Astrobiology
Lecture 2

Physical properties and chemical ingredients of life

Trieste University, Academic Year 2021-2022
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Thermodynamical constraints

Thermodynamical laws, being universal,
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

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

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

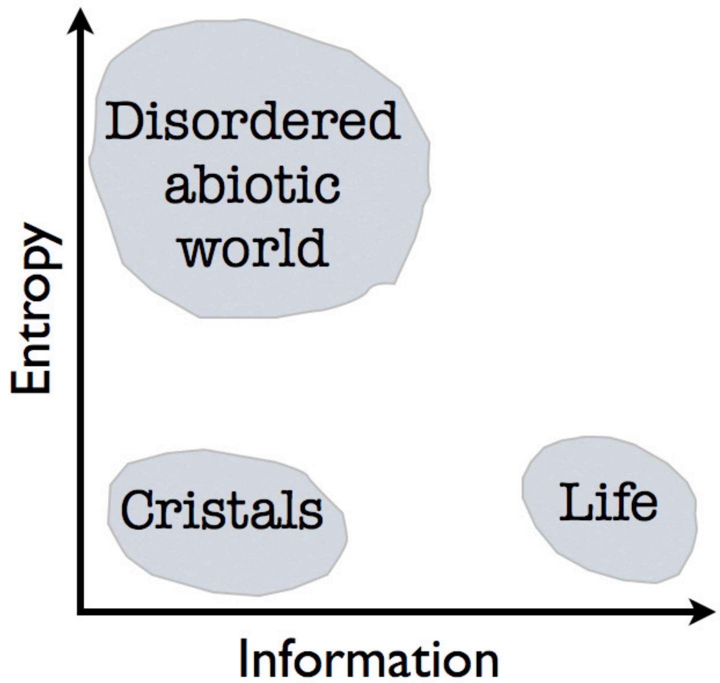
Thermodynamical properties of life

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>



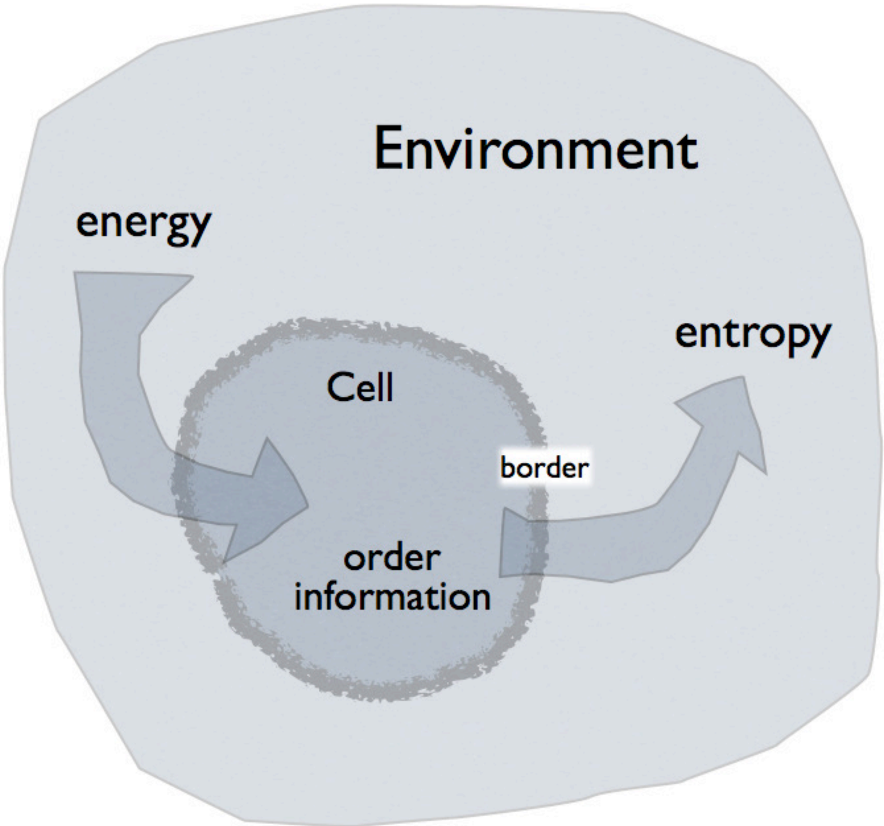
Living organisms as open thermodynamical systems

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

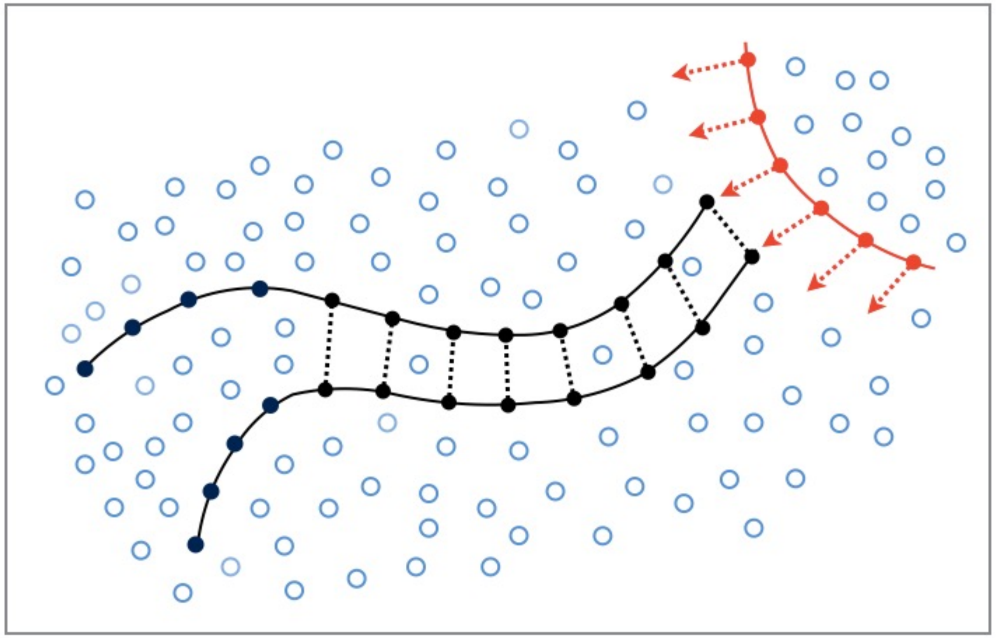


Life as a molecular process

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,
molecular sub-units need to have mobility in order to interact
In turn, this requires the existence of a
<u>liquid molecular medium that allow the molecular constituents to move</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
<u>general characteristics that are expected to be shared by any form of life</u>,
<u>terrestrial or non-terrestrial</u>

