# Astrobiology

## Role of carbon & water in terrestrial life

Planets and Astrobiology, Academic Year 2019-2020
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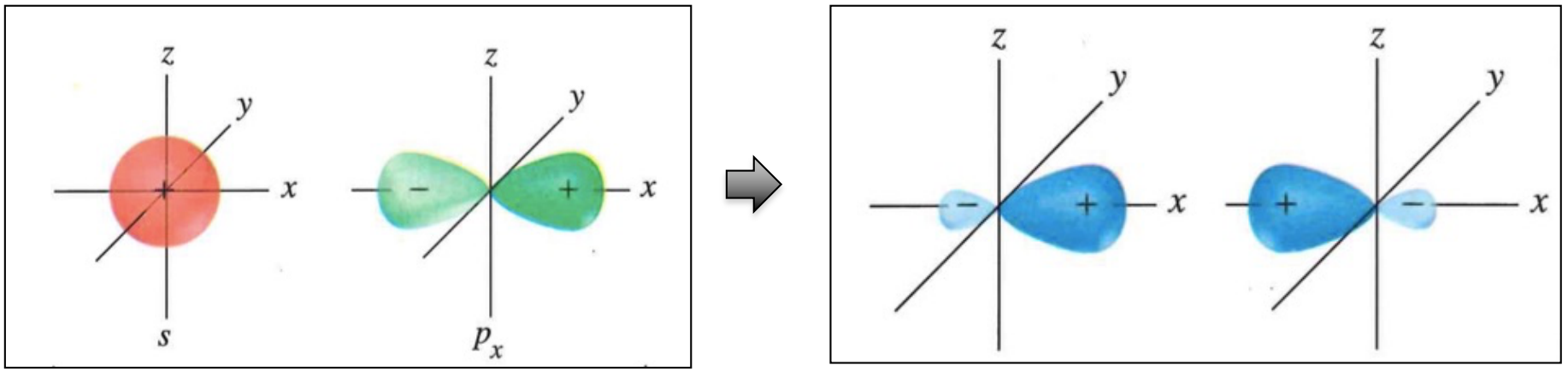
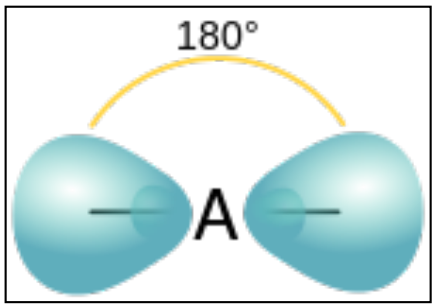
# Hybridization of carbon valence orbitals

**sp orbitals**: two atomic orbitals are mixed to form two hybrid orbitals

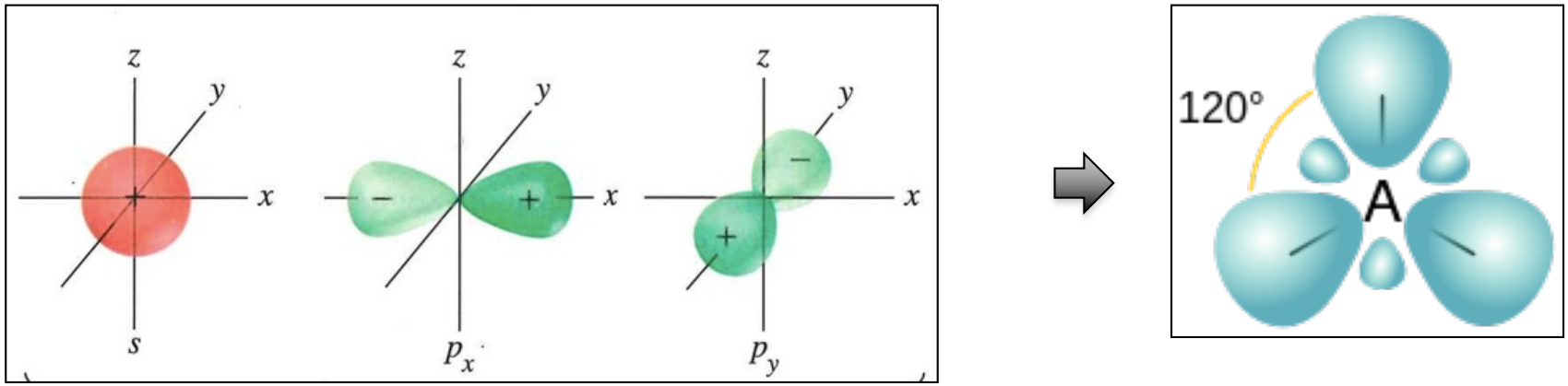



The two sp hybrid orbitals arrange themselves in three dimensional space to get as far apart as possible with a bond angle of 180°.
The geometry which achieves is linear.



