribution of electric charges of the molecule
    - Water is polar because of the asymmetric distribution of charges
    - Methane is non polar (no electric dipole)
- Polar molecules
  - can be solved in water
  - are hydrophilic
- Non-polar molecules
  - cannot be solved in water
  - are hydrophobic

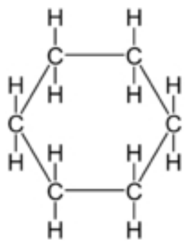


Methane: a non-polar molecule

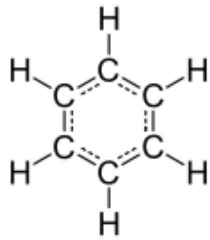
Chemical properties of molecules relevant to life (2)

Saturated/unsaturated molecules

A saturated molecule is one in which all the valences of the carbon atoms are satisfied by single covalent bonds.



Example of saturated molecule:
Cyclohexane



Example of unsaturated molecule:
aromatic ring of Benzene

Chemical bonds in biology

Most important chemical bonds in biological molecules

<u>Covalent bonds</u>
<u>Hydrogen bonds</u>
Van der Waals forces

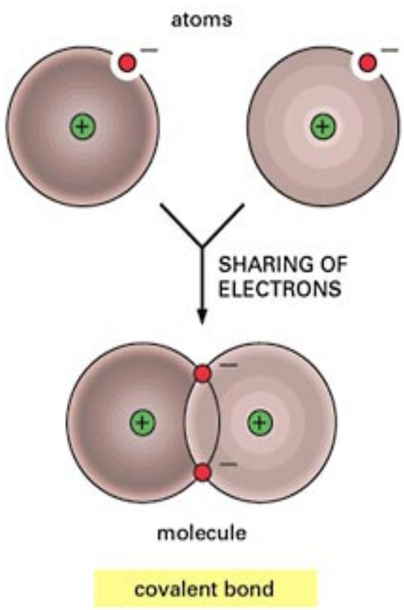
These bonds allow the formation of a extremely large variety of 3-D, stable and flexible structures

Chemical bonds not used biological molecules

Ionic bonds
Metallic bonds

Covalent bonds:

used in the “skeleton” of biological molecules



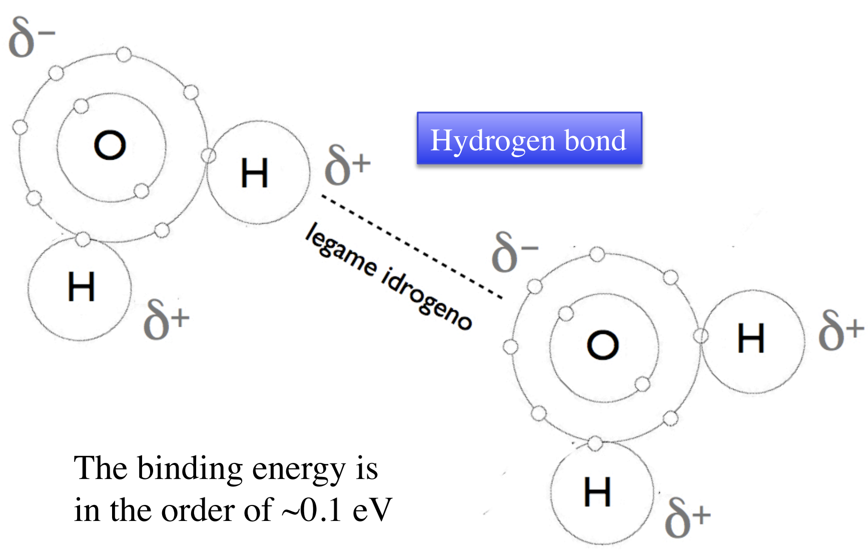
The binding energy is in the order of ~4 eV

Hydrogen bonds

Examples:

Intermolecular forces between water molecules

<u>Intramolecular</u> and <u>intermolecular</u> forces in biological macromolecules



The binding energy is in the order of ~0.1 eV

Functional groups in biomolecules

Groups of atoms that are responsible for the characteristic chemical properties of molecules and, in particular, of biological macromolecules

TABLE 2.1 Common Functional Groups Found in Biomolecules

Functional group	Chemical formula	Structure	Chemical property
Hydroxyl	—OH	—O—H	Polar
Sulfhydryl	—SH	—S—H	Polar
Phosphate	$—HPO_4^-$	—O—P(=O)(—OH)—O^-	Polar
Carboxyl	—COOH	—C(=O)—OH	Acid
Amino	$—NH_2$	—N(—H)—H	Base

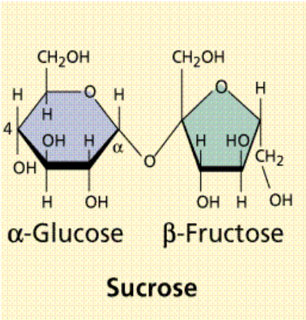
proton donor

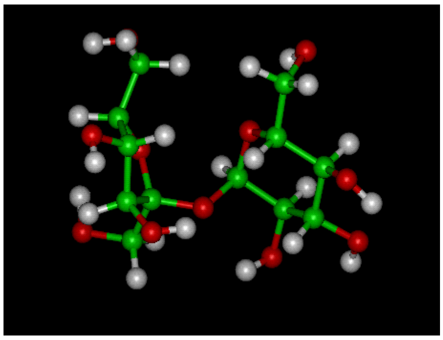
Biological macromolecules

Macromolecules are created by polymerization of a large number of subunits (monomers)

There are four types of biological macromolecules: carbohydrates, lipids, proteins and nucleic acids

Biological macromolecules
1. Carbohydrates (saccharides)





The most abundant molecules in the biological world

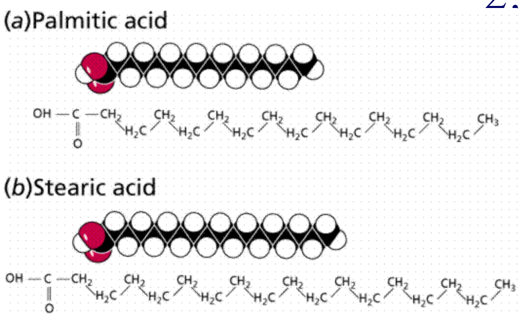
Primary source of <u>chemical energy</u> for most organims

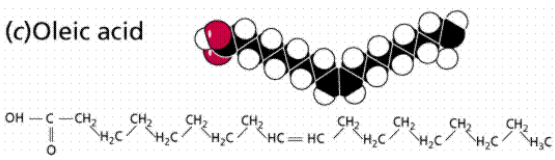
General formula: $C_x(H_2O)_y$

- Monosaccharides
- Oligosaccharides
  - From 2 to 10 units of monosaccharides
- Polysaccharides
  - More than 10 monosaccharides

