Astrobiology
Lecture 2

Physical properties and chemical ingredients of life

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Thermodynamical constraints

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

Life is an ongoing physical 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

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

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

Thermodynamical constraints

A useful thermodynamical quantity in biochemistry is the Gibbs energy

$$G = H - TS$$

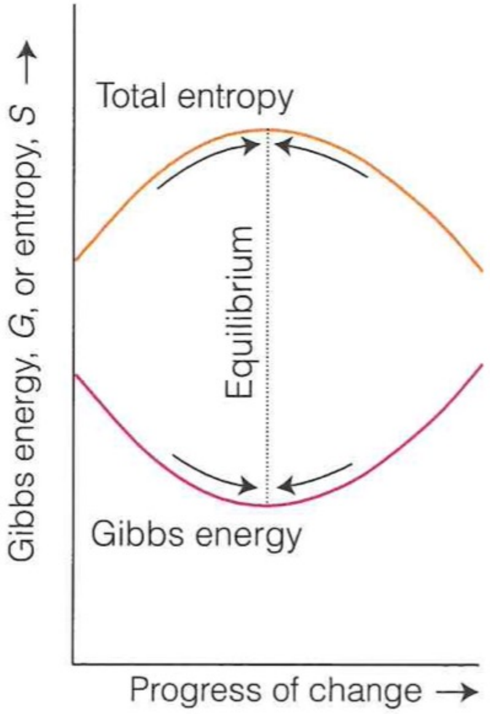
Where $H = U + pV$ is the enthalpy
(U is the internal energy and pV the mechanical work;
p is the pressure and V the volume)

It is possible to show that, at constant T and p,

$$\Delta G = -T\,\Delta S_{tot}$$

The Gibbs energy must decrease
in a spontaneous change at constant T and p

This conclusion shows which is the allowed direction
of chemical reactions of biological interest



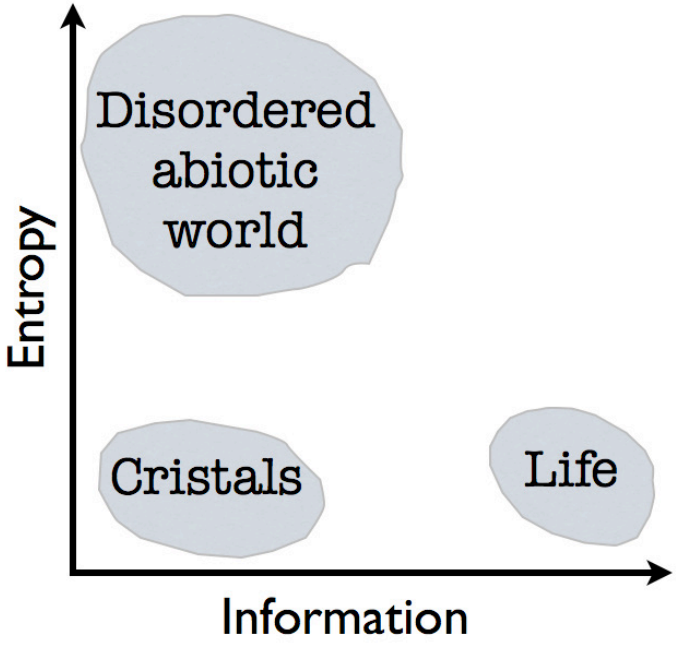
Atkins & De Paula,
Physical Chemistry for
Life Sciences, 2011, p.85

Thermodynamical properties of life

Life is characterized by a low-entropy state

The internal structure of cells is extremely ordered

At variance with the order that can be found in the non-biological world
(e.g. internal arrangement of atoms in crystals),
life is characterized by a very high informational content



In principle, this property offers a way to discriminate life from the non-living world

Living organisms as open thermodynamical systems

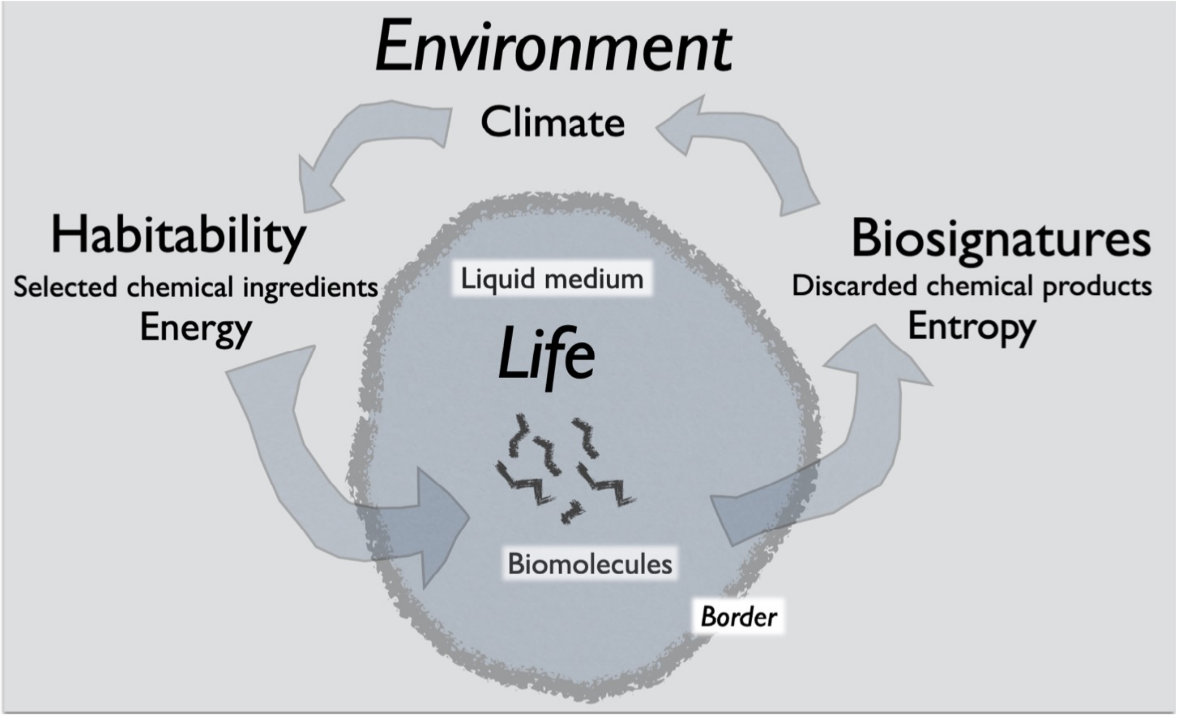
Due to the requirement of self-maintenance,