# Hybridization of carbon valence orbitals

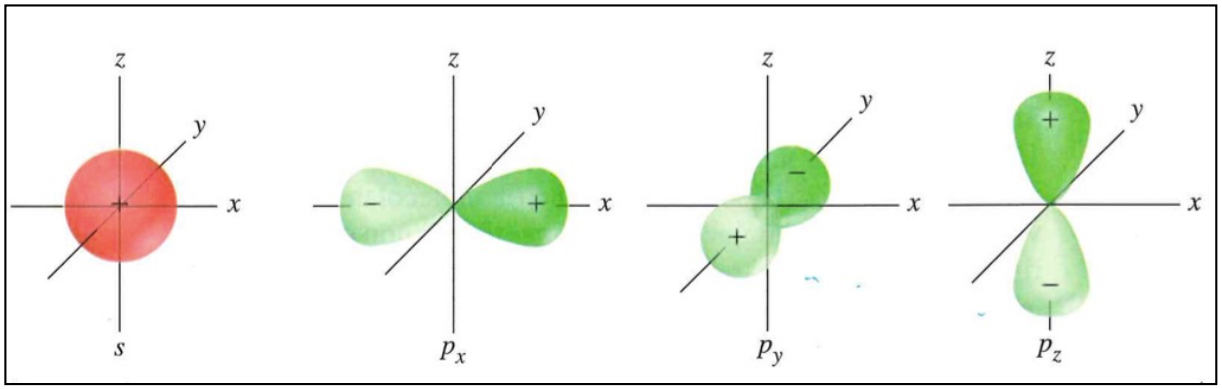
**$sp^2$ orbitals**: three atomic orbitals are mixed to form three hybrid orbitals

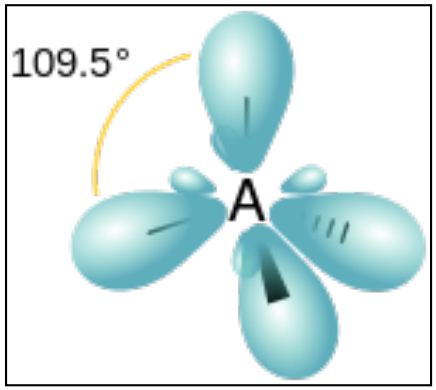






**$sp^3$ orbitals**: four atomic orbitals are mixed to form four hybrid orbitals



# Carbon

- Structural properties
  - In summary, carbon has 4 oriented covalent bonds that allow the formation of a great variety of 3D molecular structures
  - The valence orbitals 2s and 2p can hybridize forming:

    two sp hydrid orbitals ➔ linear structures

    three $sp^2$ hybrid orbitals ➔ planar structures

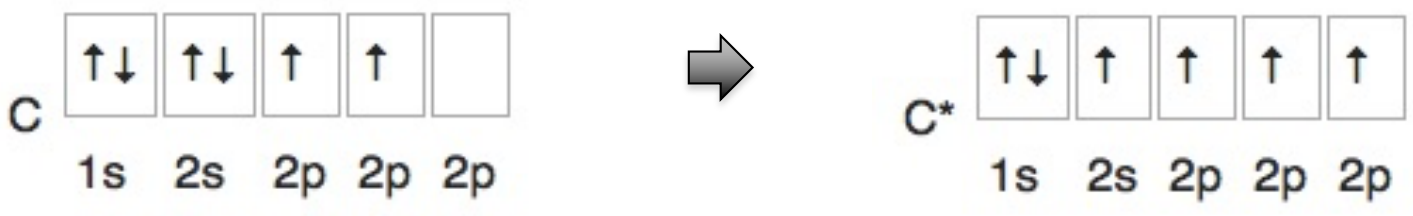
    four $sp^3$ hybrid orbitals ➔ tetrahedrical structures
  - The same flexibility of forming geometrical structures is not found in other atoms

# Carbon

In terrestrial life carbon is the building block of biological molecules

- With respect to other cosmically abundant atoms, carbon offers several advantages in terms of structural and metabolic properties