Ribose and deoxyribose are essential constituents of the <u>nucleic acids</u>

Biological macromolecules
2. Lipids





Heterogeneous class of organic molecules with common solubility properties

- Soluble in certain types of non-polar solvents
- <u>Insoluble in water</u>

Characterized by a larger number of C−H bonds with respect to carbohydrates

- Used to <u>store energy</u>

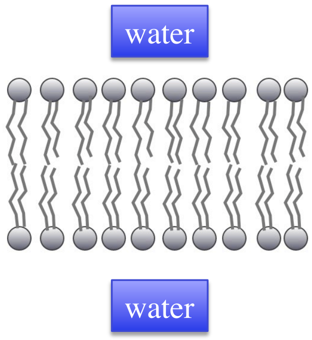
Examples of different types of lipids:

- Triglycerids
- Phospholipids
  - Constituents of the <u>cell membranes</u>

Phospholipids and cell membranes

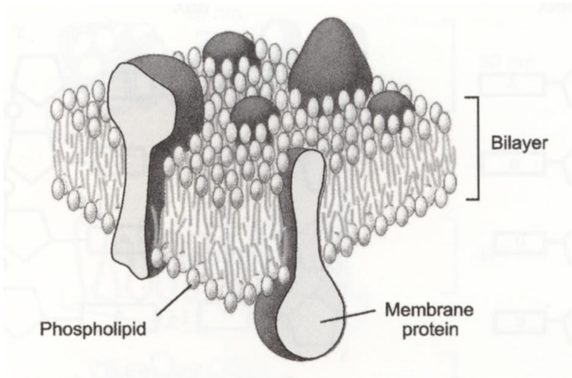
Phospholipids

Examples of amphiphilic molecules, i.e. molecules with a hydrophilic end and a hydrophobic end



In liquid water amphiphilic molecules spontaneously form a double layer of molecules (bilayer), with the hydrophobic ends facing each other in the inner part, and the hydrophilic ends facing the water

Bilayers of phospholipids are the main structural components of cell membranes



Biological macromolecules
3. Proteins

Proteins perform different types of fundamental functions in living organisms

Structural and enzymatic functions, among others

They contribute to about half the mass of the cell

Proteins are polymers of amino acids

Amino acids are molecules featuring an amino group and a carboxyl group

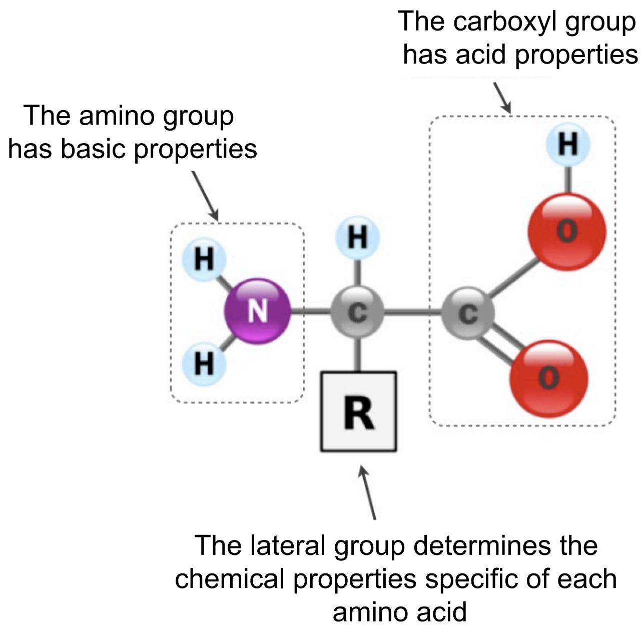
Short chains of amino acids are called peptydes

Long, unbranched peptyde chains are called polypeptides

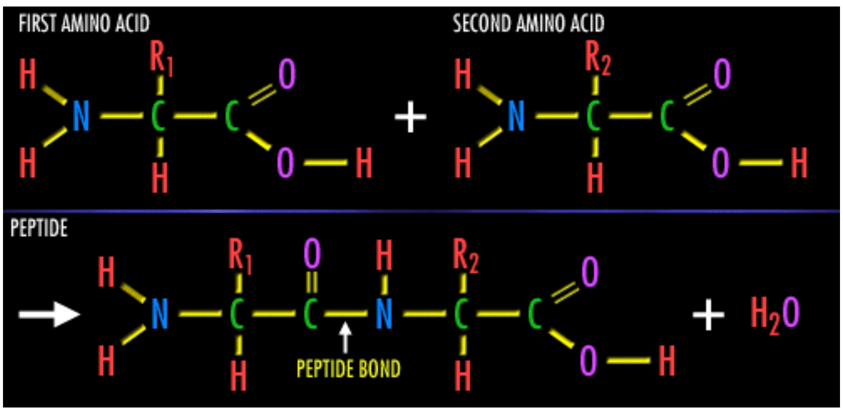
Proteins are formed by one or more chains of polypeptides

Molecular masses of proteins vary between ~10^3 e ~10^6 atomic mass units

Amino acids



From amino acids to polypeptides



Amino acids are bound to each other with peptide bonds

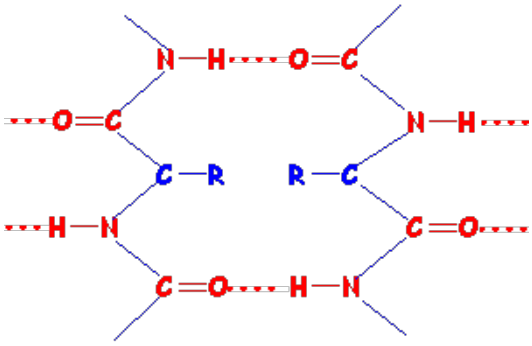
The carboxyl end of one molecule is tied to the amino end of the next molecule

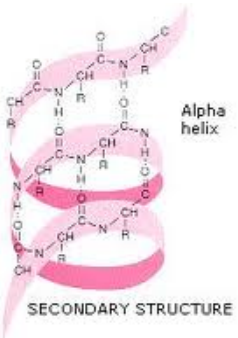
A sequence OC-NH is formed (peptide bond)

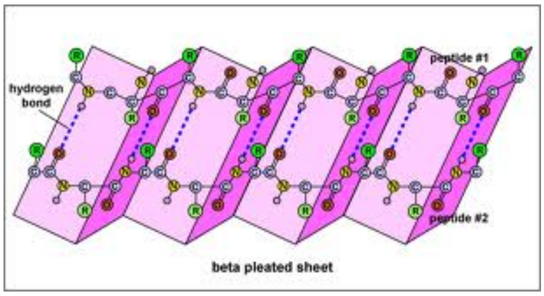
A water molecule is produced each time a peptide bond is created

From polypeptides to proteins

Importance of hydrogen bonds as intramolecular forces







Biological amino acids

Proteins use only 20 types of amino acids

Organic chemistry allows for the existence of thousands of amino acids

Apparently, terrestrial life has "chosen" a short list of amino acids, sufficiently representative of the different types of chemical properties required to build up the variety of proteins necessary to living organisms