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



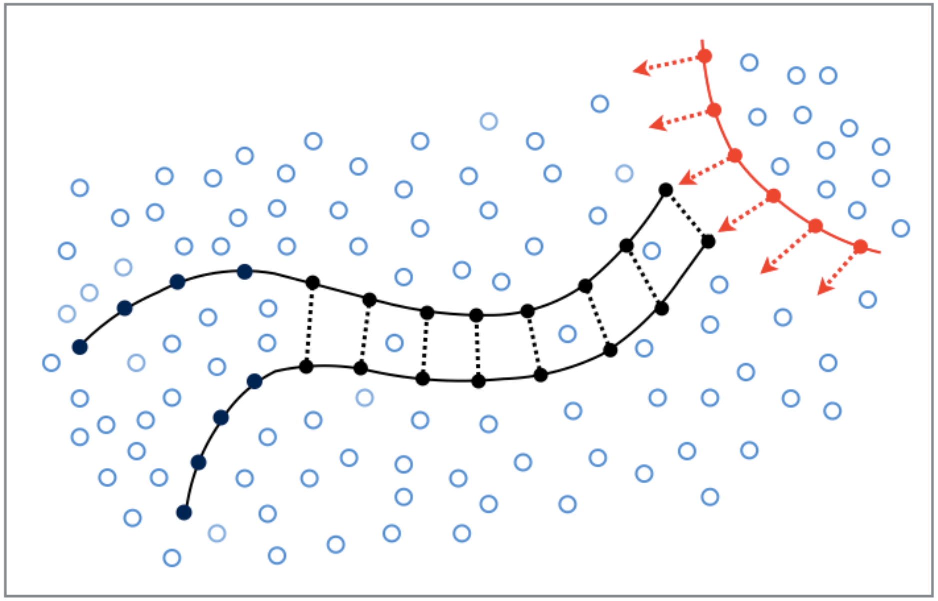
Life as a molecular process

Necessity of a liquid molecular medium

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

For these processes to take place,
biomolecules need to have mobility in order to interact;
biomolecules also need external support

Mobility and external support are provided by a
<u>liquid molecular medium</u>



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

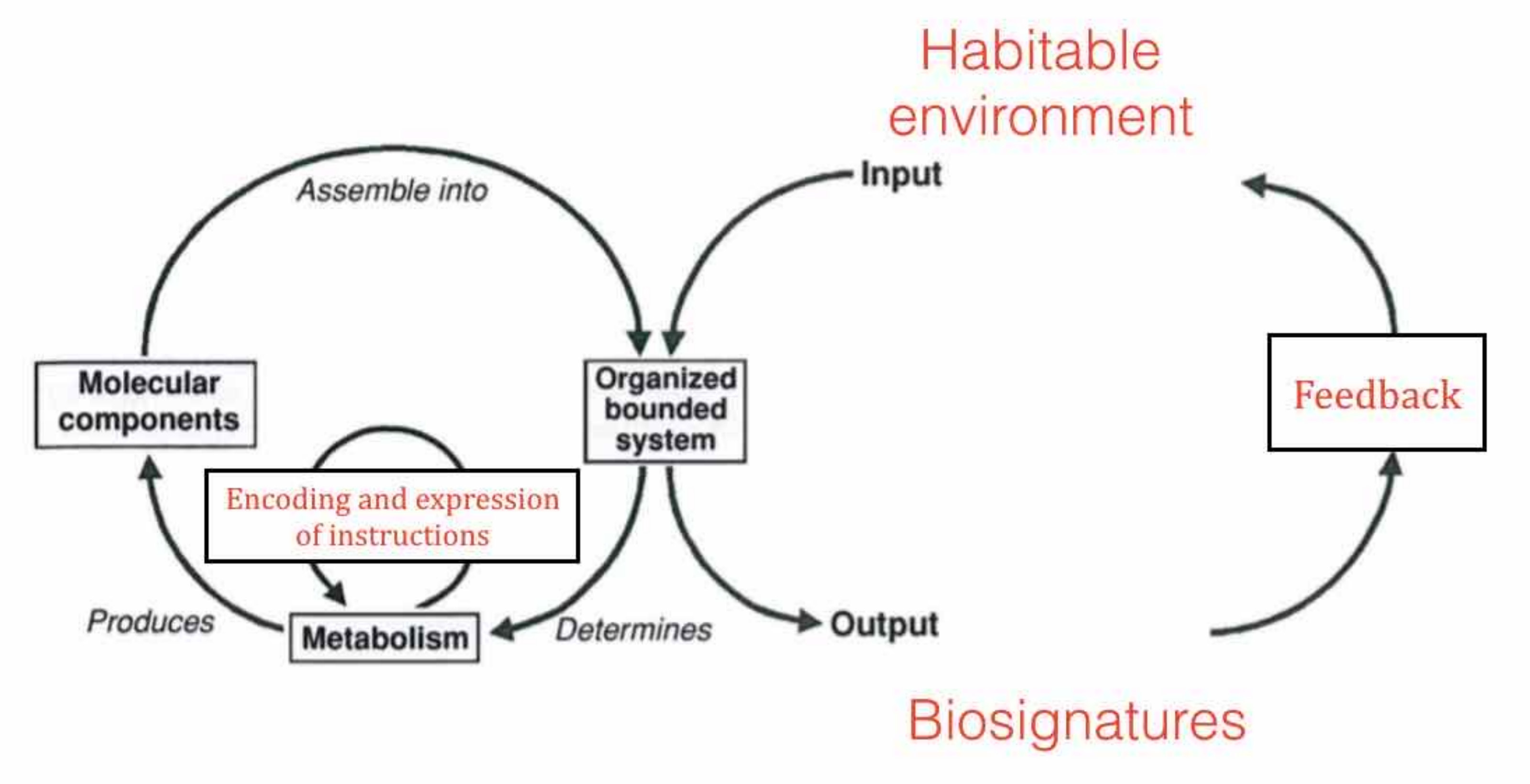
The existence of an open border, the presence of a liquid medium, the injection of entropy and chemical disequilibrium in the environment are universal properties of life

