Astrobiology

Physical properties and chemical constituents of life

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Giovanni Vladilo (INAF-OATs)

Thermodynamical requirements of life

Thermodynamical laws are useful to set terrestrial life in a cosmic context

We consider life as a process

As any other physical process, life must obey the laws of thermodynamics in particular, to the second law

In the course of metabolic processes, the entropy variation must be

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

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

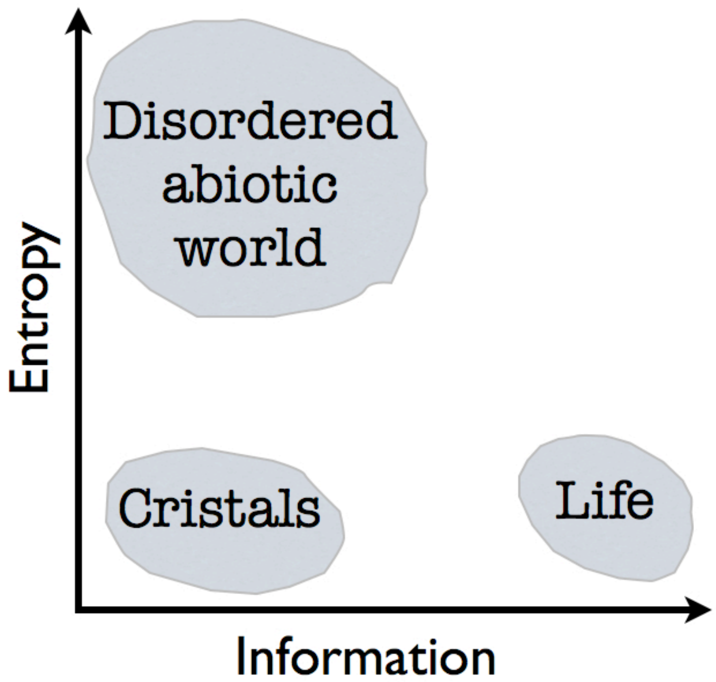
Thermodynamical properties of life

Life is characterized by a low-entropy state

The internal structure of cells is extremely ordered

However, at variance with the order that can be present in the non-biological world (e.g. internal structure of crystals),

life is characterized by a <u>very high informational content</u>



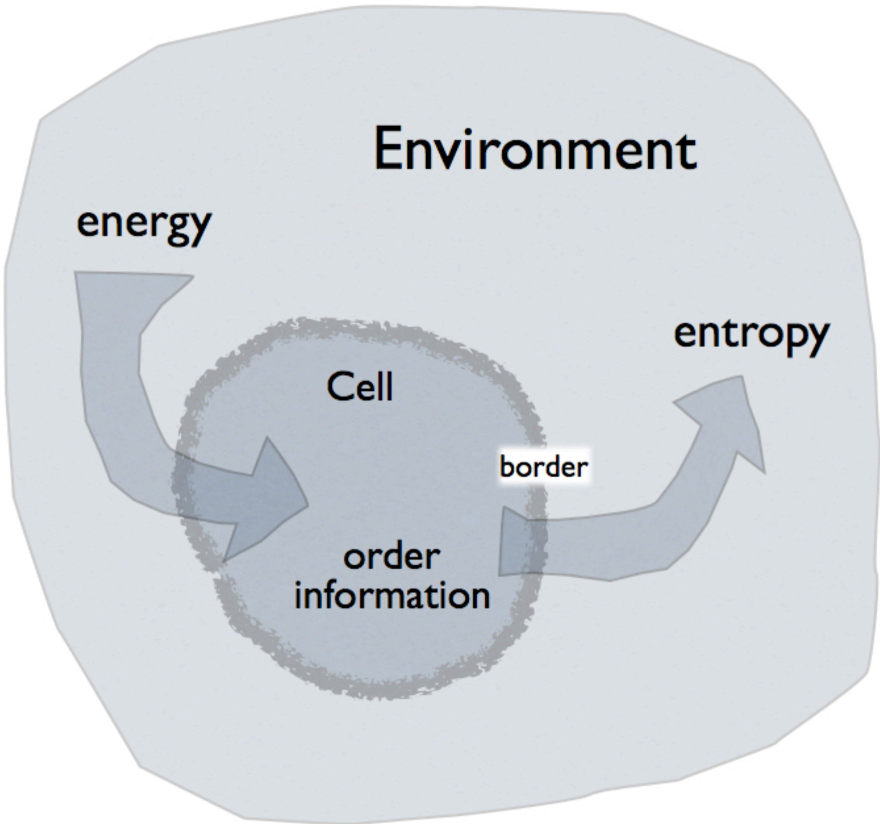
Living organisms as open thermodynamical systems