Table 7.2 *The Twenty Amino Acids Found in Living Organisms*

*Amino Acid**	*Chemical Formula*	*Number of Atoms*
L-Alanine	$C_3H_7O_2N$	13
L-Arginine	$C_6H_{15}O_2N_4$	27
L-Asparagine	$C_4H_8O_3N_2$	17
L-Aspartic Acid	$C_4H_6O_4N$	15
L-Cysteine	$C_3H_7O_2NS$	14
L-Glutamic Acid	$C_5H_8O_4N$	18
L-Glutamine	$C_5H_{10}O_3N_2$	20
Glycine	$C_2H_5O_2N$	10
L-Histidine	$C_6H_9O_2N_3$	20
L-Isoleucine	$C_6H_{13}O_2N$	22
L-Leucine	$C_6H_{13}O_2N$	22
L-Lysine	$C_6H_{15}O_2N_2$	25
L-Methionine	$C_5H_{11}O_2NS$	20
L-Phenylalanine	$C_9H_{11}O_2N$	23
L-Proline	$C_5H_9O_2N$	17
L-Serine	$C_3H_7O_3N$	14
L-Threonine	$C_4H_9O_3N$	17
L-Tryptophan	$C_{11}H_{12}O_2N_2$	27
L-Tyrosine	$C_9H_{11}O_3N$	24
L-Valine	$C_5H_{11}O_2N$	19

Biological macromolecules
4. Nucleic acids

Nucleic acids store and use the genetic information

There are different types; some of them are specialized in storing the information, others in using the information for driving metabolic/replication processes

Nucleic acids are polymers of nucleotides

Depending on the type of organism, they may contain ~ $10^6 – 10^8$ nucleotides

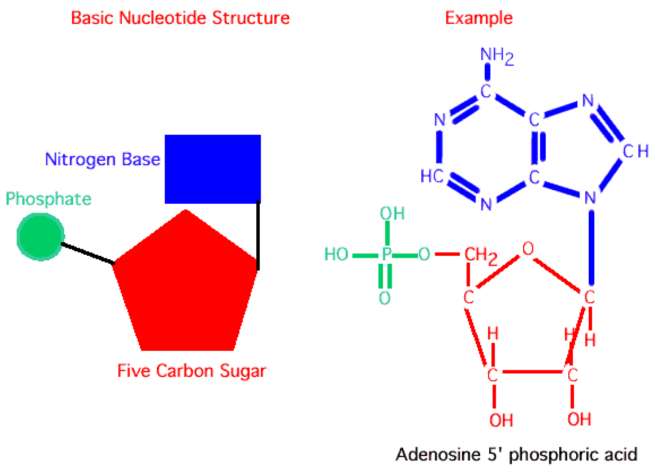
Nucleotides

Each nucleotide features:

a nitrogenous organic base (nucleobase)

a 5 carbon atoms sugar

a phosphate group



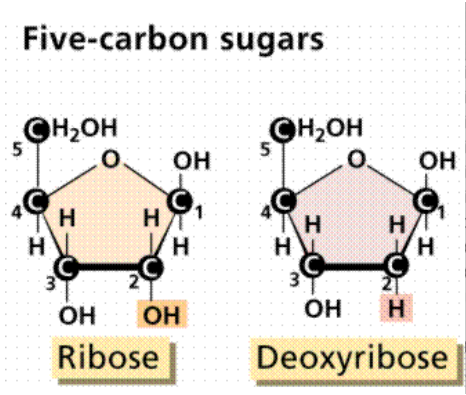
Constituents of nucleotides

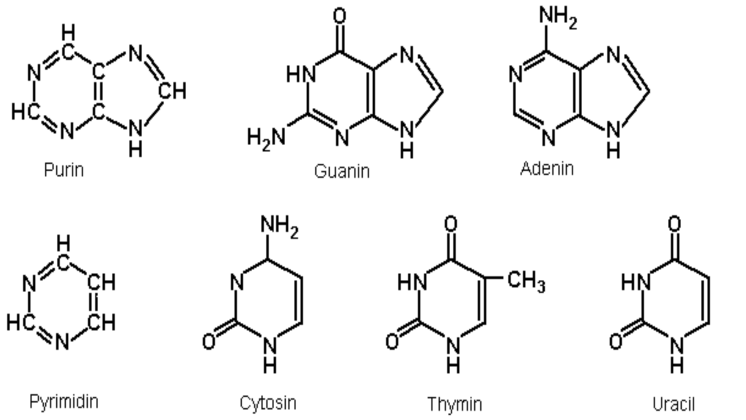
Sugars

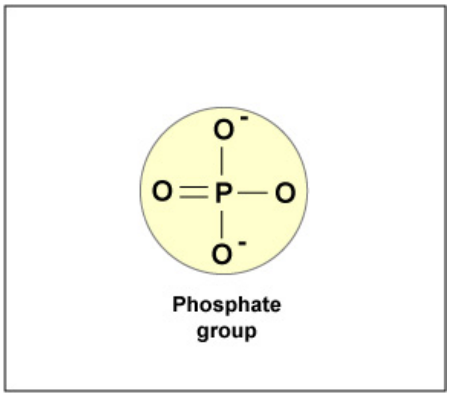
- Ribose
- Deoxyribose

Nitrogenous bases

- Aromatic rings with N substitutions
- Purines and Pyrimidines
- Double and single rings







Nucleic acids: RNA

RNA has a single strand of nucleotides

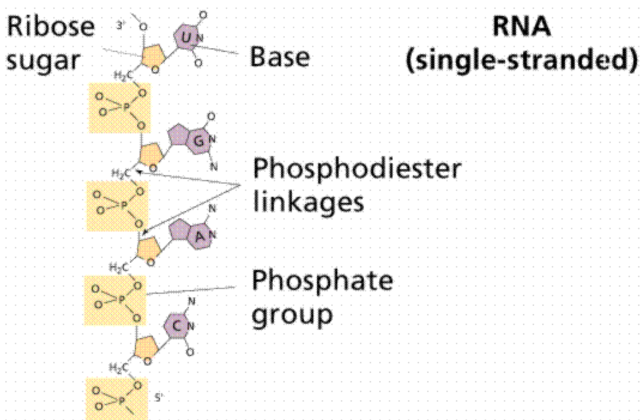
The backbone of the strand is made up of a sequence of phosphate groups and <u>ribose</u> sugars

Has 4 types of nucleobases

- Purines
  - Adenine, Guanine
- Pyrimidines
  - Cytosine, Uracyl

RNA drives the synthesis of proteins

The order of the nitrogen bases on the backbone determines the sequence in which amino acids are assembled



Nucleic acids: DNA

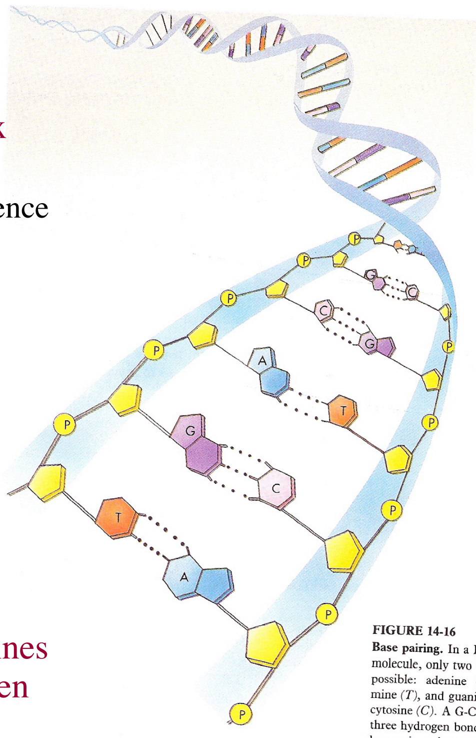


FIGURE 14-16
Base pairing. In a DNA molecule, only two base p
possible: adenine (*A*) w
mine (*T*), and guanine (*G*
cytosine (*C*). A G-C base
three hydrogen bonds; an
base pair, only two.