Life and its environment

(1) Life processes require specific ambient conditions, which define the "habitability" of a given environment

(2) By influencing its environment, life affects its own ambient conditions, i.e. feedbacks are established between life and habitability

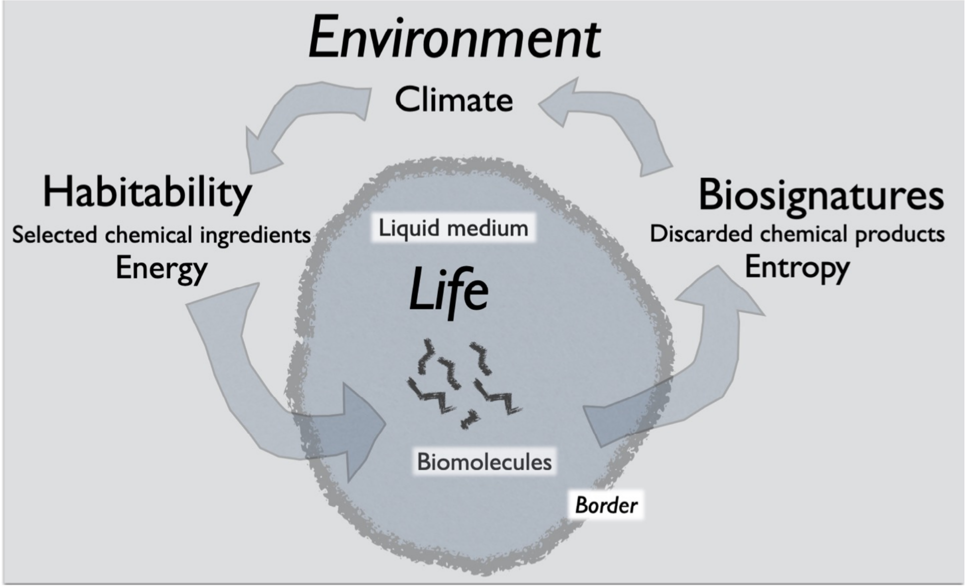
(3) By influencing its environment, life generates "biosignatures" that, in principle, could be used to reveal its presence



Implications of the chemical disequilibrium generated by life processes

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 biosignatures"
in studies of extrasolar planets



Implications of the requirement of a liquid substrate

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

This general conclusion can be used
for constraining the physical conditions of habitability

The “liquid water” criterion can be seen as a special case
of this general requirement

On the size of the minimum structural units of life

Most terrestrial cells have sizes in the range between 1 to 100 µm

Is there a universal limit to the minimum structural unit of life?

The need to exchange energy and matter with the environment is likely to limit the cell size

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

The requirements of energy/matter inside the cell scales with the <u>volume</u> of the cell

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

<u>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</u>

Exceptions: cells with elongated shape

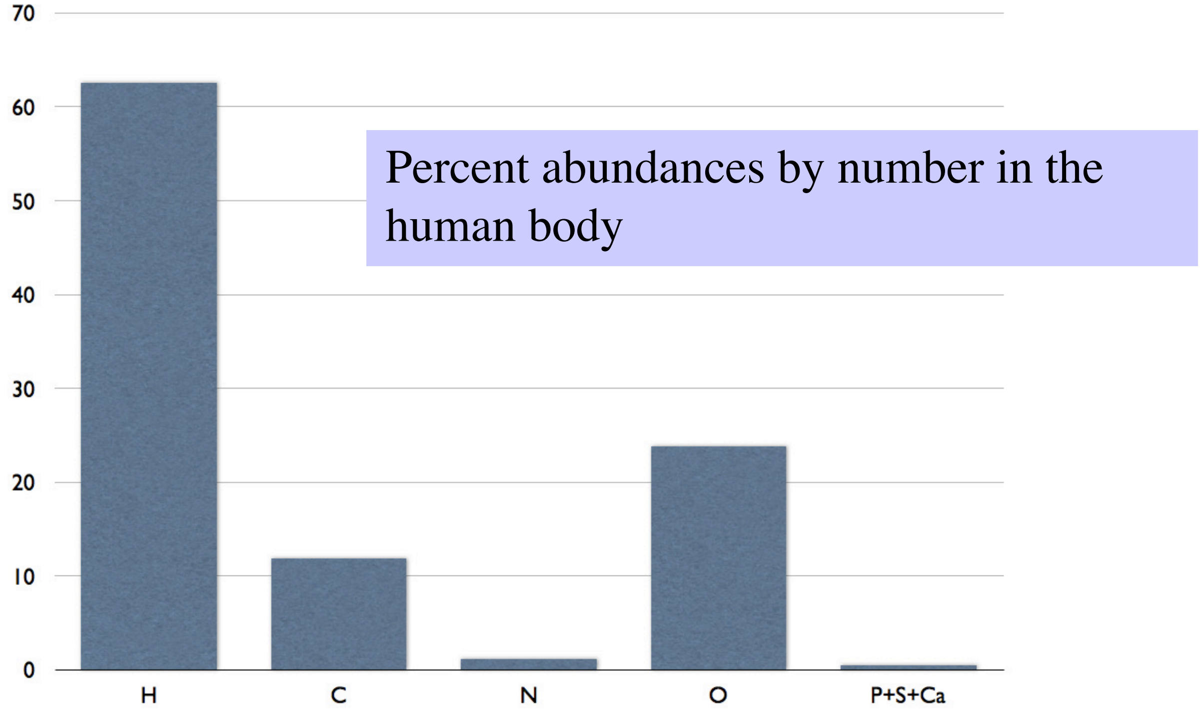
Chemical ingredients of terrestrial life