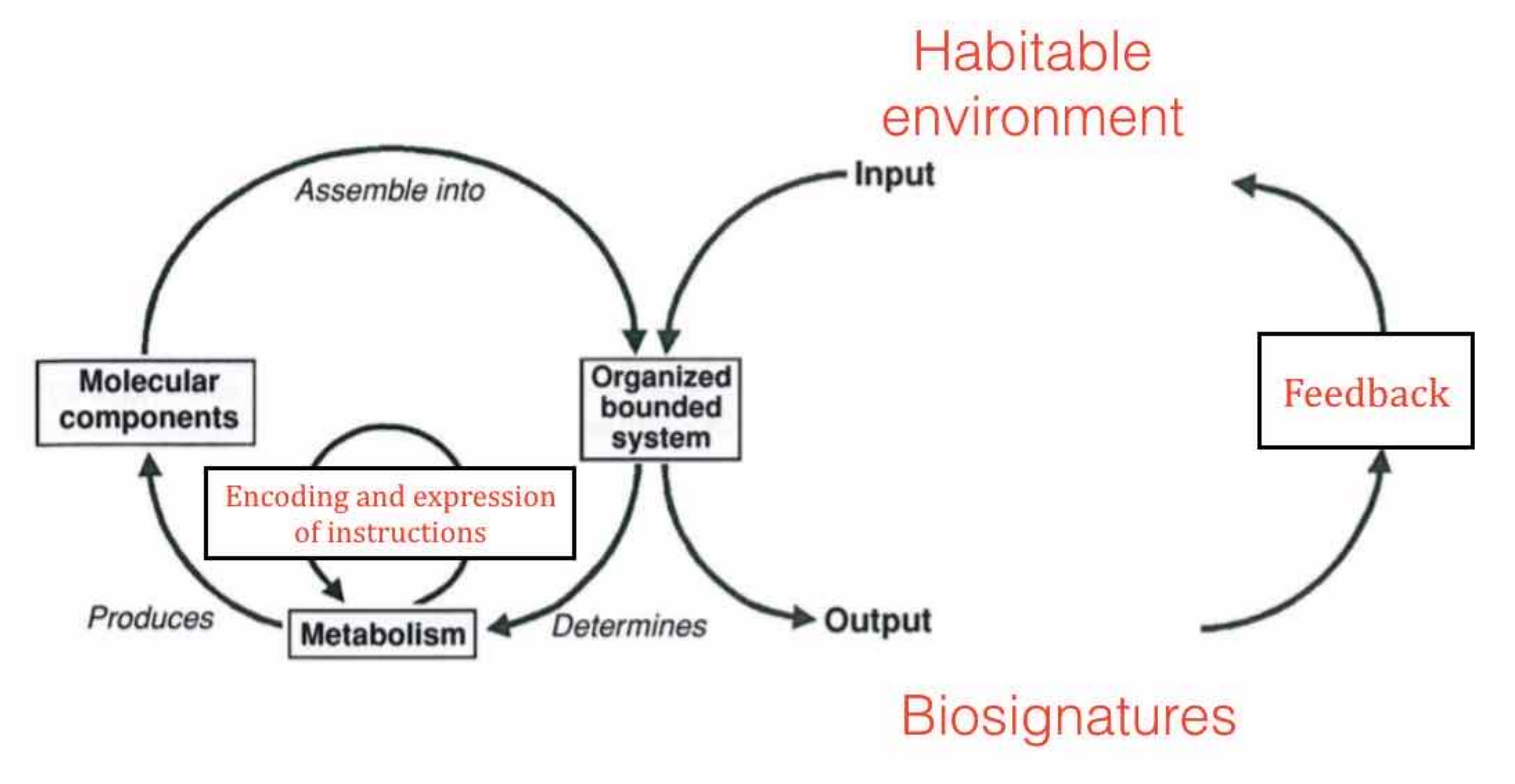
The existence of an open border, the presence of a liquid medium,
the injection of entropy and chemical disequilibrium in the environment
are universal properties of life