DNA has two strands that form a double helix structure

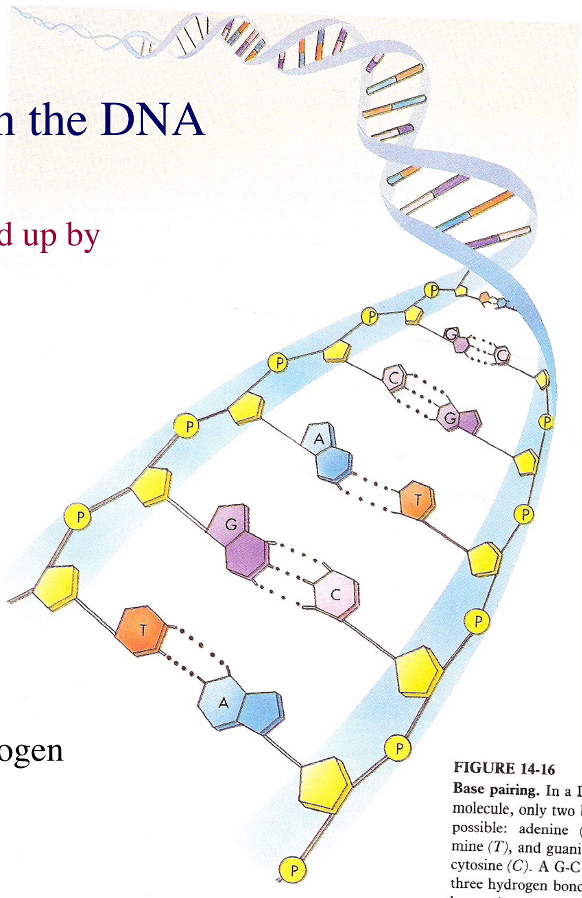
The backbone of each strand is made up of a sequence of phosphate groups and <u>deoxyribose</u> sugars

DNA has 4 types of nucleobases

- 2 purins
  - Adenine e Guanine
- 2 pyrimidins
  - Cytosine e Thymine
    - Thymine replaces Uracyl, which is instead used in the RNA

The complementarity of purines and pyrimidines plays a fundamental role in the pairing between the two strands

Hydrogen bonds in the DNA



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The two strands of the DNA are tied up by hydrogen bonds

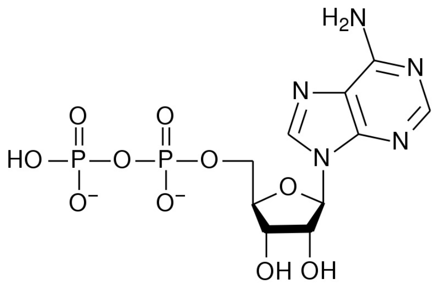
- G-C pairs have 3 bonds
- T-A pairs have 2 bonds

Example of the importance of hydrogen bonds as intramolecular forces

Molecules used for energy exchange

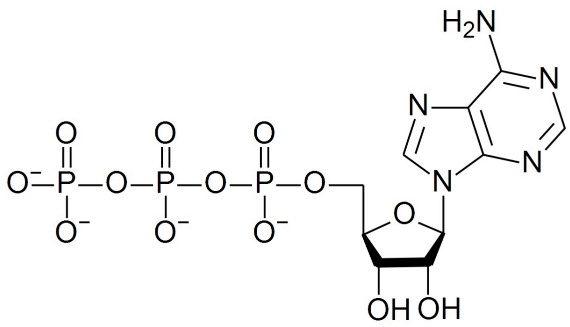
ADP

Adenosine diphosphate



ATP

Adenosine triphosphate



Homochirality of biological macromolecules

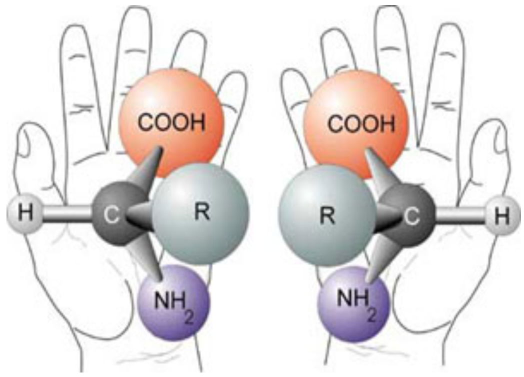
Chiral molecules are a special case of isomers, i.e. molecules with same chemical formula, but different structure

Chiral molecules cannot be superimposed to their mirror image

- Chiral molecules have a center of symmetry
- The two mirror images of a chiral molecule are called enantiomers
  - The two types of enantiomers are called, for instance, “left” (L) and “right” (D)

Amino acids are examples of chiral molecules

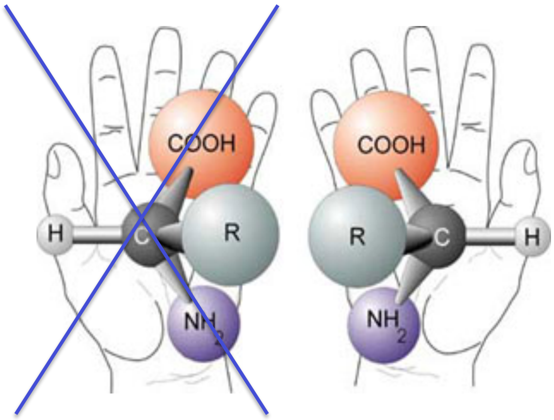
- The carbon atom at the center of the amino acid is the center of symmetry (stereocenter) of the molecule



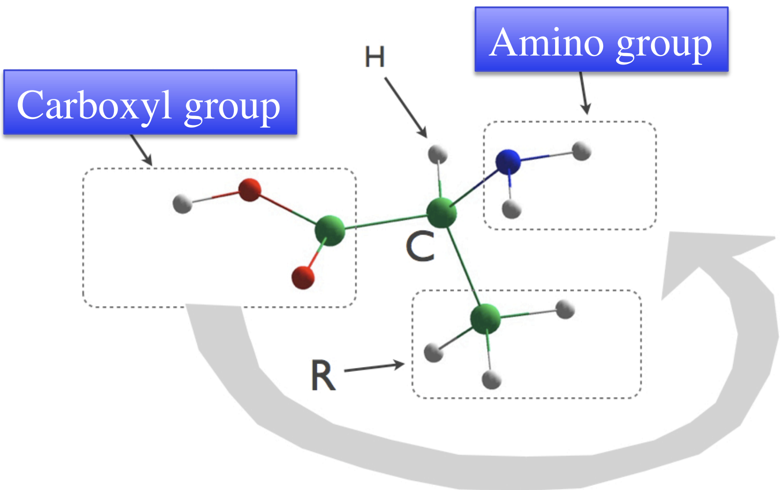
Homochirality of biological macromolecules