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 selective border able to absorb energy and emit entropy

they mantain a disequilibrium with the outside world

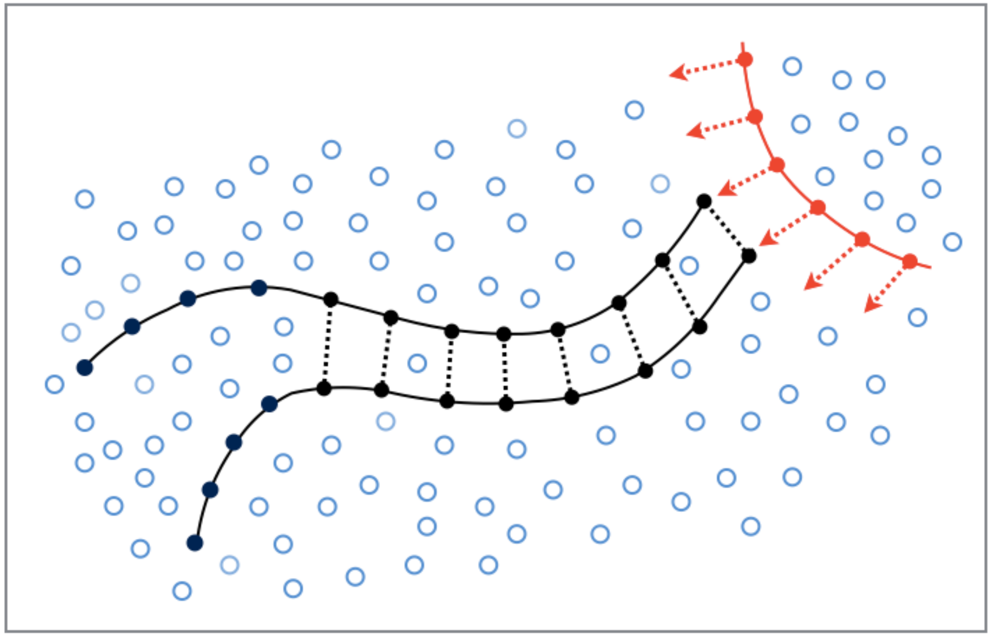


Life as a molecular process

Necessity of a liquid molecular substrate

At the microscopic level, metabolic and genetic processes
require a continuous synthesis and breakage of molecular constituents

For these processes to take place,
a liquid molecular medium with solvent properties must exist
to allow the mobility and the interaction of the molecular sub-units