- Electronic configuration
  - Carbon's ground state configuration is $1s^2\ 2s^2\ 2p^2$



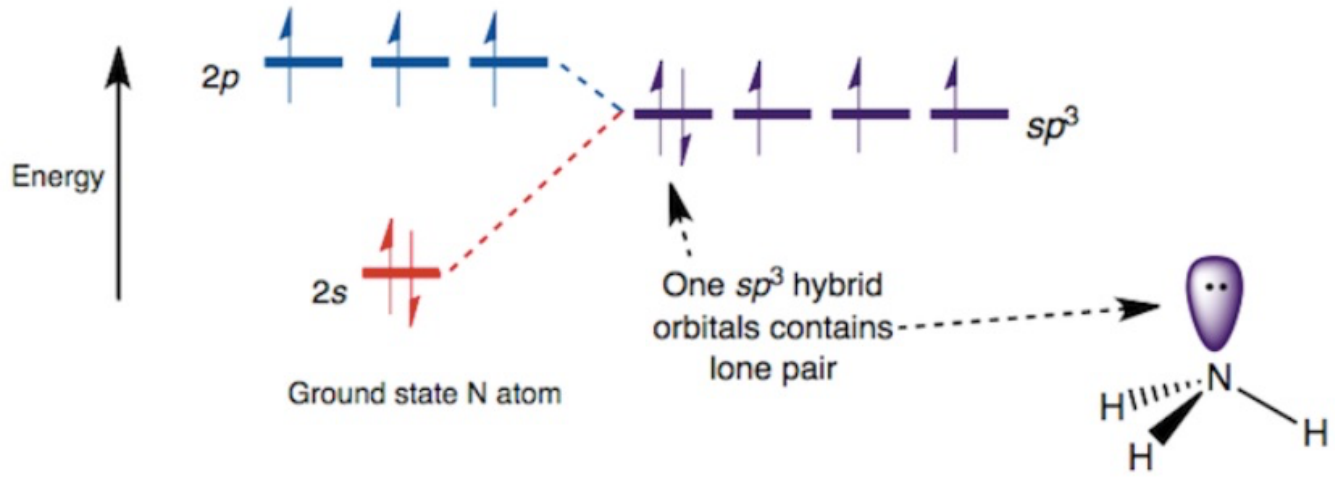

  - The excitation of one electron of the 2s orbital easily provides a configuration with 4 orbitals with a single electron
  - The 4 oriented covalent bonds allow the formation of a great variety of 3D molecular structures:

    linear, planar, tetrahedical

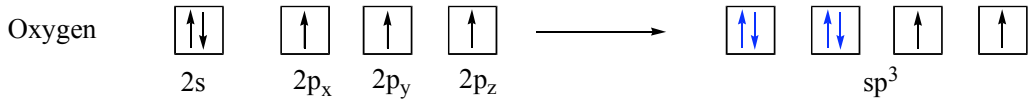
# Carbon versus nitrogen and oxygen

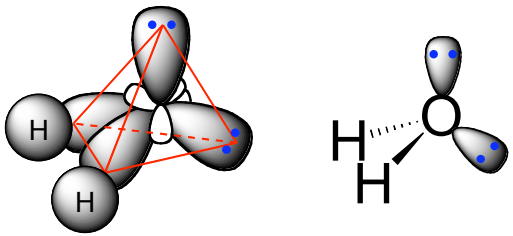
The flexibility of carbon to form 3D structures is not found in other atoms

Nitrogen has 3 covalent bonds which tend to form planar structures




Oxygen has 2 covalent bonds which tend to form linear structures

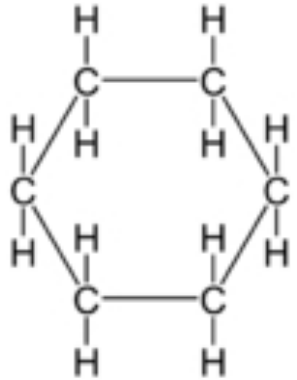


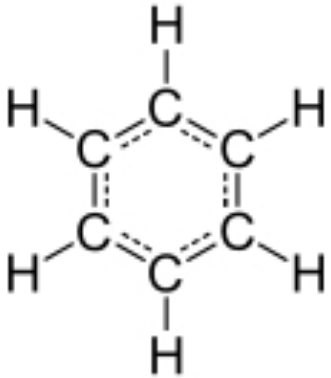
# Organic ring structures

## Carbon can form a variety of ring structures

Carbon is the only atom with the capability of forming aromatic rings



Cyclohexane
(saturated molecule)