Amino acids of biological molecules are homochiral because they only show one type of the two enantiomers

Specifically, protein amino acids only show the L-type enantiomers



Example of homochiral amino acid: L-alanine

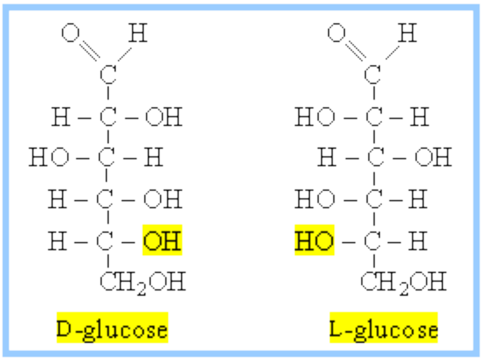


"CORN" convention used to distinguish L and D aminoacids

Homochirality of biological macromolecules

In addition to amino acids, also most biological sugars are homochiral

The convention used to discriminate "L" and "D" is a different one (we are not interested)



Racemic mixture

has equal amounts of left- and right-handed enantiomers of a chiral molecule

The non biological world is racemic

The biological world shows enantiomeric eccess

This fact provides a way to discriminate biological from non-biological compounds

Energy and Life

Energy and carbon sources

Living organisms require energy and carbon to carry out their metabolism

Living organisms can be classified according to the way they fix carbon and energy

Autotrophs adquire energy directly from the abiotic world

From solar photons or from redox (reduction-oxidation) reactions

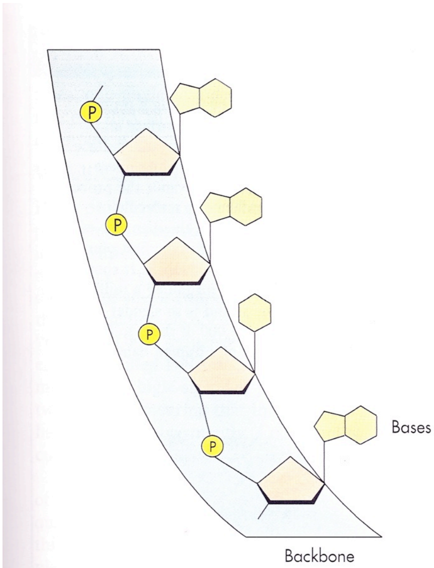
Eterotrophs adquire energy from organic molecules

The organic molecules that have been previously produced by autotrophs

The genetic information

The genetic information is stored in the <u>sequence</u> of nucleobases attached to the backbone of the nucleic acids

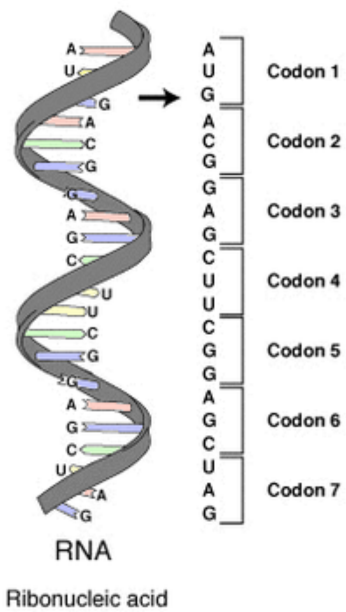
The order of the nucleobases is not constrained by chemical laws



The genetic information

The genetic information is stored in <u>digital</u> form

- The information is coded <u>in triplets of nucleobases called codons</u>
- Each codon uses 3 of the 4 nucleobases of the nucleic acid
  - In the case of the RNA the nucleobases are: A=Adenine,G=Guanine, C=Citosine, U=Uracyl



The genetic code

Each codon uniquely identifies a single amino acid

Some aminoacids are coded by more than one codon

Some codons are used as a “stop” signal of the sequence

Second letter

First letter	U	C	A	G	Third letter
U	UUU Phe UUC Phe UUA Leu UUG Leu	UCU Ser UCC Ser UCA Ser UCG Ser	UAU Tyr UAC Tyr UAA Stop UAG Stop	UGU Cys UGC Cys UGA Stop UGG Trp	U C A G
C	CUU Leu CUC Leu CUA Leu CUG Leu	CCU Pro CCC Pro CCA Pro CCG Pro	CAU His CAC His CAA Gln CAG Gln	CGU Arg CGC Arg CGA Arg CGG Arg	U C A G
A	AUU Ile AUC Ile AUA Ile AUG Met	ACU Thr ACC Thr ACA Thr ACG Thr	AAU Asn AAC Asn AAA Lys AAG Lys	AGU Ser AGC Ser AGA Arg AGG Arg	U C A G
G	GUU Val GUC Val GUA Val GUG Val	GCU Ala GCC Ala GCA Ala GCG Ala	GAU Asp GAC Asp GAA Glu GAG Glu	GGU Gly GGC Gly GGA Gly GGG Gly	U C A G

The genetic code

The <u>code is universal, for all terrestrial life forms</u>, from bacteria to man

with a few, partial exceptions

Second letter

First letter	U	C	A	G	Third letter
U	UUU Phe UUC Phe UUA Leu UUG Leu	UCU Ser UCC Ser UCA Ser UCG Ser	UAU Tyr UAC Tyr UAA Stop UAG Stop	UGU Cys UGC Cys UGA Stop UGG Trp	U C A G
C	CUU Leu CUC Leu CUA Leu CUG Leu	CCU Pro CCC Pro CCA Pro CCG Pro	CAU His CAC His CAA Gln CAG Gln	CGU Arg CGC Arg CGA Arg CGG Arg	U C A G
A	AUU Ile AUC Ile AUA Ile AUG Met	ACU Thr ACC Thr ACA Thr ACG Thr	AAU Asn AAC Asn AAA Lys AAG Lys	AGU Ser AGC Ser AGA Arg AGG Arg	U C A G
G	GUU Val GUC Val GUA Val GUG Val	GCU Ala GCC Ala GCA Ala GCG Ala	GAU Asp GAC Asp GAA Glu GAG Glu	GGU Gly GGC Gly GGA Gly GGG Gly	U C A G