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

In practice, however, the definition of "biosignature"
is extremely challenging

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

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

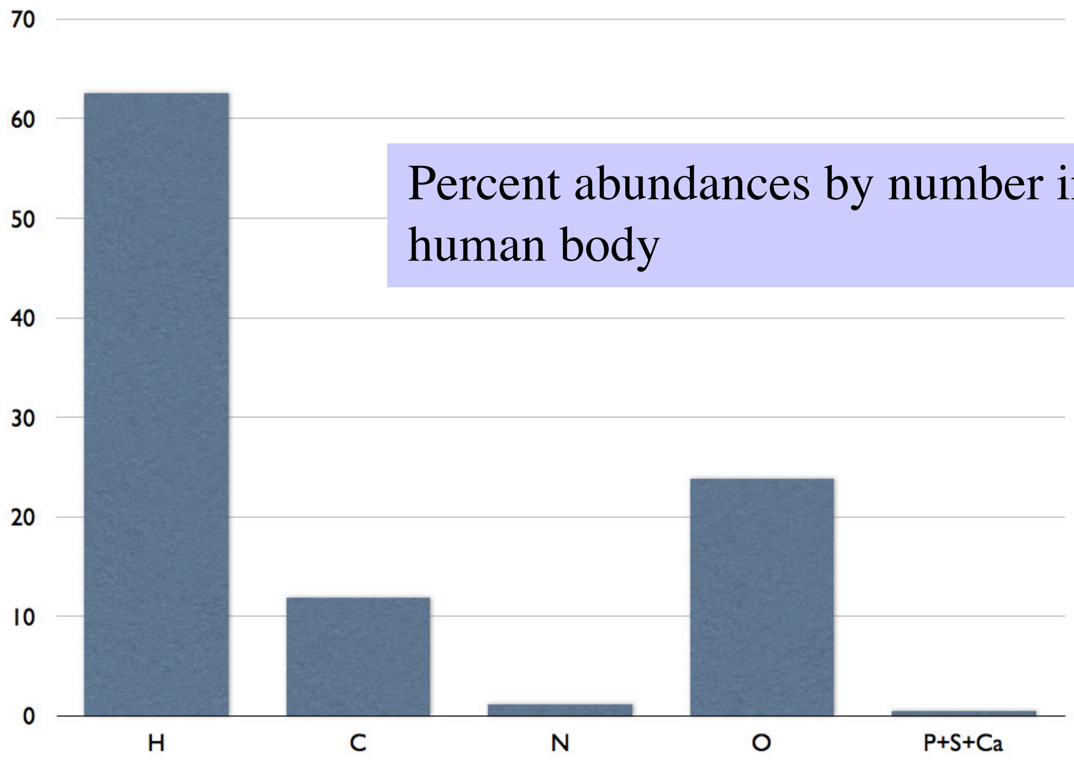
Chemical ingredients of terrestrial life

Chemical elements
Chemical bonding and interactions

The chemical elements of terrestrial life (1)

Most abundant elements in terrestrial organisms:

H, C, N, O



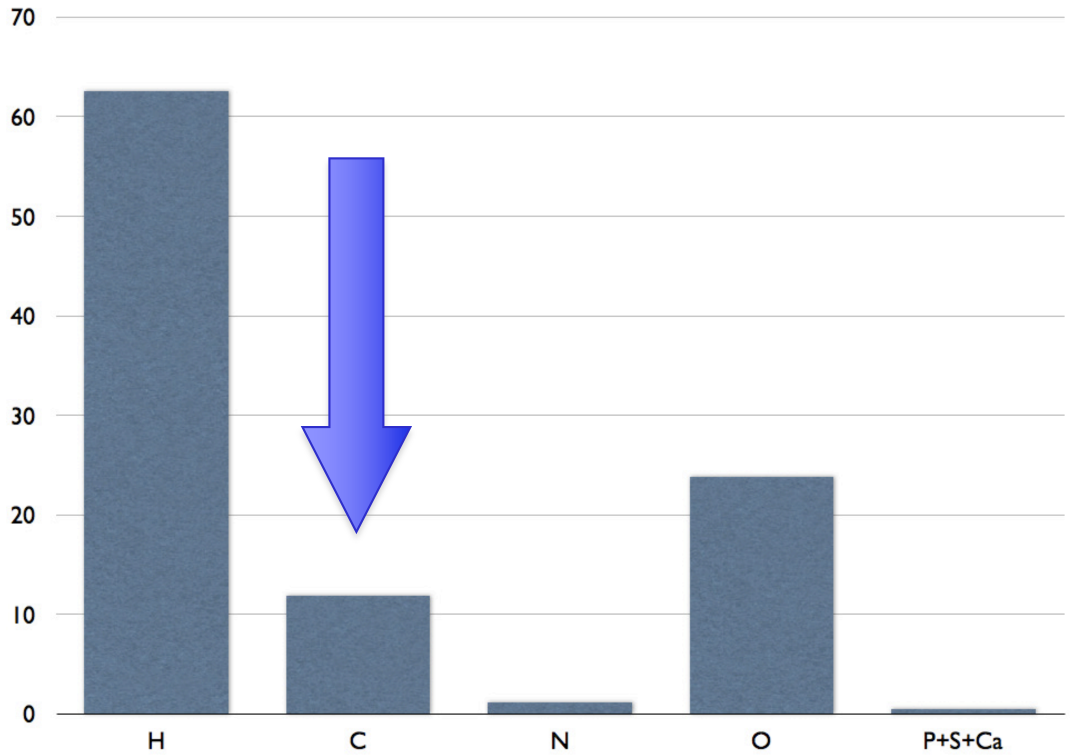
Percent abundances by number in the human body

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)