Importance of the thermodynamical perspective

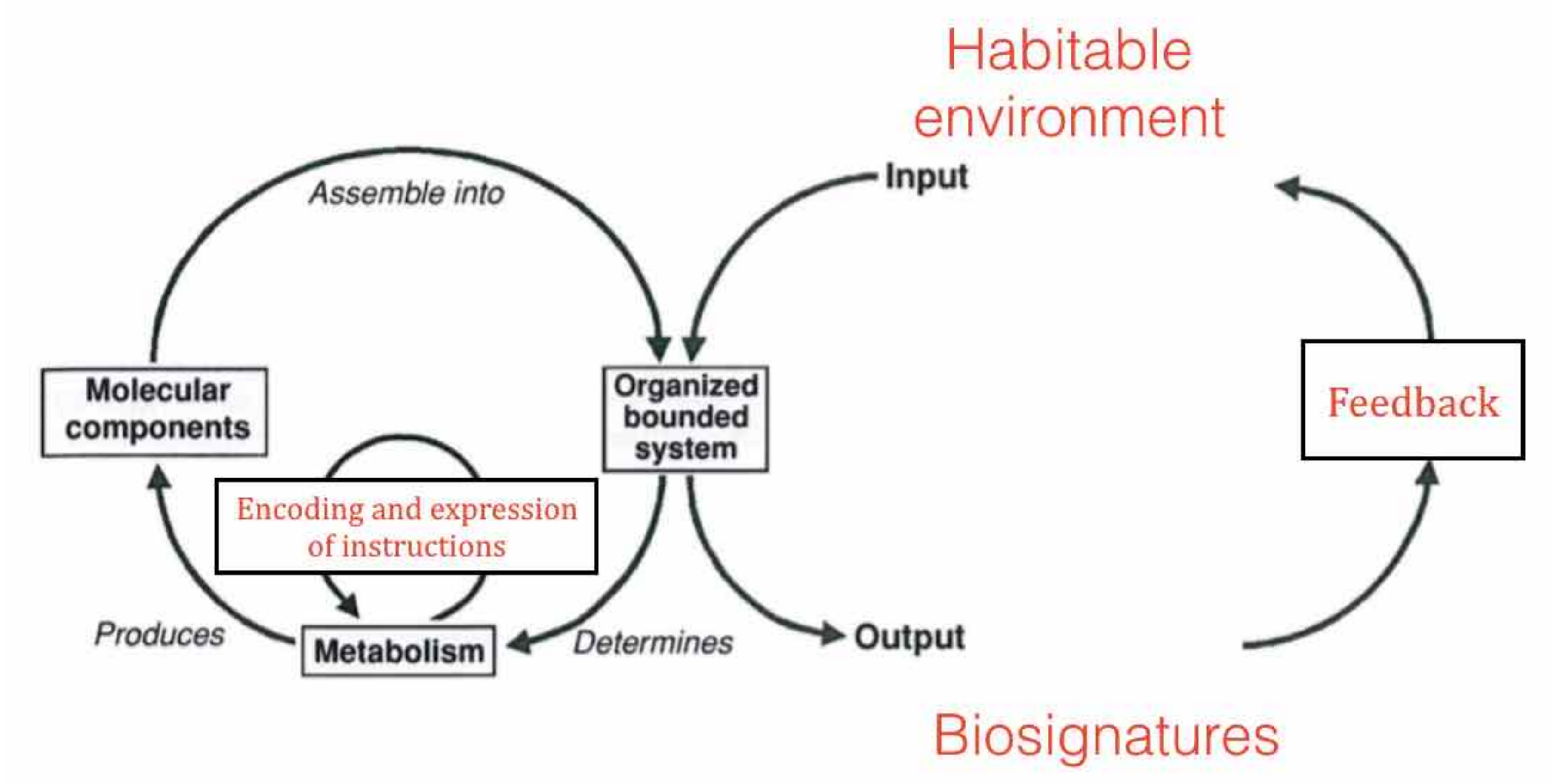
The thermodynamical aspects of life are independent of the biochemical processes or structural components specific of terrestrial life

Therefore the thermodynamical properties provide a universal perspective on general characteristics that are expected to be shared by any form of life, terrestrial or non-terrestrial

The existence of an open border, the presence of a liquid medium, the injection of entropy and chemical disequilibrium in the environment are universal properties of life

Relationship between life and its environment

Life requires specific ambient conditions,
which define the "habitability" of a given environment
By influencing the external environment, life affects its own ambient conditions
and generates "biosignatures" that could, in principle, be detected



Implications of the chemical disequilibrium generated by life

If life is diffuse on a planet,
the chemical abundances of the environment that hosts life
(such as the planetary atmosphere)
will be out of equilibrium

This concept is fundamental for the definition of
"atmospheric biomarkers"
in studies of extrasolar planets

Implications of the requirement of a liquid substrate

The requirements of a liquid substrate implies that
the thermodynamical state variables, such as temperature and pressure,
must lie in the liquid-phase interval of the molecular medium
in which life processes take place

These conclusions are fundamental
for the definition of “habitable environment”

The minimum structural unit of life

The cell is the minimum structural unit which has all the properties that define life (e.g. metabolism, reproduction, evolution, etc.)