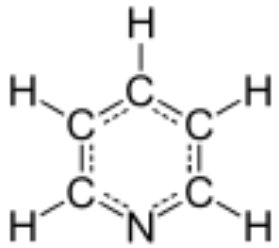
Aromatic ring of Benzene
(unsaturated molecule)

# Hetero-organic molecules

- 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

  For instance, N can replace C in ring structures




The large flexibility of carbon in terms of geometrical structure, coupled with the possibility of substitutions of other abundant elements, leads to a infinite number of possible molecular structures potentially suitable for different biological functions

# Advantages of carbon

- Metabolic properties
  - Carbon can easily be transformed from the completely oxidized form, $CO_2$, to the completely reduced form, $CH_4$

    This is an advantage for the capability of activating metabolic processes, which are largely based on redox reactions

    This provides the possibility of cycling carbon between its "inorganic form" and its "organic form"

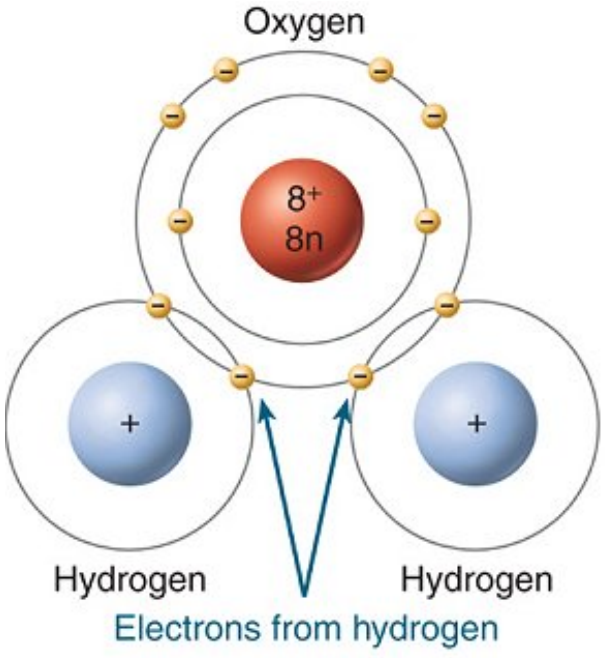
$CO_2$: "inorganic carbon"

$CH_4$: "organic carbon"