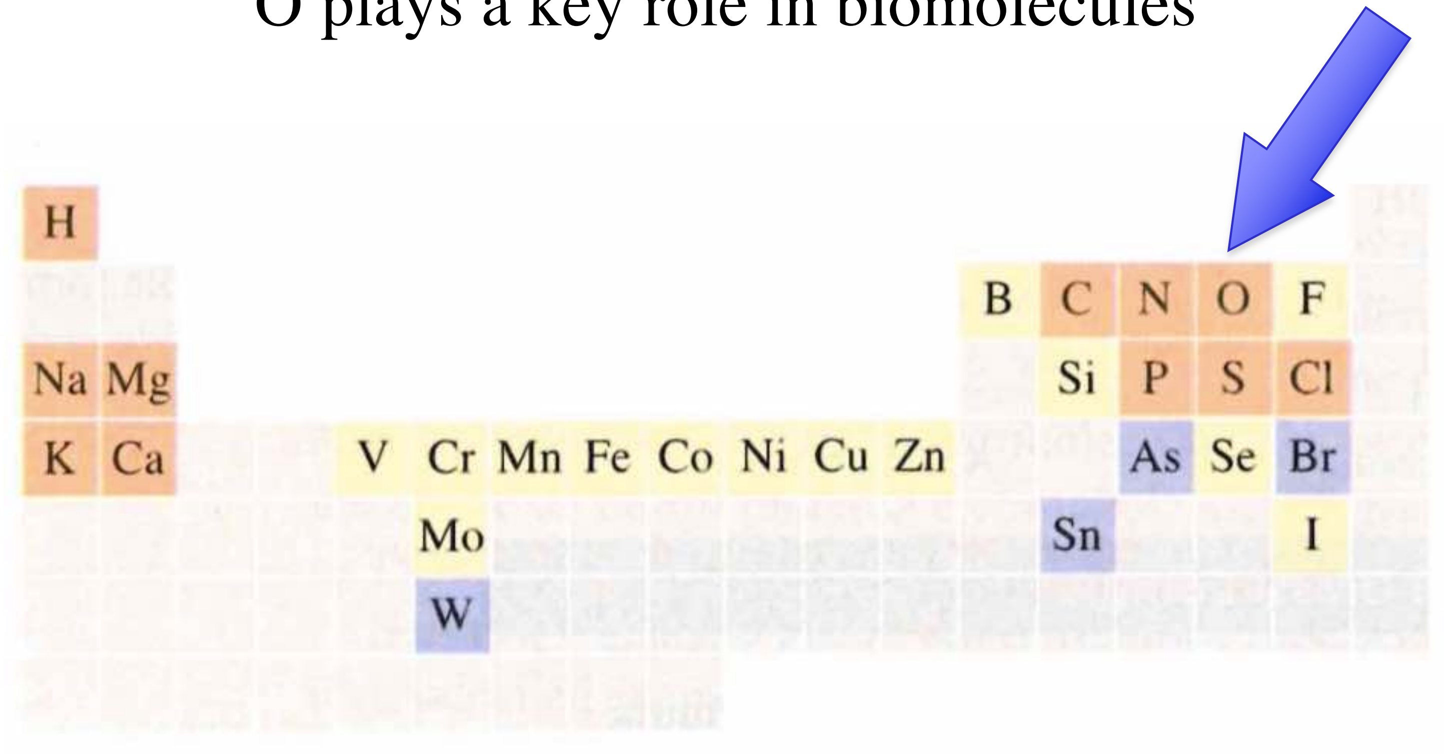
If we exclude the contribution of H and O (mostly in water), the most abundance atom is <u>carbon</u>

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



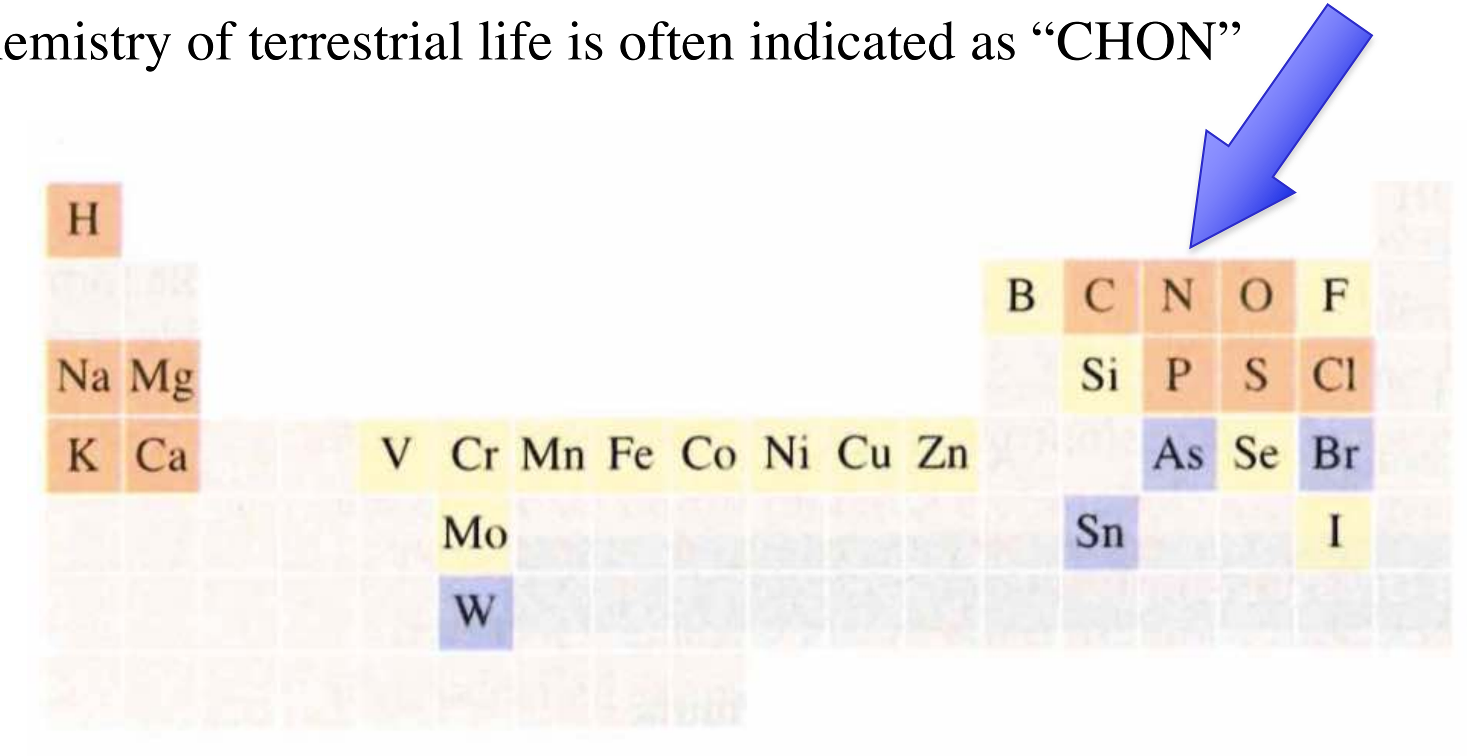
Orange: Main elements in terrestrial life
Yellow: Trace elements necessary for animals and plants
Magenta: Trace elements occasionally present in some forms of life