Cells of terrestrial life are “microenvironments” since they sizes range between 1 to 100 μm in most cases

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

The border allows for selective exchanges of energy and matter with the environment

In terrestrial life the border is a biological membrane

Limitations of the cell size

The need to exchange energy and matter with the environment limits the cell size

The capability of exchanging energy/matter with the ambient world scales with the area of the cell surface

The requirement of energy/matter inside the cell scales with the volume of the cell

The surface-to-volume ratio decreases with the size cell

The size cannot increase indefinitely, otherwise the decrease of the surface-to-volume ratio would limit the possibility of efficient exchanges between the interior and the exterior of the cell

From cells to macroscopic life

Microscopic organisms formed by a single cell (unicellular organisms), have a limited capability of interaction with the macroscopic world

Macroscopic biological structures bypass this limitation by establishing forms of cooperation between cells

Cells can organize themselves in colonies or multicellular organisms

- In colonies a large number of <u>cells of the same type</u> share some limited form of cooperation
- In multicellular organisms, <u>differentiated cells</u> (but with same genetic information) work in strong cooperation

The chemistry of life

Chemical bonds and chemical elements of terrestrial life

Chemical bonds in biology

Most important chemical bonds in biological molecules

Strong bonds:

Covalent bonds

Weak bonds:

Hydrogen bonds

Van der Waals forces

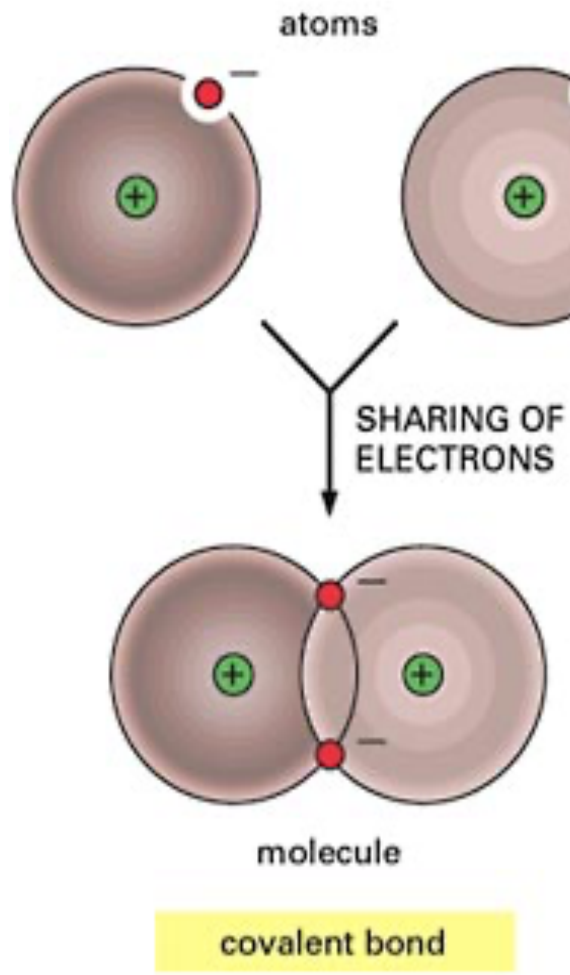
These bonds allow the formation of a extremely large variety of 3D, stable and flexible structures