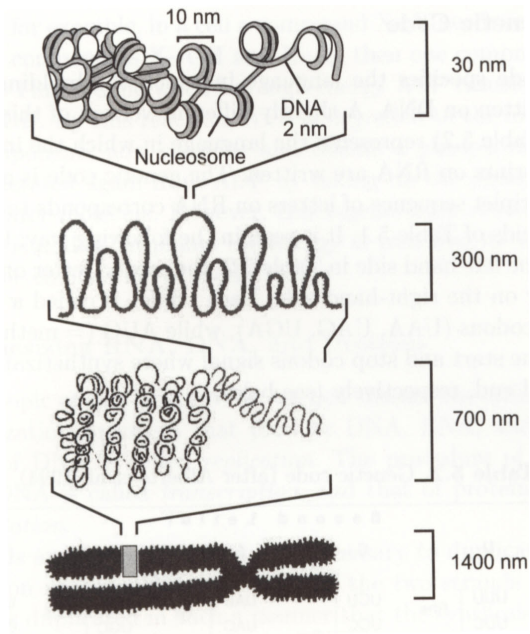
Genes

From the point of view of the information content, a gene is a sequence of codons with a specific function

As an example, a sequence that specifies how to build up a specific amino acid

In practice, genes are a sequence of nucleobases along a strand of a nucleic acid

In complex organisms, the number of genes is extremely high and the DNA needs to be stored in very compact structures, called chromosomes



Genetic sequences and classification of organisms

The techniques of molecular biology allow us to classify organisms on the basis of their genetic sequences, rather than on their morphology or phenotype (composite of observable traits and behaviour of organisms)

The classification based on genetic sequences has revolutionized our understanding of unicellular organisms

The classification based on genetic sequences has lead to distinguish three different types of unicellular organisms:

archaea, eubacteria and eukaryotes

Archaea and eubacteria have a much simpler cellular structure than eukaryotes and are called prokaryotes

Life in the Universe

Lessons learned from the study of terrestrial life
Expectations and requirements

The problem of life definition in astrobiological context

There are different approaches to cope with the problem of life definition in astrobiological studies

A conservative approach consists in using terrestrial life as the paradigm for the search for life in the universe

"Life-as-we-know-it" approach

In a sense, this approach is safe, since we know that terrestrial life exists and, in principle, the same type of life might exists in other environments with proper physical/chemical conditions

However, this approach is limited, since it leaves open the possibility that forms of extraterrestrial life may escape our detection just because they have different characteristics with respect to terrestrial life

The problem of life definition in astrobiological context

A more general approach consists in adopting a life definition that captures the most essential features of life, and investigating the physical and chemical requirements implied by any form of life that satisfies such general definition

Examples of essential characteristics of life common to all definitions, is the existence of metabolic and replication processes

Therefore we may require that any form of extraterrestrial life must have a metabolism and replication capabilities, carried out by molecular constituents

By not making a priori assumptions on the specific types of molecules or molecular processes involved in the metabolic and replication processes, we can investigate which general properties must be satisfied by any form of metabolic/replicative life in the universe

Thermodynamical requirements of life

As any other physical system, living systems must obey to the laws of thermodynamics and, in particular, to the second law

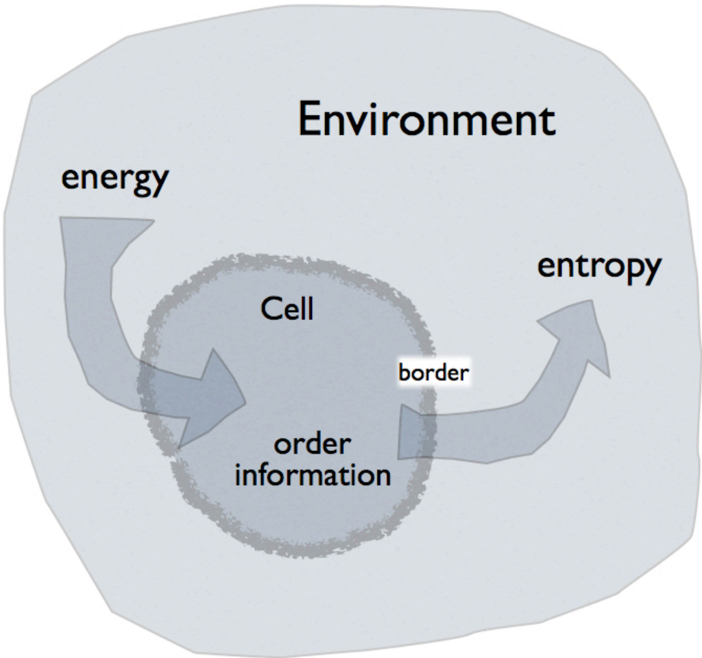
As a consequence, in the course of spontaneous metabolic processes, it must be

$$\Delta S_{univ} = \Delta S_{life} + \Delta S_{env} > 0$$

where S_{univ} is the total entropy of the living system, S_{life}, and of its environment, S_{env}

Living systems require: incoming energy to keep their metabolism active and outgoing entropy to maintain an extremely high internal order

As a consequence, they must have a border that selectively absorbs energy and emits entropy, mantaining a disequilibrium with the outside world



Necessity of a liquid substrate

Metabolic processes involve a continuous synthesis and dissolution of molecular constituents

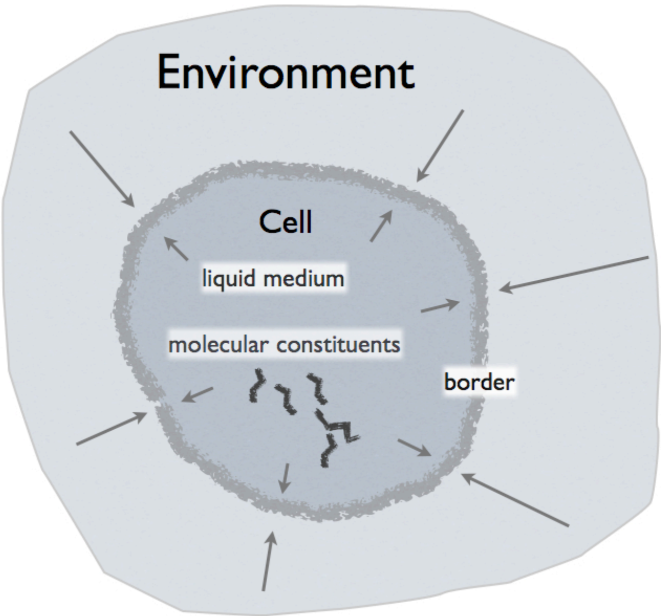
For these processes to take place, a medium must exist to allow the mobility and the capability of interaction of the molecular constituents: a liquid medium with solvent properties

The requirement of a border implies the existence of a mechanism able to keep in shape the molecular structure of the border

- The balance between the internal pressure of the liquid medium and the external pressure of the environment sustains the border structure
- If the liquid medium is a solvent, i.e. if the medium has polar properties, a self-organized border structure can be built up with amphiphilic molecules

Living systems require a liquid substrate that allows mobility and capability of interaction to its own molecular constituents

The liquid substrate gives internal pressure support to the border of the system; the internal pressure is balanced by the pressure of the external environment



Implications of the existence of a liquid substrate

The requirements of the existence of a liquid substrate implies that the thermodynamical state variables, such as temperature and pressure, must lie in intervals that allow the substrate to be in the liquid phase