Chemical elements
Chemical bonding and interactions

The chemical elements of terrestrial life (1)

Most abundant elements in terrestrial organisms:

H, C, N, O

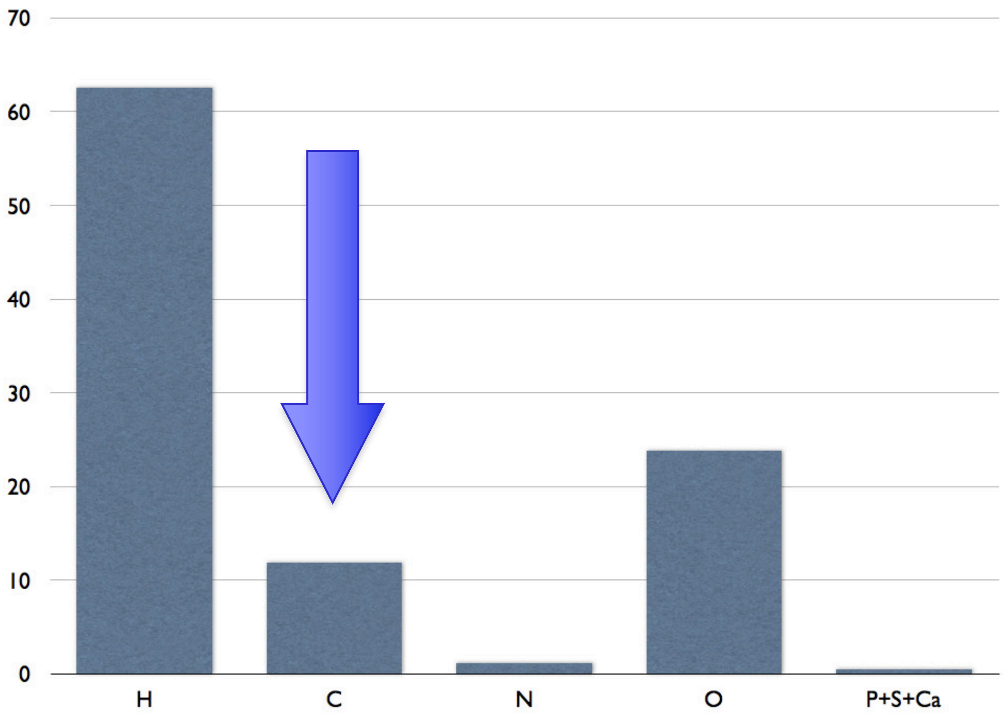

Percent abundances by number in the human body

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)

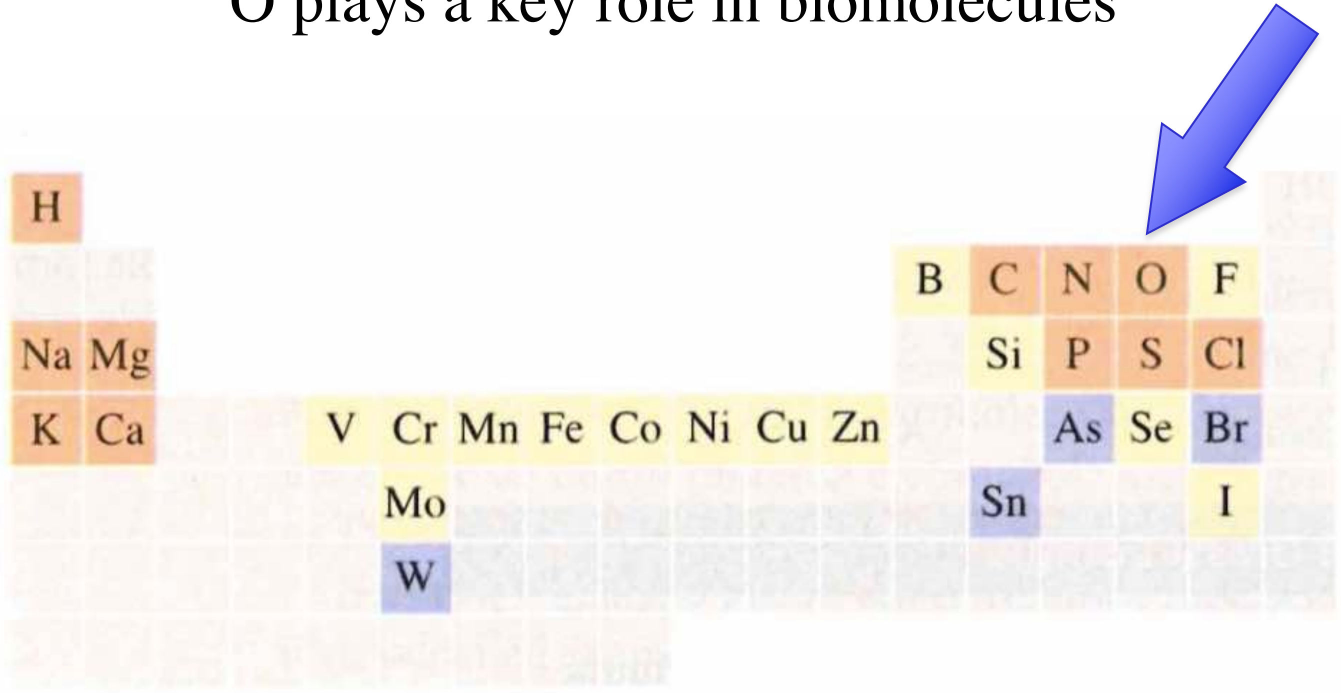
If we exclude the contribution of H and O (mostly in water), the most abundance atom is carbon