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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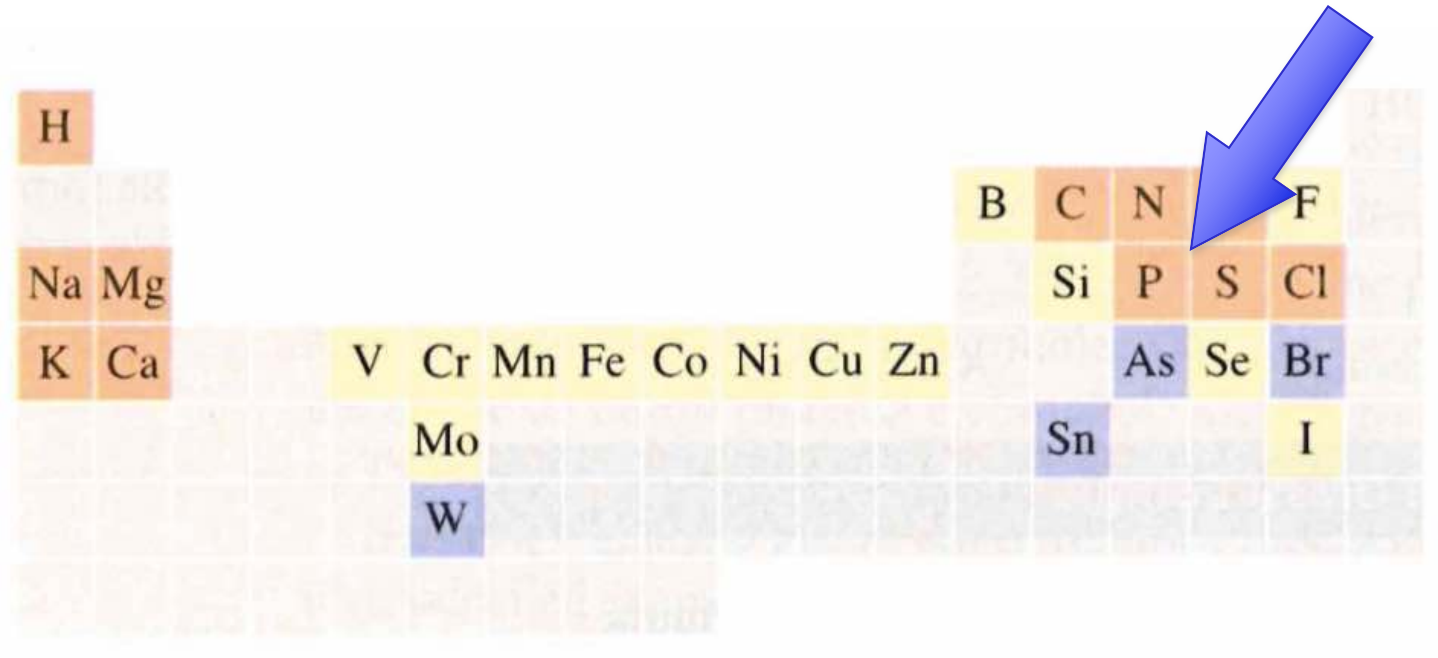
The chemical elements of terrestrial life (5)

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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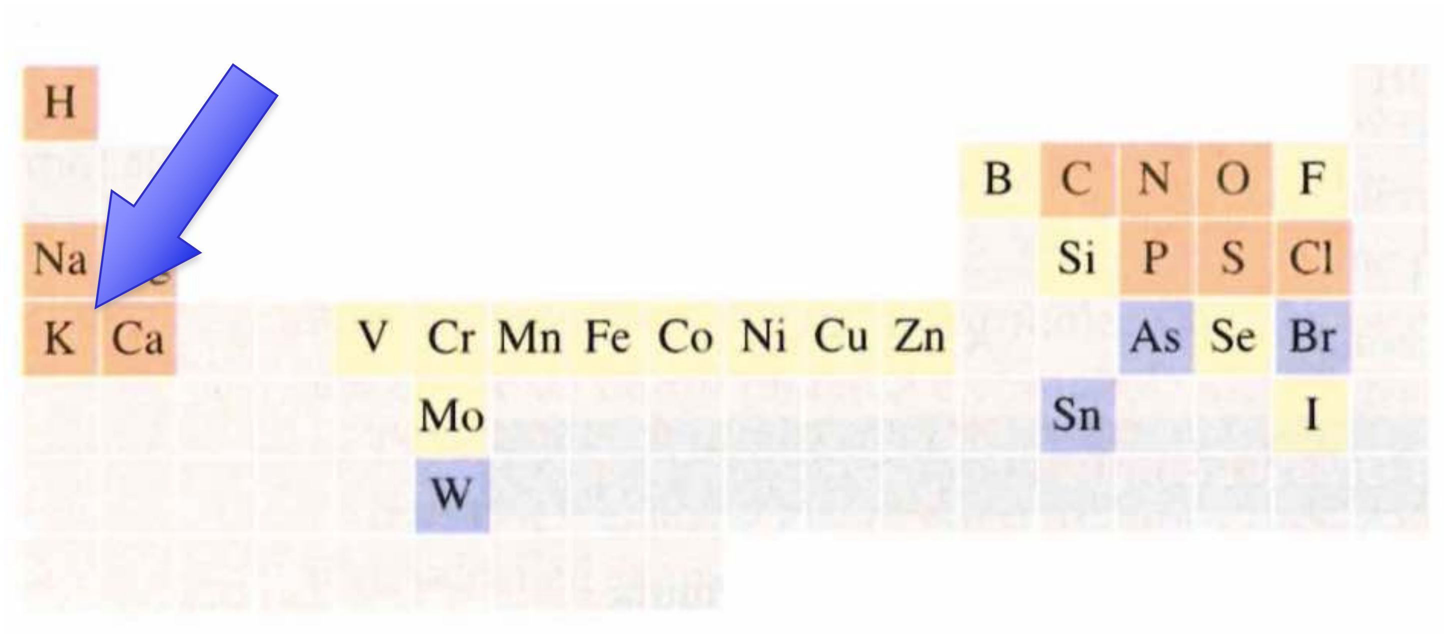
The chemical elements of terrestrial life (6)