Chemical bonds not used biological molecules

Ionic bonds

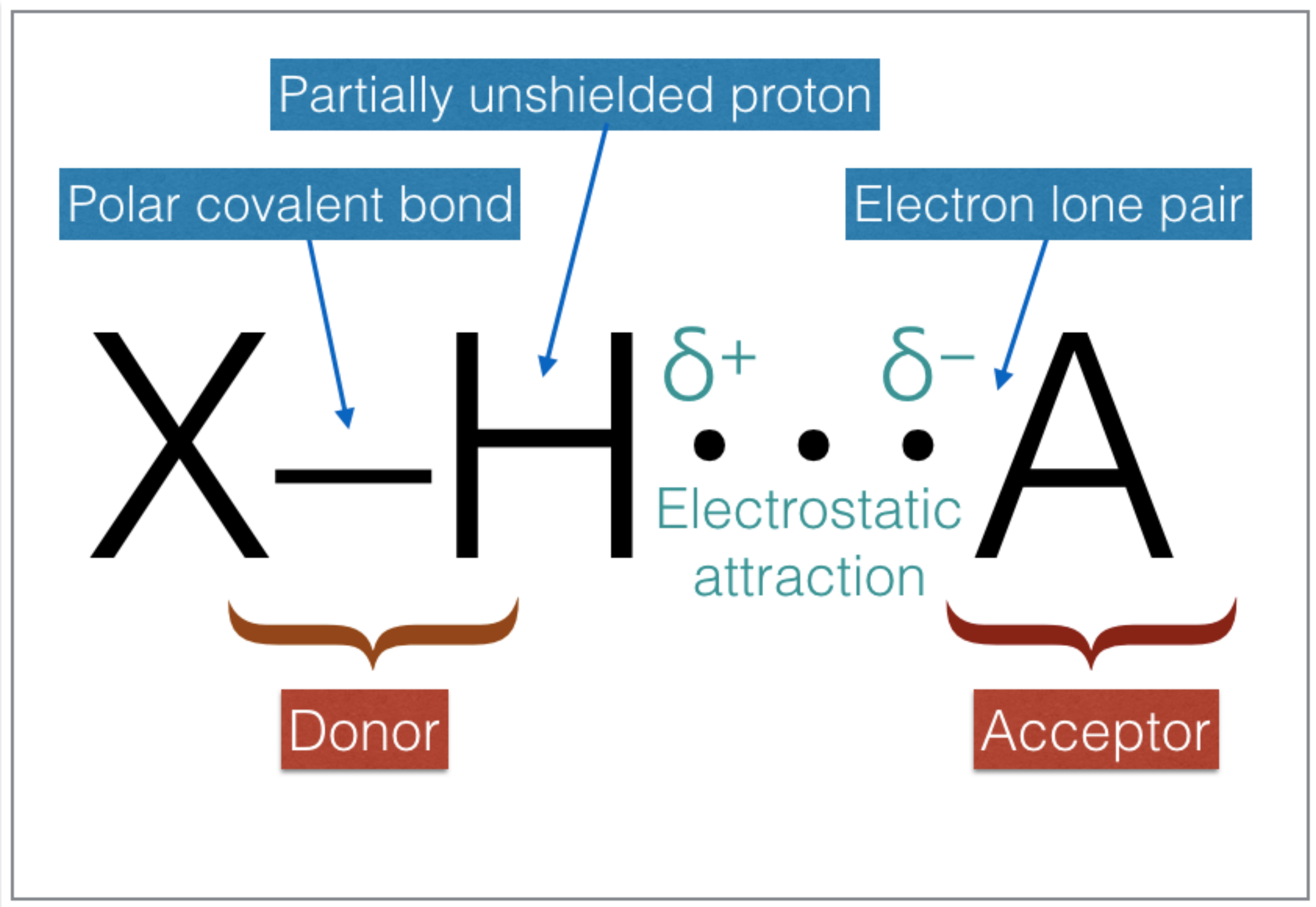
Metallic bonds

Covalent bonds:
used in the “skeleton” of biological molecules



The binding energy of covalent bonds is in the order of ~ 4 eV

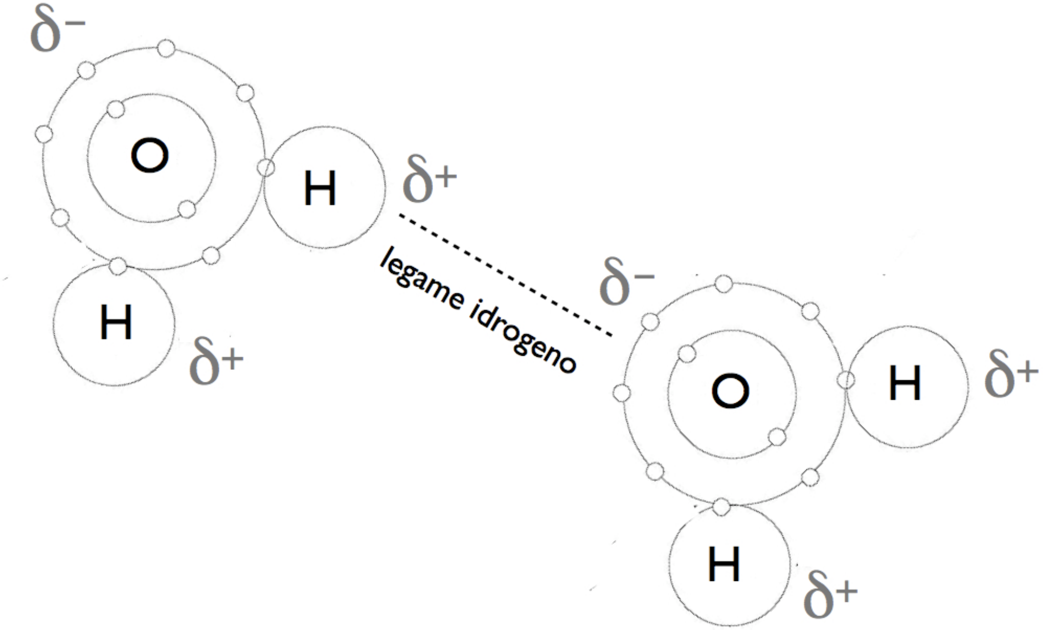