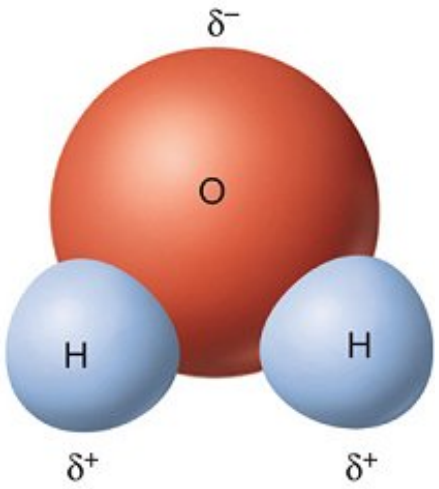
# The water molecule

## Most abundant molecule in living organisms

The water molecule is polar

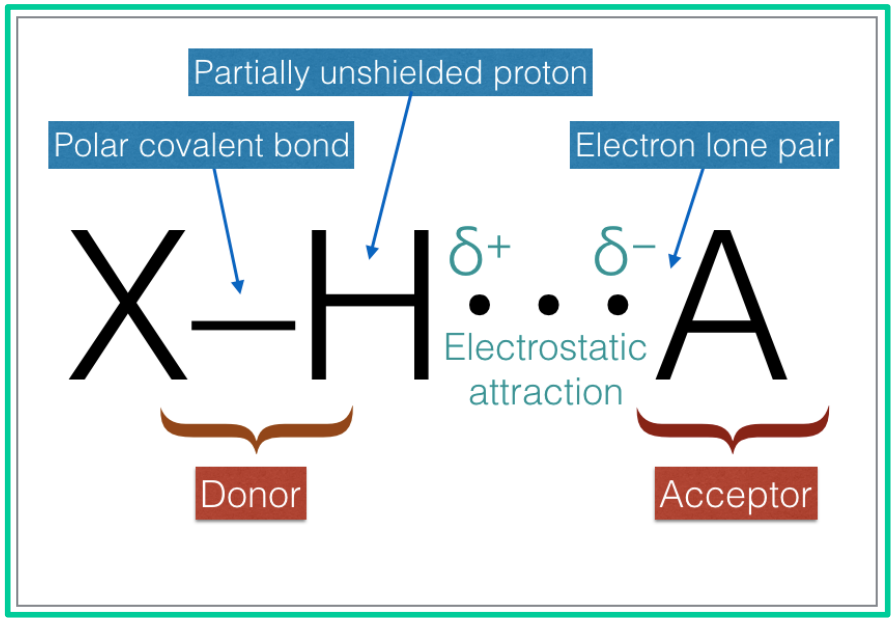



(a) Electron shells in a water molecule

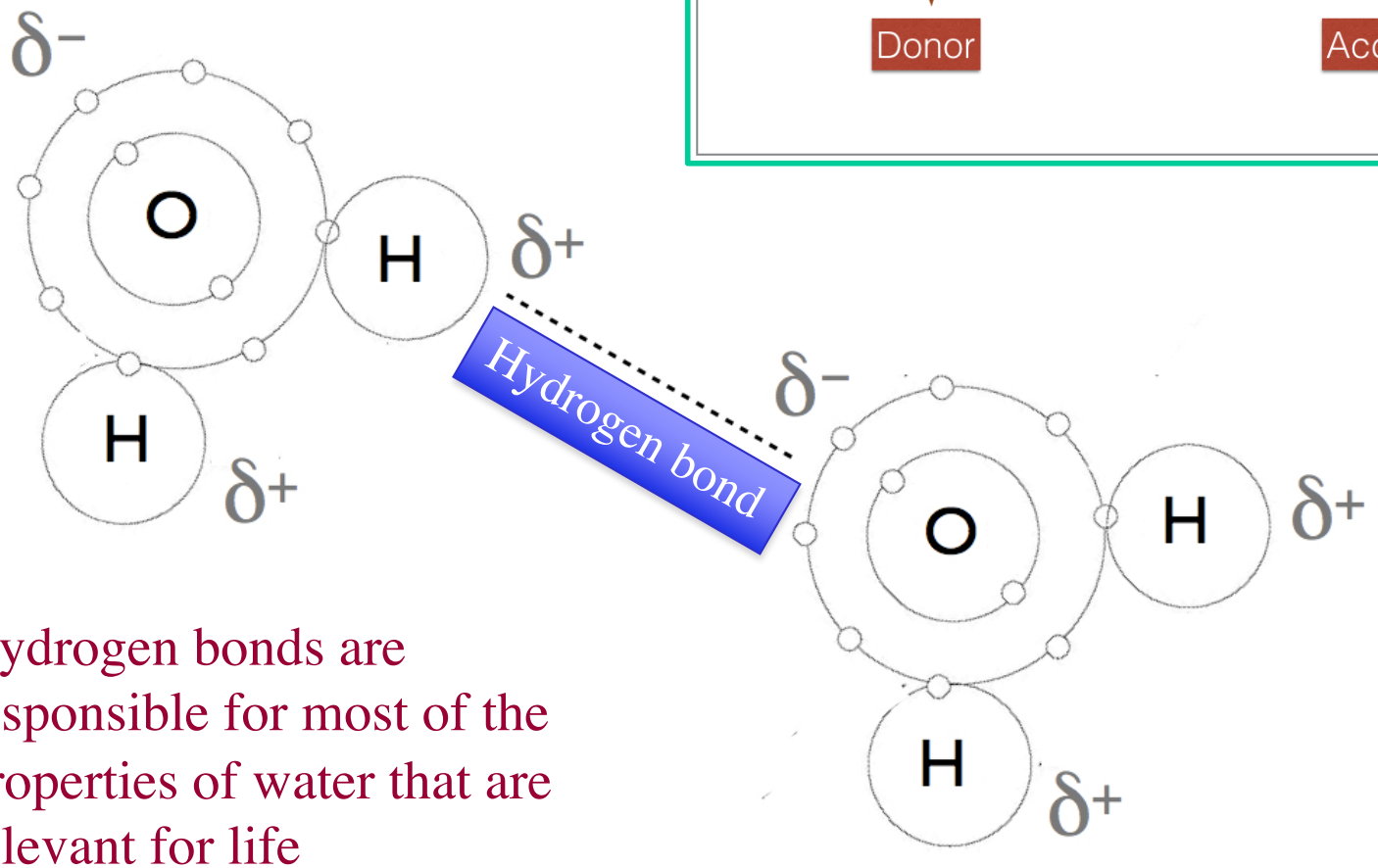



(b) Distribution of partial charges in a water molecule

# Hydrogen bonds & life




## Hydrogen bonds between water molecules




Hydrogen bonds are responsible for most of the properties of water that are relevant for life

