Thermodynamical and chemical properties

Useful to set life in a cosmic context

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Thermodynamical requirements of life

We consider life as a process

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

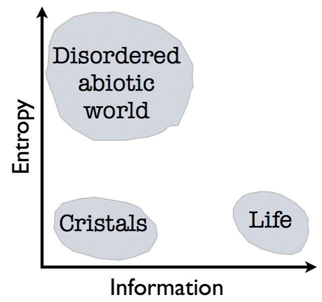
In the course of metabolic processes, the entropy variation must be

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

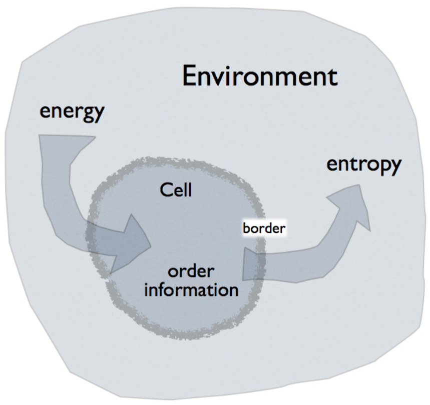
where S_{tot} is the total <u>entropy</u> ,
$S_{\rm life}$, the entropy of the living system, and
$S_{\rm env}$ of its environment

Life is characterized by a <u>low-entropy state</u>

The internal structure of living systems is extremely ordered
(e.g. this must be true for the genetic sequences)
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 systems require: <u>incoming energy</u> to keep their metabolism active and <u>outgoing entropy</u> to maintain an extremely high internal order
As a consequence, <u>they must have a border</u> that selectively absorbs energy and emits entropy, mantaining a <u>disequilibrium</u> with the outside world



Implications of the chemical disequilibrium generated by life

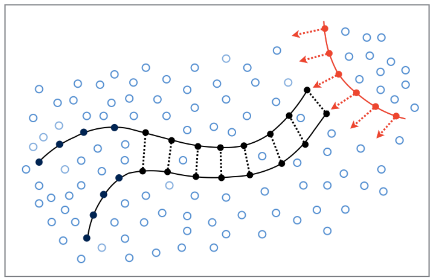
If life is diffuse in a biosphere,
the chemical abundances of the planet atmosphere
will be out of equilibrium

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

Life as a 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



Implications of the existence 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

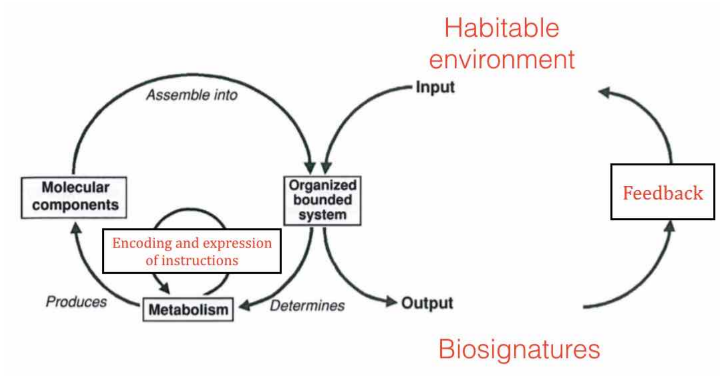
These conclusions are fundamental
for the definition of "habitable environment":

For life molecular processes to proceed,
the temperature and pressure of the molecular medium
must lie in the liquid-phase intervals

This in turn constrains the temperature and pressure of habitable environments

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



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 the general characteristic that must be shared by any form of life, terrestrial or non-terrestrial

This is true for the existence of an open border,
the presence of a liquid medium,
the generation of entropy and chemical disequilibrium in the 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 of individual cells

Cells organize themselves in colonies or multicellular organisms

- In colonies a large number of cells of the same type share some limited form of cooperation
- In multicellular organisms, differentiated cells (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

<u>Strong bonds:</u>

Covalent bonds

<u>Weak bonds:</u>

Hydrogen bonds

Van der Waals forces

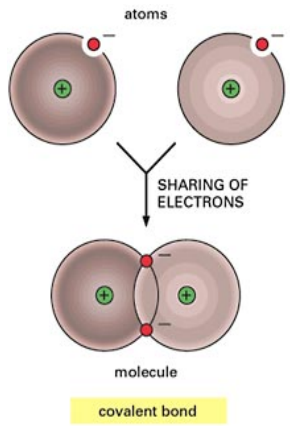
These bonds allow the formation of a extremely large variety of 3D, stable and flexible structures