Carbon is the basic structural component of organic molecules



The chemical elements of terrestrial life (3)

Apart from its presence in water,
O plays a key role in biomolecules



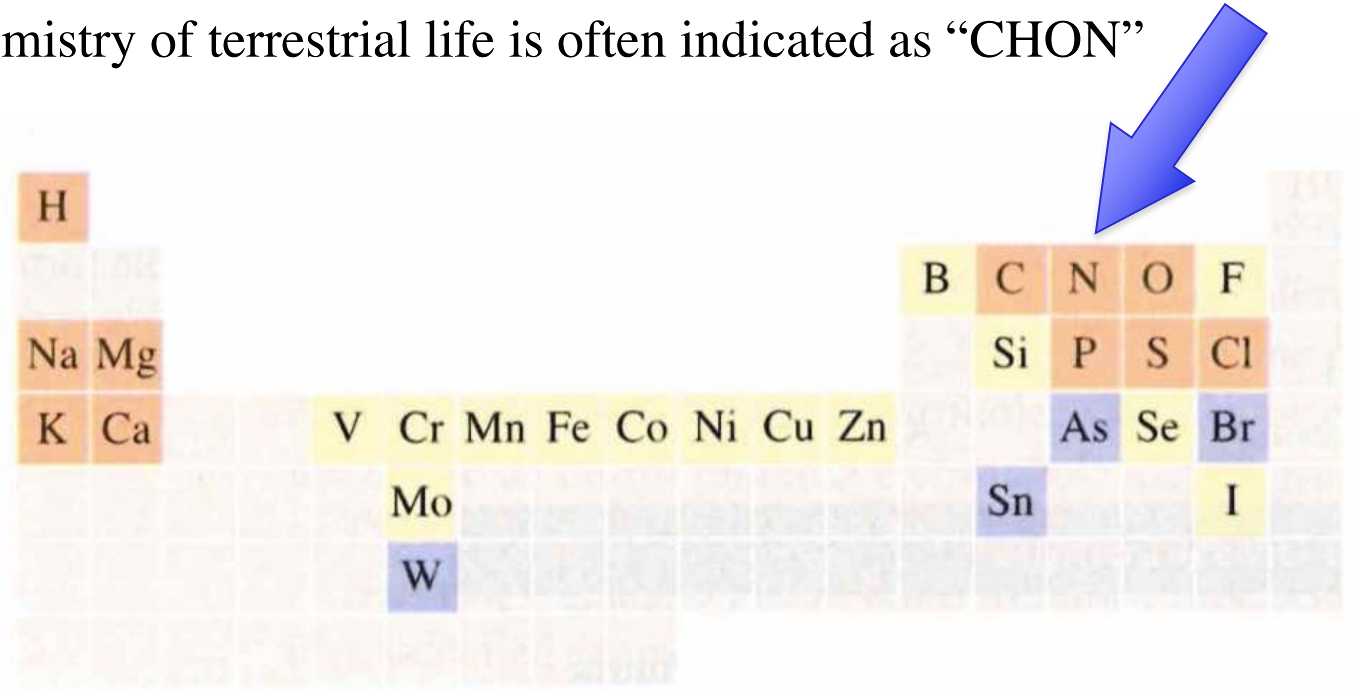
Orange: Main elements in terrestrial life
Yellow: Trace elements necessary for animals and plants
Magenta: Trace elements occasionally present in some forms of life

The chemical elements of terrestrial life (4)

N is the next abundant element

In terrestrial life N is as important as O

The chemistry of terrestrial life is often indicated as “CHON”