Hydrogen bonds

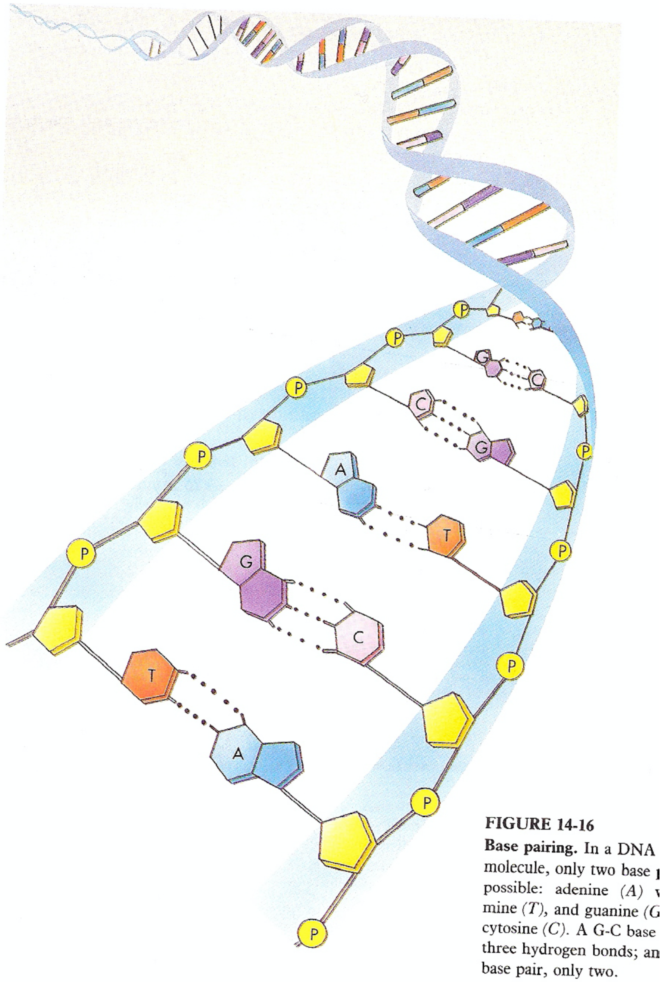


The binding energy of hydrogen bonds is in the order of ~0.1 eV

Hydrogen bonds in terrestrial life

Intermolecular forces between water molecules
Intramolecular and intermolecular forces in biological macromolecules