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



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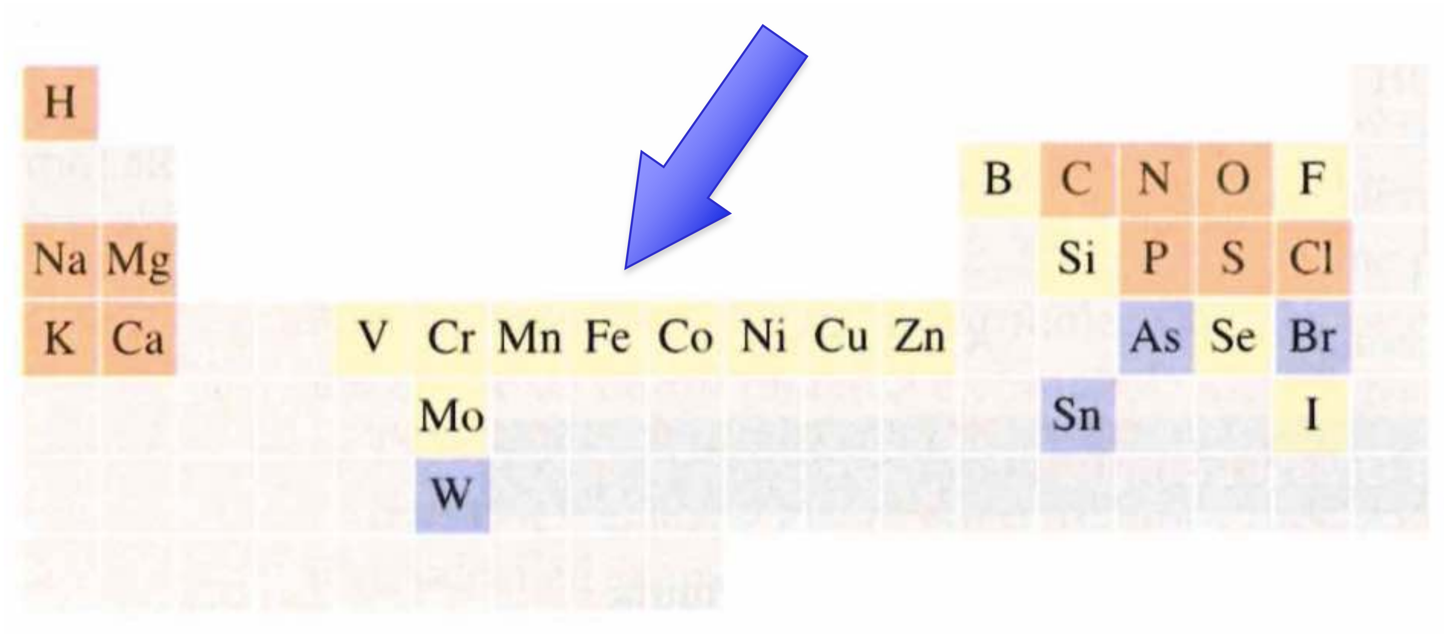
The chemical elements of terrestrial life (7)

Metals only appear in trace quantities, but they are essential



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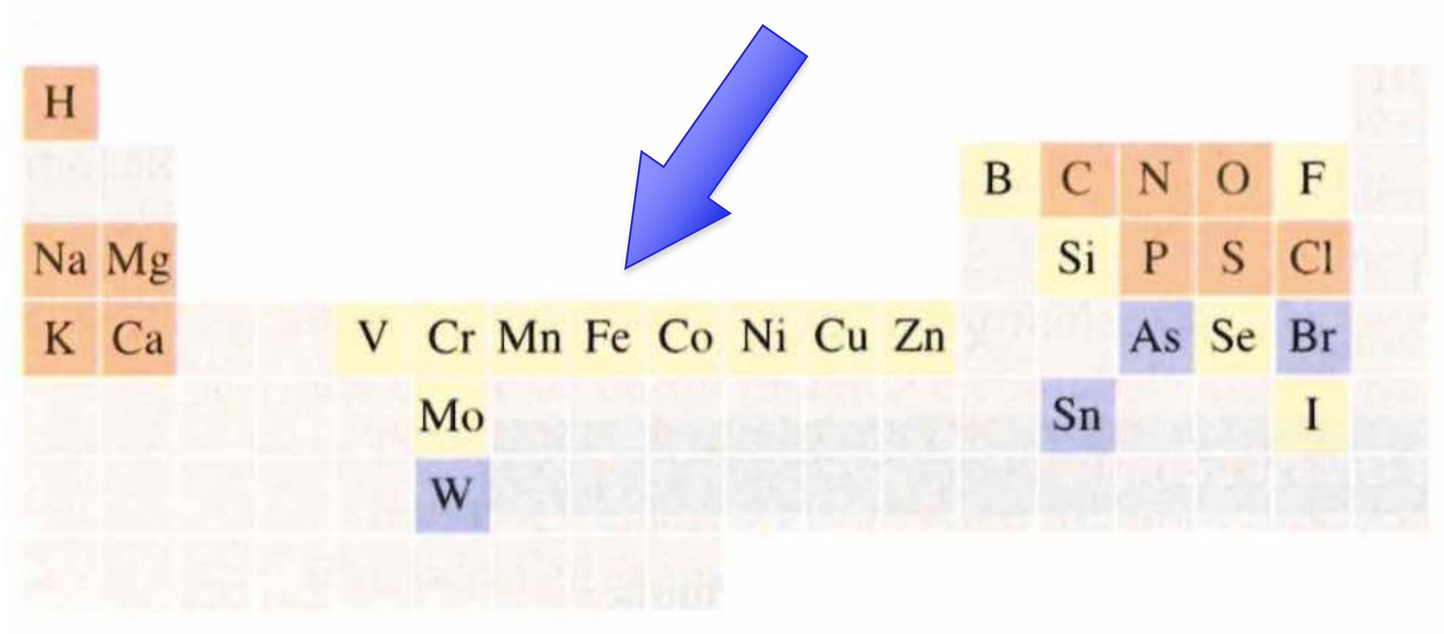