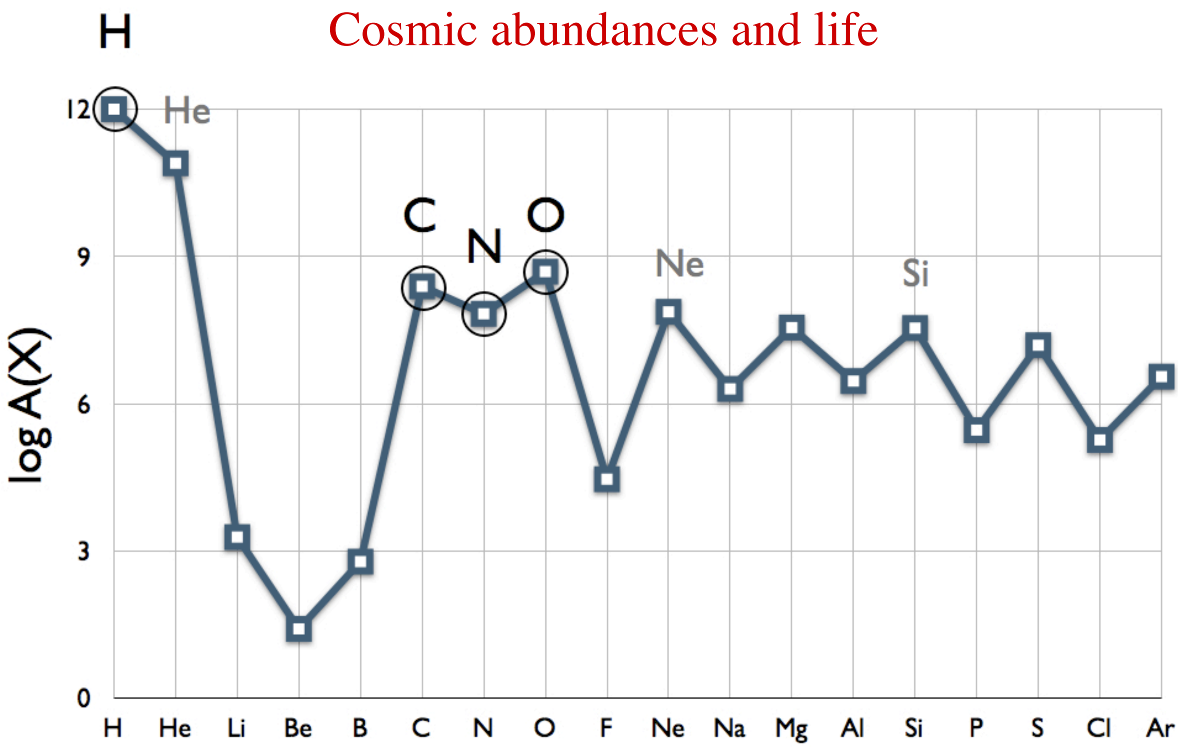
These conclusions are fundamental for the definition of "habitable environment": for living processes to be active, the temperature and pressure of the environment are constrained by the liquid phase criterion

Chemical requirements of life in the Universe

Chemical elements

Liquid medium

Cosmic abundances and life



Chemical elements and astrobiology

The periodic table of the elements in the universe

Astronomical observations show us that the chemical properties of the elements are the same everywhere

Spectroscopic observations of astronomical sources

Lack of variation of the physical constants in space-time

The chemical properties of the elements tell us whether they are suitable or not for taking part in living systems

Examples of elements not suitable for life processes

Nobles gases

Noble gases do not interact chemically with other elements and are not suitable for the development of metabolic processes

Metals

Pure metal constituents would not allow the existence of electric gradients, which are essential for the cell physiology

Metals can exist in trace abundances (as they do in terrestrial life)

The basic element of biological molecules

Carbon has several advantages over other elements

- Structural properties
  - Carbon has 4 oriented covalent bonds that allow the formation of 3D molecular structures

    Nitrogen and Oxygen have 3 and 2 covalent bonds which tend to form planar or linear structures, respectively
  - Carbon is capable of forming complex molecules not only with itself, but also with H, O and N

    This is because the bonds C-C, C-H, C-O, and C-N have similar energies
  - Carbon is the only atom with the capability of forming aromatic rings
- Metabolic properties
  - Carbon can easily be transformed from the completely oxydized form, CO_2, to the completely reduced form, CH_4

    This is an advantage for the capability of activating metabolic processes based on redox reactions

Comparison between carbon and silicon

Si lies in the same column of the periodic table of the elements

- It has been investigated as a possible alternative for building up biological molecules in exobiology

Silicon based chemistry, however, is by far less flexible than carbon chemistry

- Si is not able to form double covalent bonds with the same easiness as C does
- The larger volume occupied by the external electronic orbitals of silicon tend to reduce the superposition of p orbitals

Table 5.6 Physical properties of carbon and silicon.

Physical Properties	Carbon	Silicon
Molecular Weight	12.011	28.086
Melting Point (in °C at 1 bar)	~ 3500	1414
Boiling Point (in °C at 1 bar)	~ 3900	3265
Density (g/cm^3 at 20 °C)	2.27[1]	2.34
Electronegativity	2.55	1.90
Single Bond Covalent Radius (pm)	77	118
Heat Capacity (J/g L at 25 °C)	0.709	0.705
Enthalpy of Fusion (kJ/mol)	0.00[2]	50.6
Enthalpy of Vaporization (kJ/mol)	394[3]	383

The greater flexibility of C with respect to Si is demonstrated by the large number of complex organic molecules found in interstellar clouds and meteorites

Complex molecules based on Si have not been found

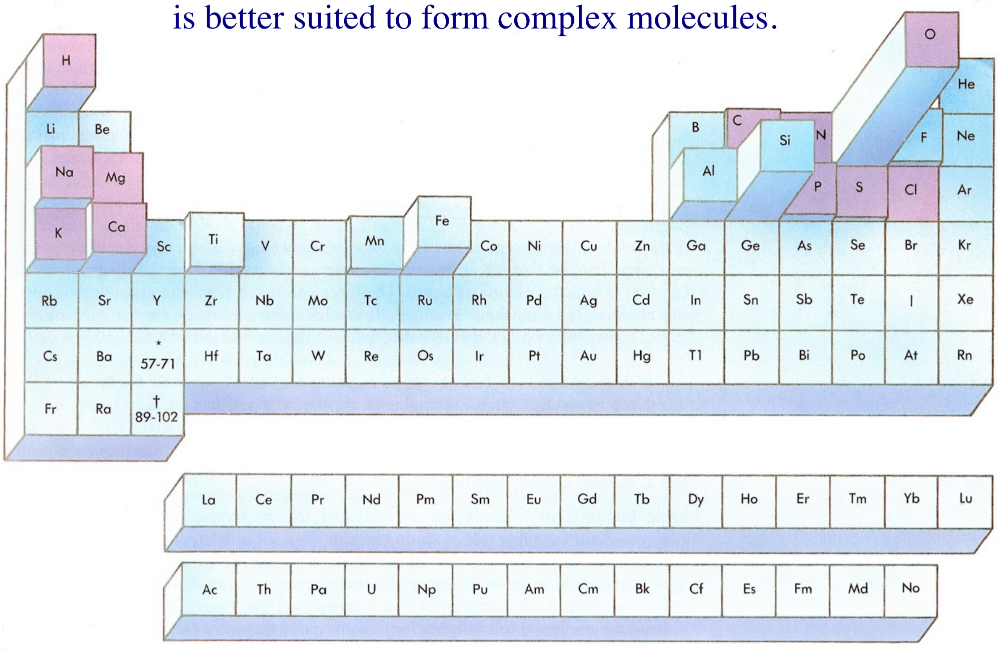
Table 5.4 Some complex carbon compounds detected in the interstellar medium and meteorites.