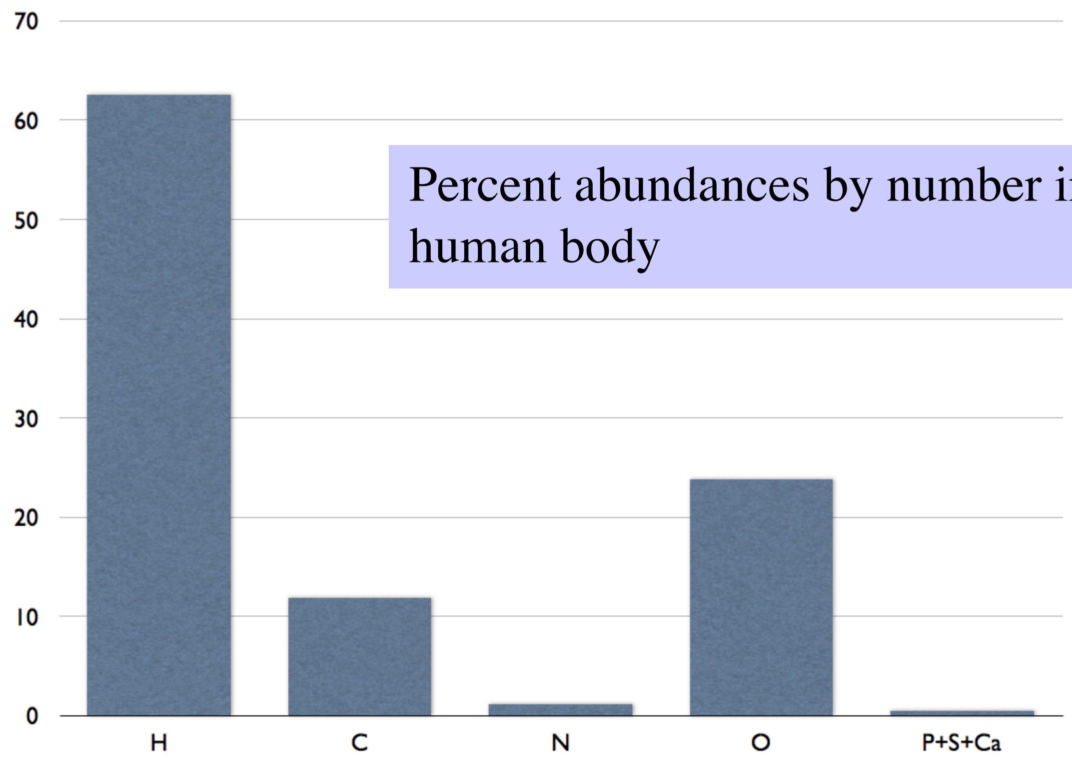




The chemical elements of terrestrial life (1)

Most abundant elements in terrestrial organisms:

H, C, N, O

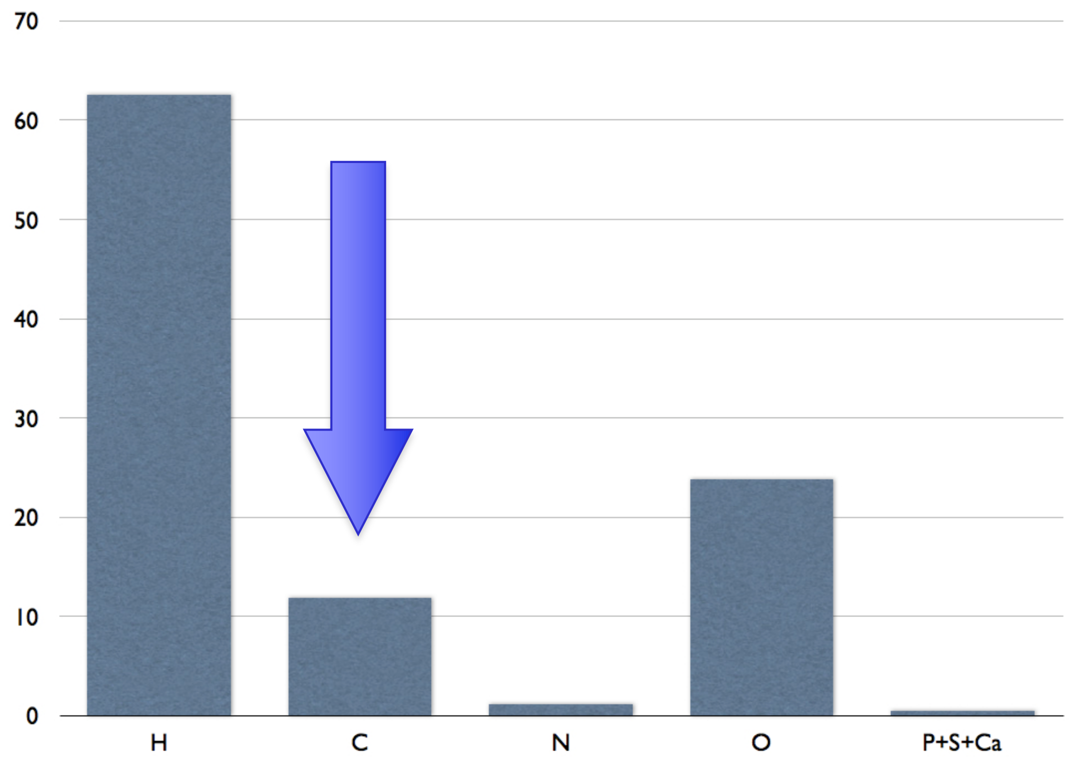


Percent abundances by number in the human body

The high abundance of H and O and their ratio ~2:1 is due to the fact that water is the liquid medium (substrate) of terrestrial life

The chemical elements of terrestrial life (2)

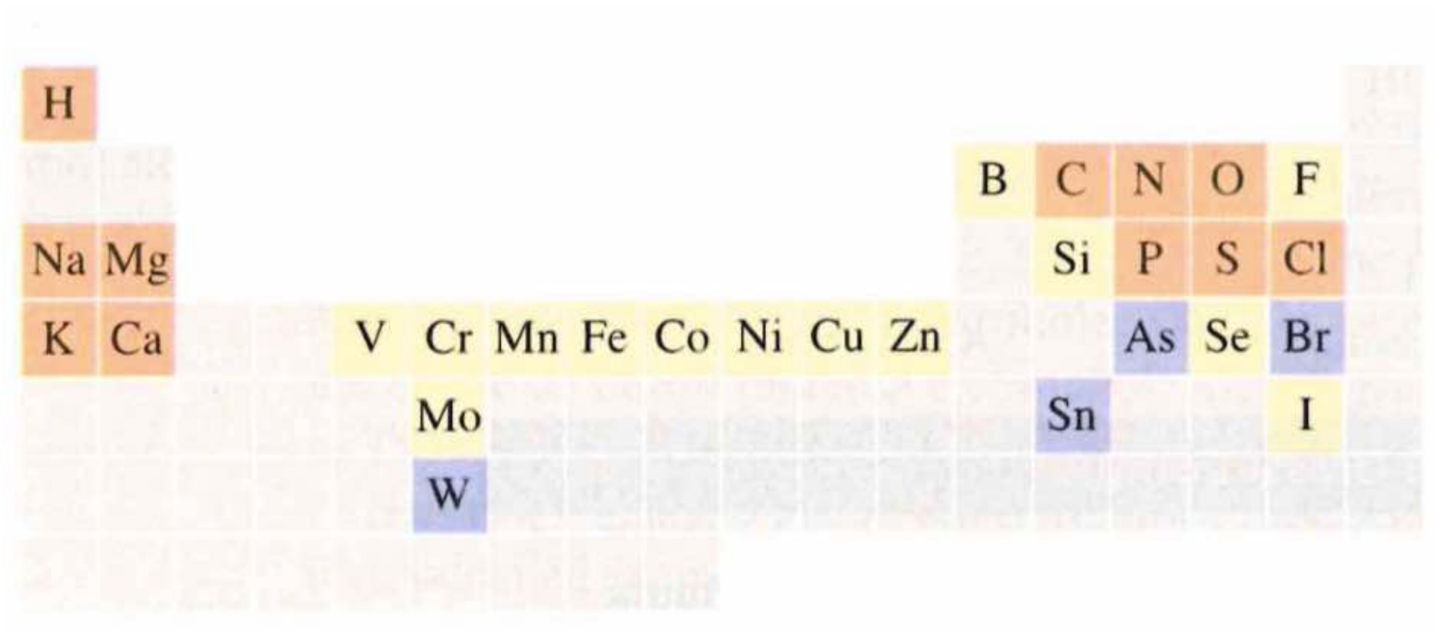
If we exclude the contribution of H and O (mostly in water), the most abundance atom is carbon



Carbon is a the basic structural component of organic molecules

The chemical elements of terrestrial life (3)

N, P & S are also particularly important



Orange: Main elements in terrestrial life

Yellow: Trace elements necessary for animals and plants

Magenta: Trace elements occasionally present in some forms of life