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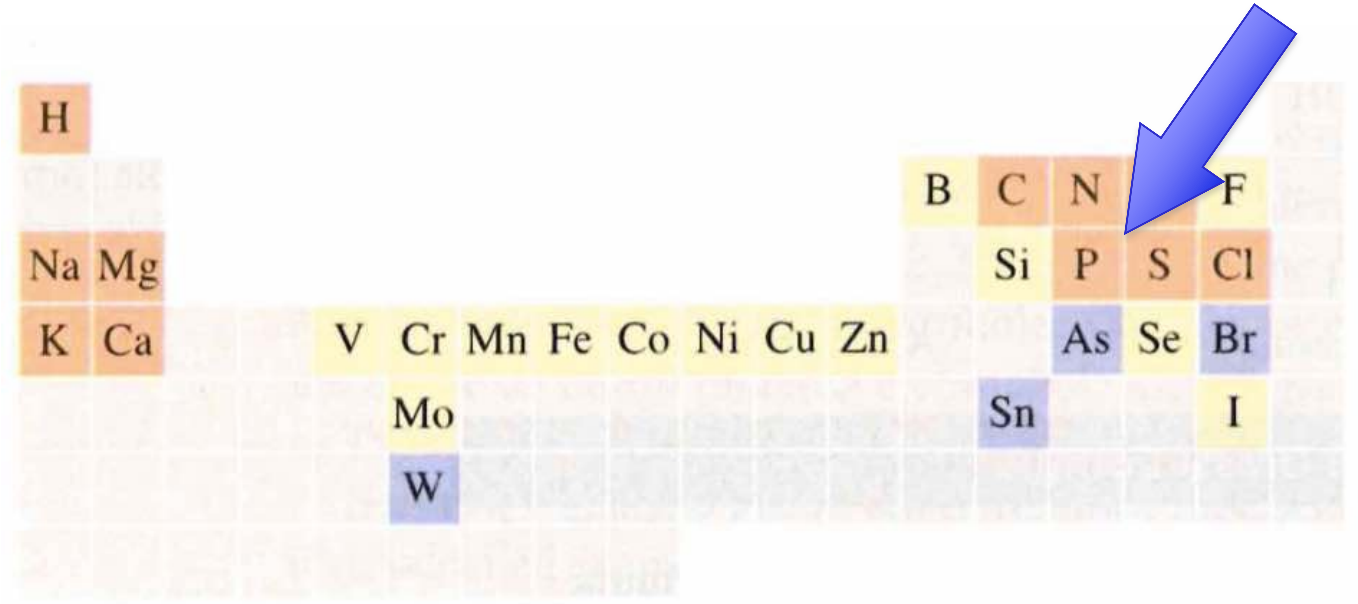
The chemical elements of terrestrial life (5)

P & S are also particularly important

Phosphate groups are frequent in essential biomolecules

S may play a role similar to O in some biomolecules



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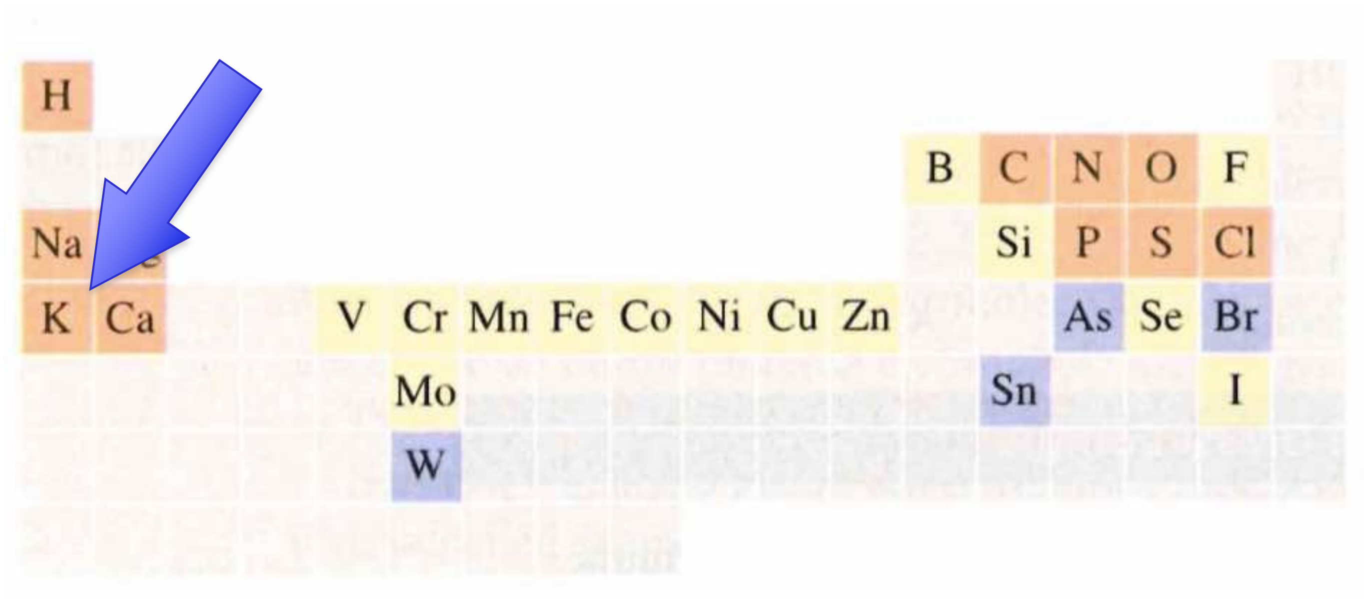
The chemical elements of terrestrial life (6)