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From chemical elements to biomolecules: chemical bonds

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

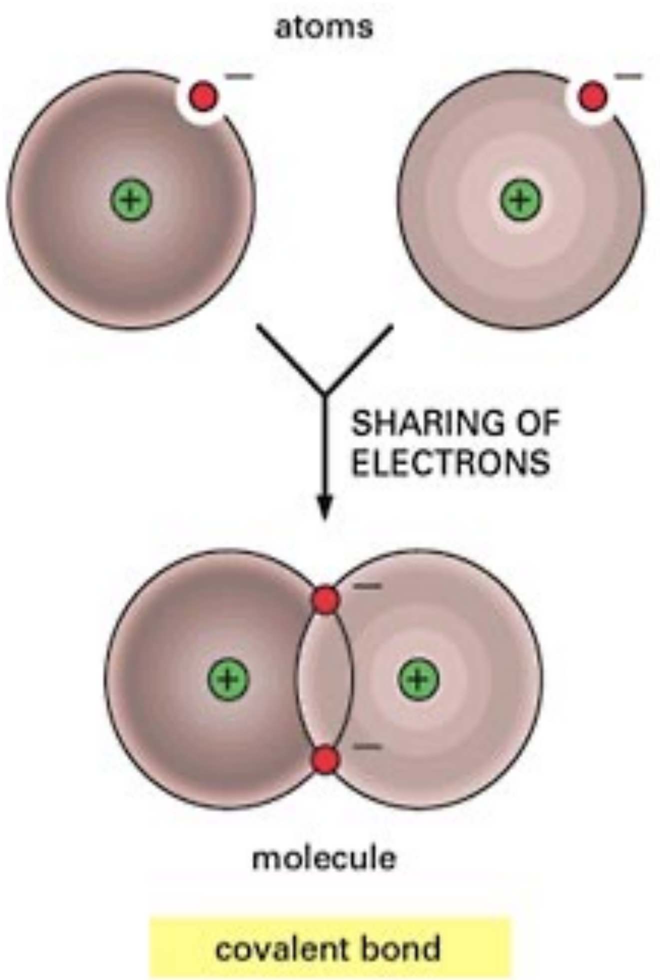
Strong chemical bonds in nature can be
covalent, ionic, and metallic

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

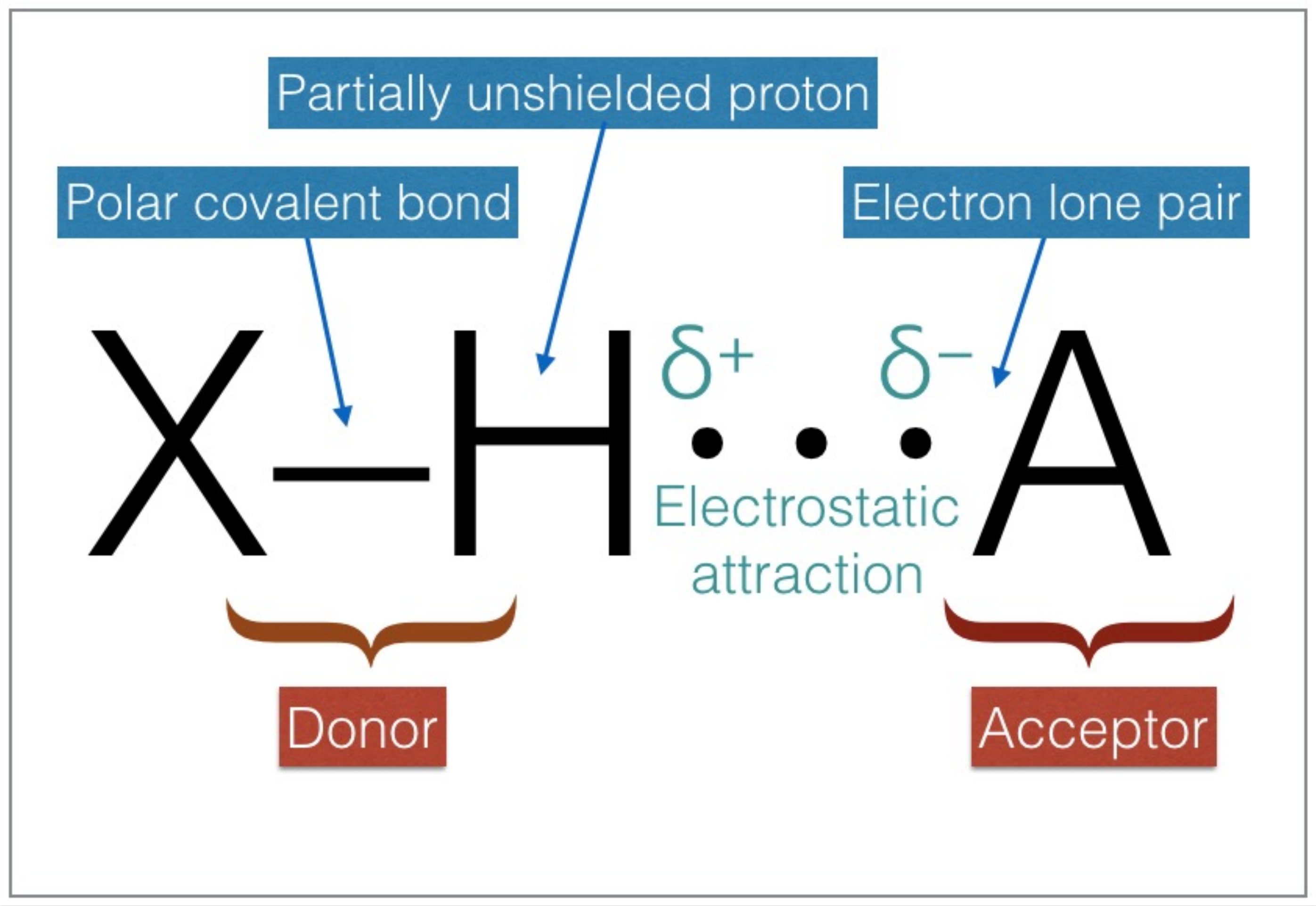
The need for biomolecules to interact without altering
their (covalent-bond) structure implies
that biomolecules should interact via weak chemical bonding/forces