Chemical bonds <u>not</u> used biological molecules

Ionic bonds

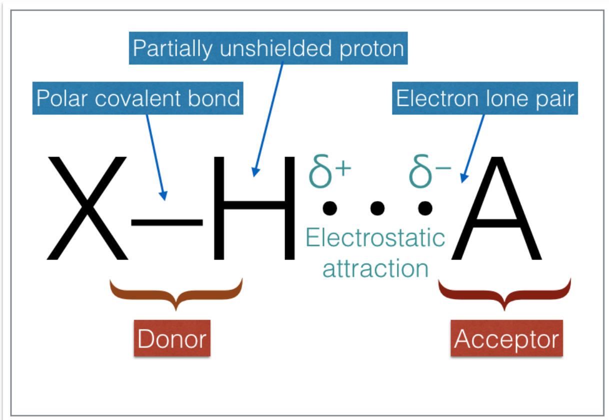
Metallic bonds

Covalent bonds:
used in the "skeleton" of biological molecules



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

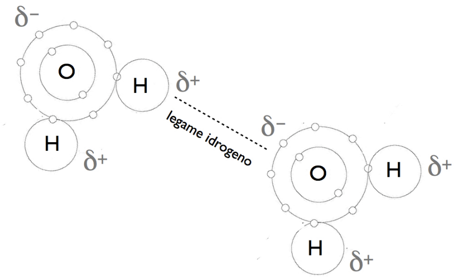
Hydrogen bonds



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



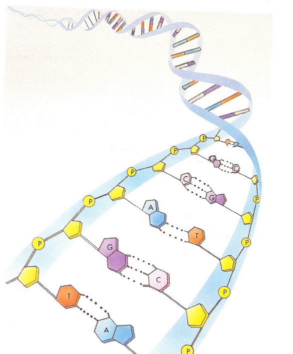
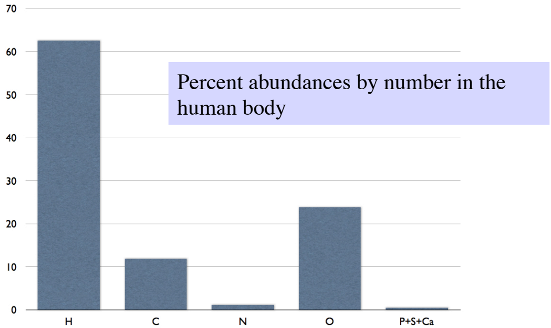


FIGURE 14-16
Base pairing. In a DNA molecule, only two base p
possible: adenine (A) w
mine (T), and guanine (G
cytosine (C). A G-C base
three hydrogen bonds; an
base pair, only two.

The chemical elements of terrestrial life (1)

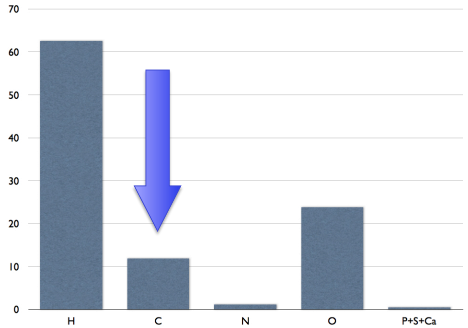
Most abundant elements in terrestrial organisms:
H, C, N, O



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)

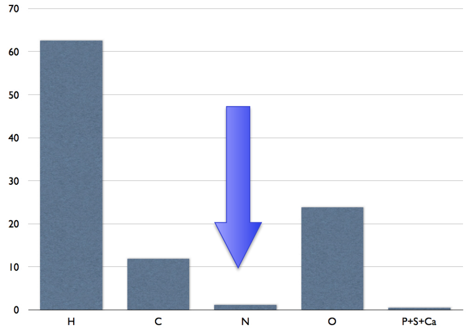
If we exclude the contribution of H and O in water,
the most abundance atom is carbon



Carbon is a the basic structural component of organic molecules

The chemical elements of terrestrial life (3)

Nitrogen is less abundant than carbon, but it is present in the essential biological molecules (amino acids, nucleic acids, ATP)

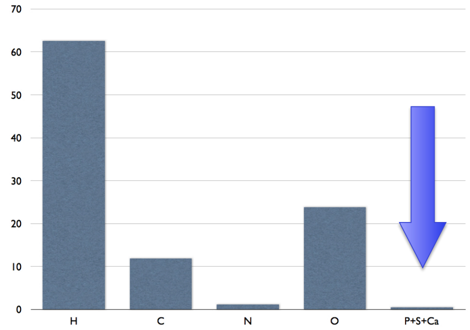


The chemical elements of terrestrial life (2)

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

Which chemistry in exobiology ?

Some general considerations suggest that the chemistry of terrestrial life
may be the logical consequence of universal laws
rather than a specific result of
the only form of life that we know

If this is true, we may expect that non-terrestrial life
may share the same type of chemistry

The periodic table of the elements is universal

Astronomical spectroscopic observations prove that the chemical properties of the elements are the same everywhere

Lack of variation of the physical constants in space-time (e.g. constancy of the fine-structure constant) indicates that the atomic structures (and chemistry) are the same everywhere

The potential relevance to life of chemical elements is universal

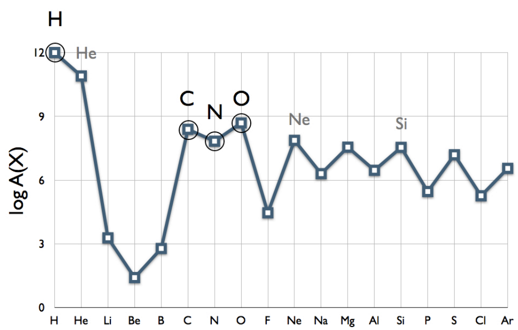
The fact that the biochemistry that we know is based on carbon and water may not be accidental

Abundance of biological elements in the universe

The most abundant elements of terrestrial life are also abundant in the universe

This implies that the ingredients of terrestrial-type chemistry are widely available in the universe

This argument, by itself, does not prove that non-terrestrial life would use the same chemical elements of terrestrial life



The chemical properties of the elements are more important than their cosmic abundances

Some elements that are cosmically abundant are not used by terrestrial life

The chemical properties of the elements give us a preliminary indication about their potential usefulness for life (terrestrial or non-terrestrial)

Examples of elements not suitable for life

Nobles gases

Do not react with other elements and are not suitable for metabolic processes

Metals

Pure metal 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 capability of different elements to form hydrogen bonds could be relevant for any possible form of biochemistry

The elements of terrestrial life have, in general, a strong capability of forming hydrogen bonds, besides being cosmically abundant