K & Ca are essential for ion transport in and out cells



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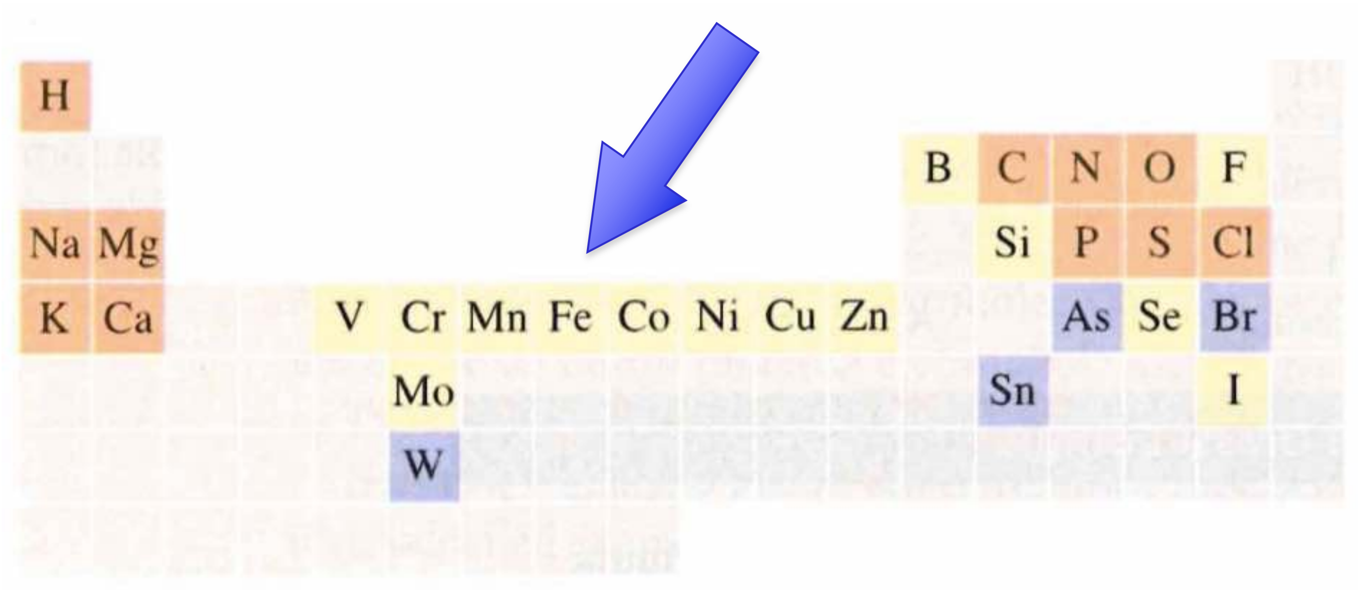
The chemical elements of terrestrial life (7)

Metals only appear in trace quantities, but they are essential



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From chemical elements to biomolecules: chemical bonds

The stability of biomolecules requires their atoms
to be tied with strong chemical bonding

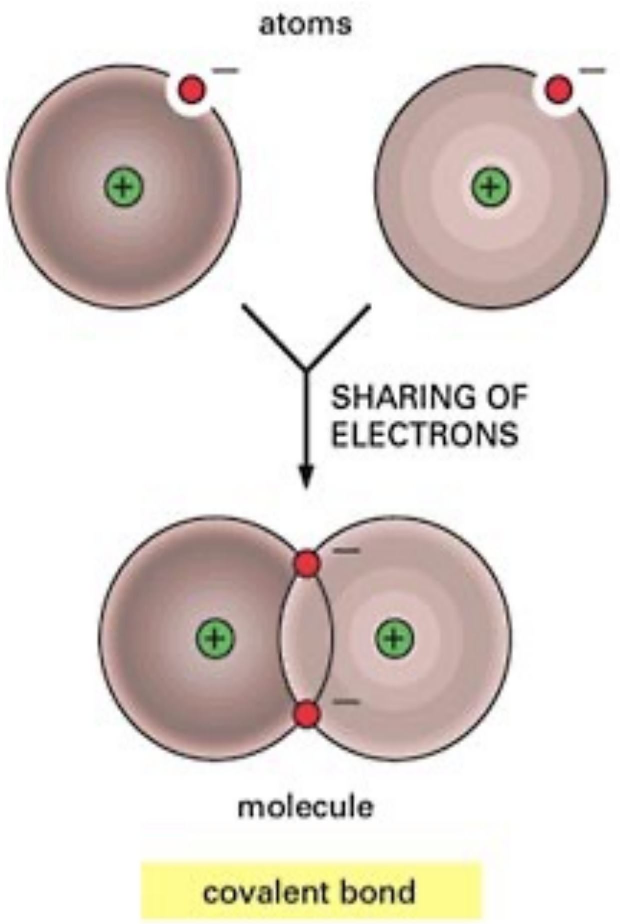
Strong chemical bonds in nature can be
covalent, ionic, and metallic

Terrestrial biomolecules are built up with covalent bonds

Ionic bonds are uncommon in terrestrial biology

Metals are present, but networks of metallic bonds are absent

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



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

Intermolecular interactions between life molecules

The need for biomolecules to interact without altering their (covalent-bond) structure implies that *biomolecules should interact via weak chemical bonding/forces*

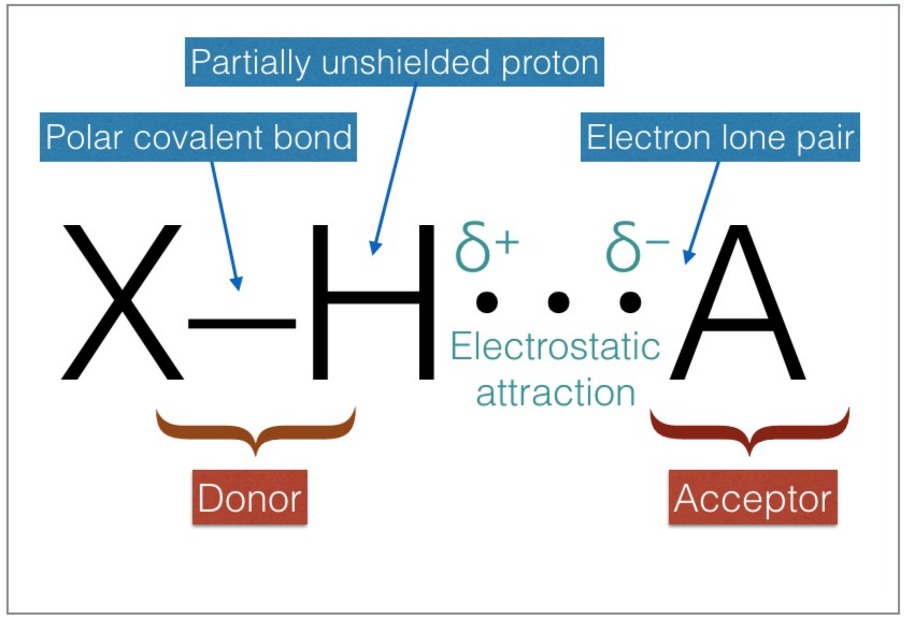
Weak chemical interactions in nature can be:
(different types of) van der Waals forces and hydrogen bonds