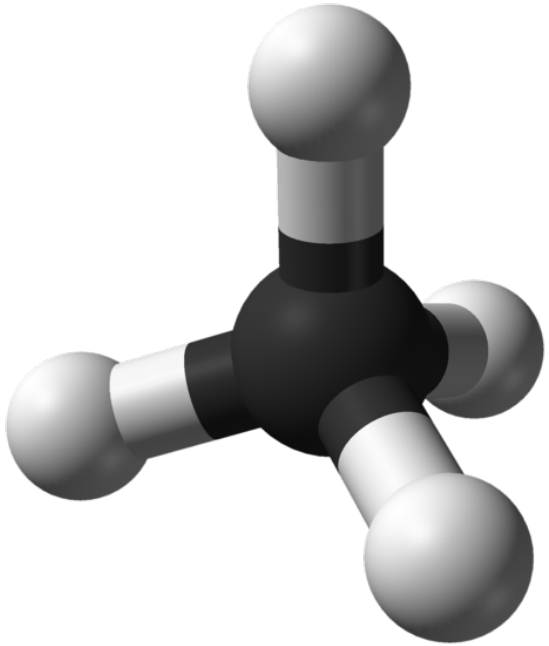
# Polar and non-polar molecules

- 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)

Methane:
a non-polar molecule



- Polar molecules
  - can be solved in water
  - are hydrophilic

- Non-polar molecules
  - cannot be solved in water
  - are hydrophobic

# Properties of water relevant to life (1)

- The water molecule has a high electric dipole

  – Water is a good solvent

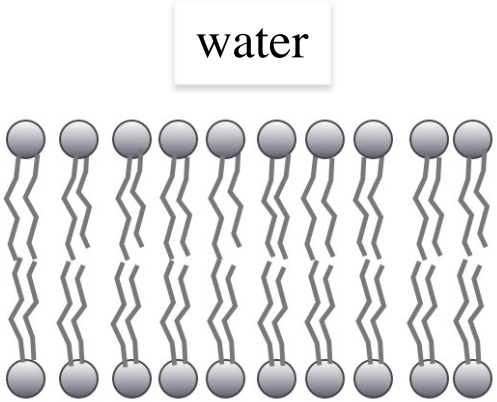
    Thanks to this property, the dissolved molecular constituents have the mobility required for metabolic processes to take place

  – Thanks to the polarity, amphiphilic molecules in water can spontaneously form structures of biological interest (bilayers, micelles)

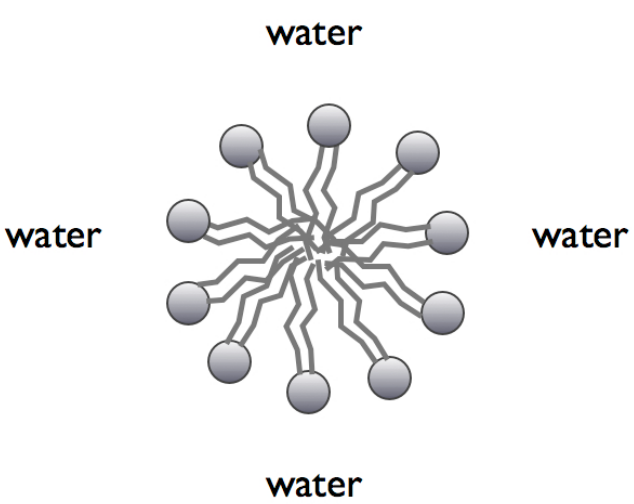
# Polar molecules allow spontaneous formation of molecular structures of biological interest

**Bilayer**

amphiphilic molecules




**Micelle**




Geometrical configurations with lowest potential energy

# Properties of water relevant to life (2)

- Water spontaneously form ions
  - Spontaneous breaking of covalent bonds in a small fraction of water molecules yields $H^+$ and $OH^-$ ions

Note: the concentration of $H^+$ ions in water is used to define the pH scale

The free ions, and in particular $H^+$,

can be used to transport electric charges

$H^+$ and $OH^-$ take part in metabolic reactions

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

– Water formation and dissociation has the potential to play an important role in metabolic processes, as it does in terrestrial life