Number of Atoms				
6	7	8	9	> 9
C_5H, HCH_2OH	CH_3C_2H	CH_3OCHO	$(CH_3)_2O$	$(CH_3)_2CO$
NH_2CHO,	CH_3CHO	CH_3C_3N	CH_3CH_2OH	HC_9N
CH_3CN	HC_5N, C_6H	C_7H, H_2C_6	CH_3CH_2CN	$HC_{11}N$
CH_3NC,	CH_3NH_2		HC_7N	C_6H_6, C_{60}^+
CH_3SH	CH_2CHCN		CH_3C_4H, C_8H	PAHs,
H_2C_4,	C_2H_4O		CH_3C_4N	glycine?
HCC_2HO,				
C_5H, C_5N,				
C_5O				

Chemical abundances of biological elements in the earth crust

In this figure the biological elements are shown in pink color, and the relative abundances in the earth crust are indicated by the height of boxes

Terrestrial life has “chosen” carbon instead of silicon, in spite of the larger abundance of silicon. This fact again suggests that carbon is better suited to form complex molecules.



The substrate of life: water and other solvents

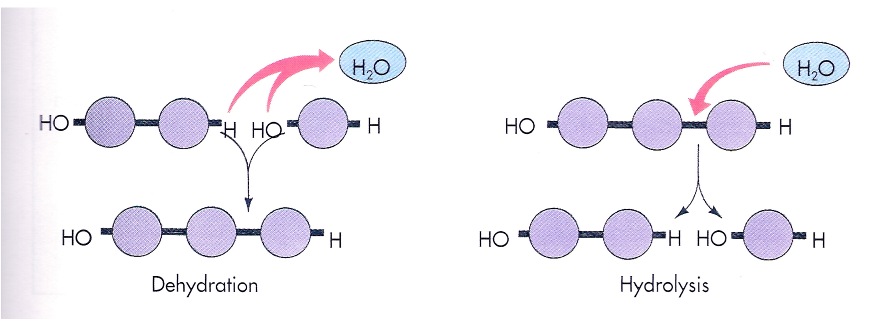
(1) Properties of water relevant to life

- The water molecule has a high electric dipole
  - This is why water is a good solvent, as required for the liquid medium of life: thanks to this property, the dissolved molecular constituents have the mobility required for metabolic processes to take place
  - Thanks to the polarity of water molecules, amphiphilic molecules can spontaneously form biological structures, such as cell membranes
- The intermolecular forces of water molecules are hydrogen bonds
  - Hydrogen bonds are fundamental to build up biological macromolecules
- Water spontaneously form ions
  - Spontaneous breaking of covalent bonds in a small fraction of water molecules yields to the formation of H^+ and OH^- ions, that can be used to transport electric charges

(2) Properties of water relevant to life

- The hydroxyl group and the hydrogen that form water molecules take part in organic chemistry reactions
  - Thanks to this fact, water formation and dissociation has the potential to play an important role in metabolic processes, as it does in terrestrial life

  Water takes part of fundamental metabolic processes, both as a reactant and as a product od reaction



Properties of water and other molecules

Main properties of water and of some polar or non-polar molecules

Proprietà	Note	H_2O	NH_3	HCN	HF	H_2S	CH_3OH	N_2H_4	CH_4	C_2H_6
μ	(a)	18.0	17.0	27.0	20.0	34.1	32.0	32.1	16.0	30.1
ρ	(b)	0.997	0.696	0.684	0.818	1.393	0.793	1.00	0.426	0.572
p	(c)	1.85	1.46	2.99	1.83	0.98	1.6	1.9	0.00	0.00
$T_{\rm fus}$	(d)	0	−78	−13	−83	−86	−94	2	−182	−172
$T_{\rm boil}$	(d)	100	−33	26	20	−60	65	114	−162	−89
$\Delta T_{\rm liq}$	(e)	100	44	39	103	26	159	111	20	83
$\Delta H_{\rm vap}$	(f)	40.7	23.3	25.2	30.3	18.7	40.5	40.9	8.2	14.7
$\Pi_i\, a_i$	(g)	−3.4	−4.3	−7.9	−7.6	−4.9	−7.1	−8.5	−3.8	−7.5

(a) Peso molecolare in unità di masse atomiche. (b) Densità in g/ml. (c) Momento di dipolo in debye (1 D = 10^{-10} esu · Å). (d) Punti di fusione e di ebollizione in °C alla pressione di 1 bar. (e) Intervallo di temperature in cui il composto è in fase liquida alla pressione di 1 bar. (f) Entalpia di vaporizzazione in kJ/mol. (g) Disponibilità cosmica.

The comparison with other molecules generally favours water as the medium of life.
Other polar solvents, such as HF, are interesting in principle, but are by far less abundant than water in the cosmos.
Water also has a relatively high specific heat, which is useful to stabilize the temperature of living systems.

Comparison of water and ammonia

- Ammonia is liquid at lower temperatures than water
  - An hypothetical life based on liquid ammonia would be characterized by low temperatures and therefore low efficiency of chemical reactions
- Like water, ammonia undergoes molecular autoionisation to form its acid and base conjugates:
  - $2\ NH_3\ (aq) \leftarrow\rightarrow NH_4^+\ (aq) + NH_2^-\ (aq)$
- However, these ions are less flexible than H^+ and OH^- ions for charge transportation and for taking part in organic chemistry pathways

Forms of chemical life in the universe

- The special properties of water, as a solvent, and of carbon, as a main constituent of macromolecules, suggest that also other forms of life potentially present outside the Earth could be based on water and carbon molecules, as terrestrial life
  - The high cosmic abundances of H, O and C is an additional argument in favour of this possibility
- However, we cannot exclude that forms of life not based on carbon and water may have developed in particular regions of the universe
  - For instance, should the local physical/chemical conditions prevent the use of carbon and water, at variance with the earth's conditions
- However, even for life based on carbon and water, we may expect significant differences at the level of molecular constituents with respect to terrestrial biomolecules

Genetic information

In non terrestrial organisms, the genetic information could be coded using molecules other than the RNA and DNA; the genetic code could be different from the terrestrial one

Chirality

In non terrestrial organisms, biological macromolecules could have a type of chirality different from that of terrestrial life (as an example the amino acids, if present, might have D, rather than L, chirality)

Possible types of chemical life in the Universe