Weak interactions are pervasive in biological systems

The role of hydrogen bonding is particularly important

Hydrogen bonds

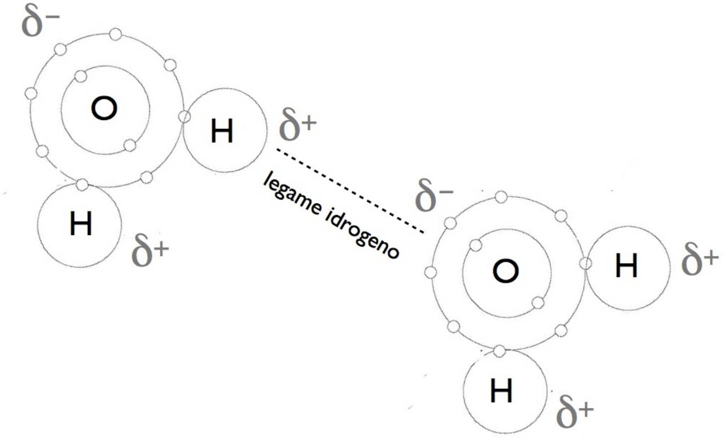
NOTE. A hydrogen bond (HB) is an attractive interaction between a hydrogen atom from a molecular group X–H, in which the element X is more electronegative than H, and an atom or group of atoms, A, that possesses at least one electron-rich region (Desiraju and Steiner 1999). Due to the difference in electronegativity, the proton in H is partially unshielded and the group X–H (the "donor"), is polarized. The electron-rich region in A (the "acceptor") attracts the partially unshielded proton.



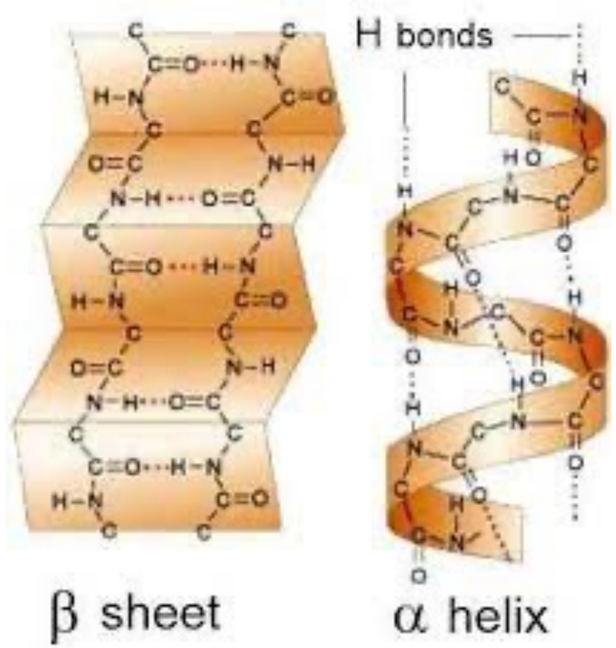
The binding energy of hydrogen bonds is in the order of ~0.1 eV

Hydrogen bonds in terrestrial life

Intermolecular forces between water molecules



Intramolecular forces in biological macromolecules



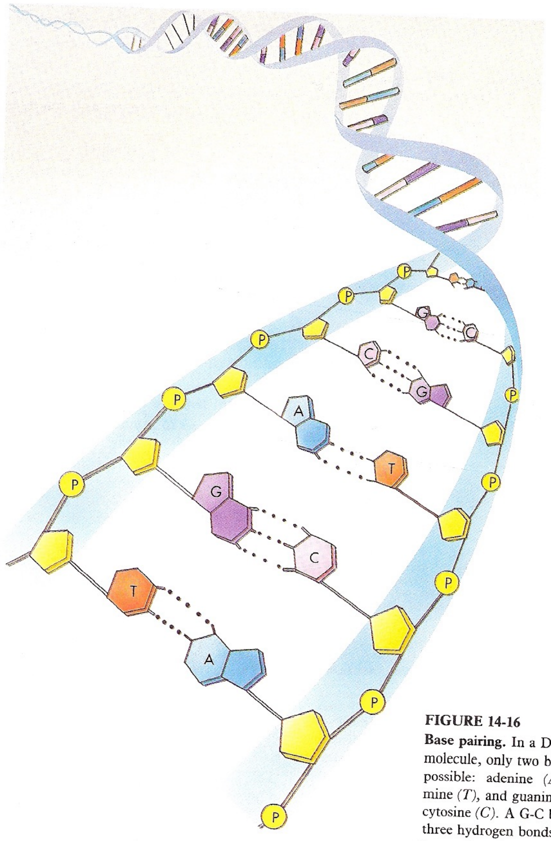


FIGURE 14-16
Base pairing. In a DNA molecule, only two base
possible: adenine (A)
mine (T), and guanine (G
cytosine (C). A G-C base
three hydrogen bonds; an
base pair, only two.