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

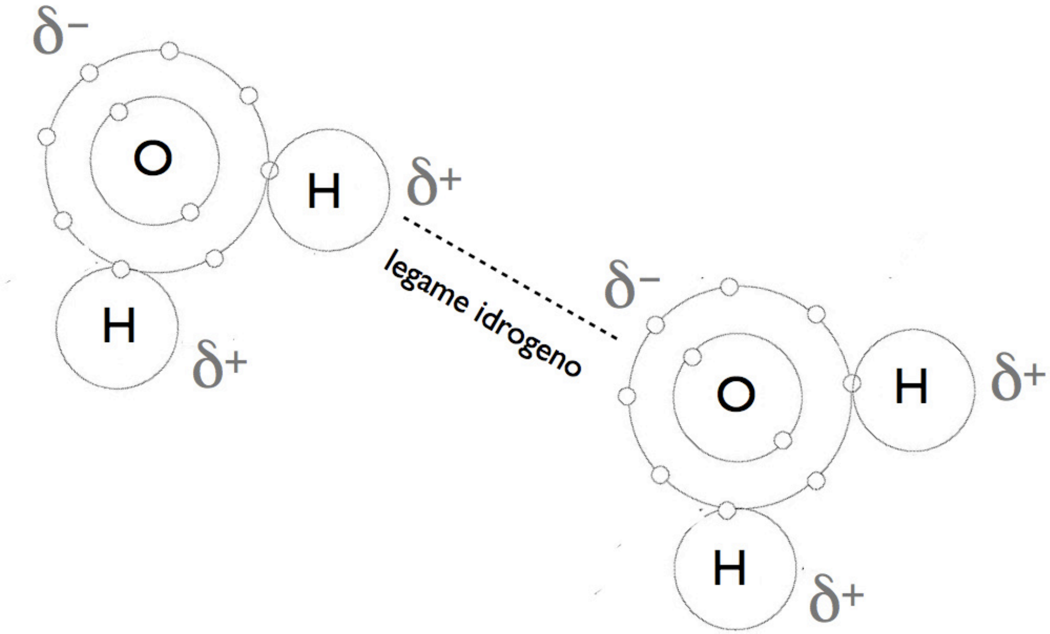
Hydrogen bonds



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



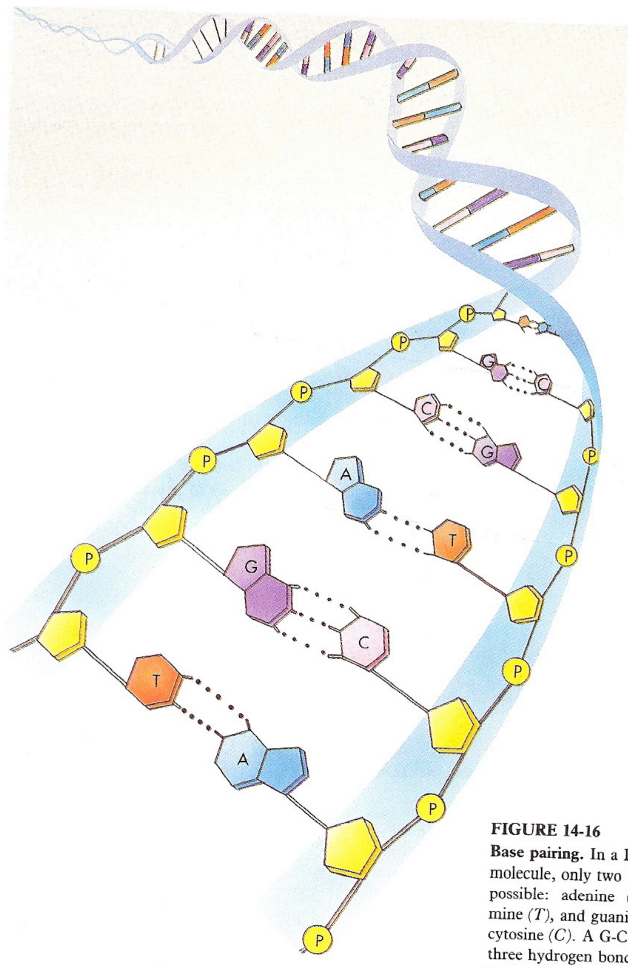


FIGURE 14-16
Base pairing. In a DNA molecule, only two base p possible: adenine (A) v mine (T), and guanine (G cytosine (C). A G-C base three hydrogen bonds; an base pair, only two.