The Definition of Life

What is life?

When we look for life in the cosmos, what are we looking for exactly?

How would we be sure we had found it?

Defining things can be trickier than it seems. What is “water”?

For centuries, people tried to define water by its **characteristics**.

Water…

- is wet
- conforms to its container
- is transparent
- is a liquid at room temperature
- solidifies when cooled
- dissolves salt

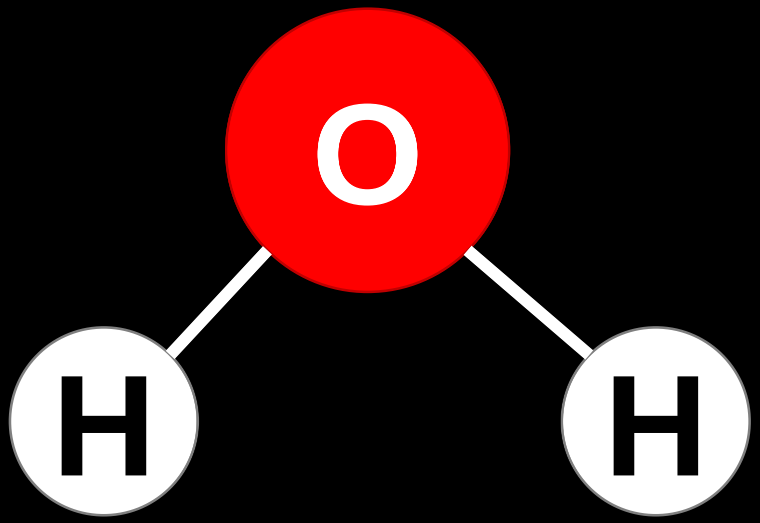
Water…

- is wet (so is ethanol)
- conforms to its container (so does ethanol)
- is transparent (so is ethanol)
- is a liquid at room temperature (so is ethanol)
- solidifies when cooled (so does ethanol)
- dissolves salt (so does ethanol)

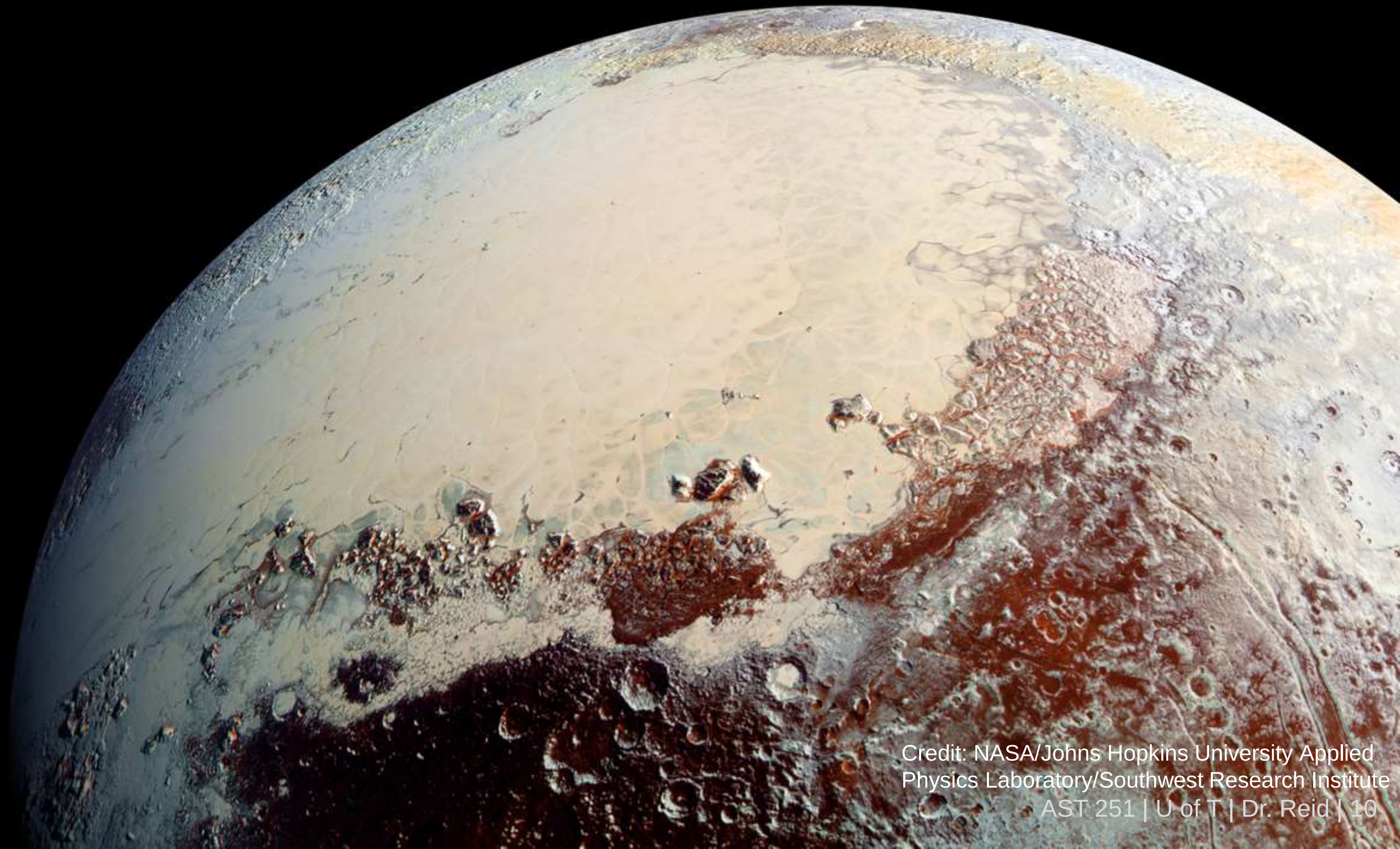
These definitions were missing a paradigm needed to fully define "water".

That paradigm was the atomic theory of matter.

water = H_2O

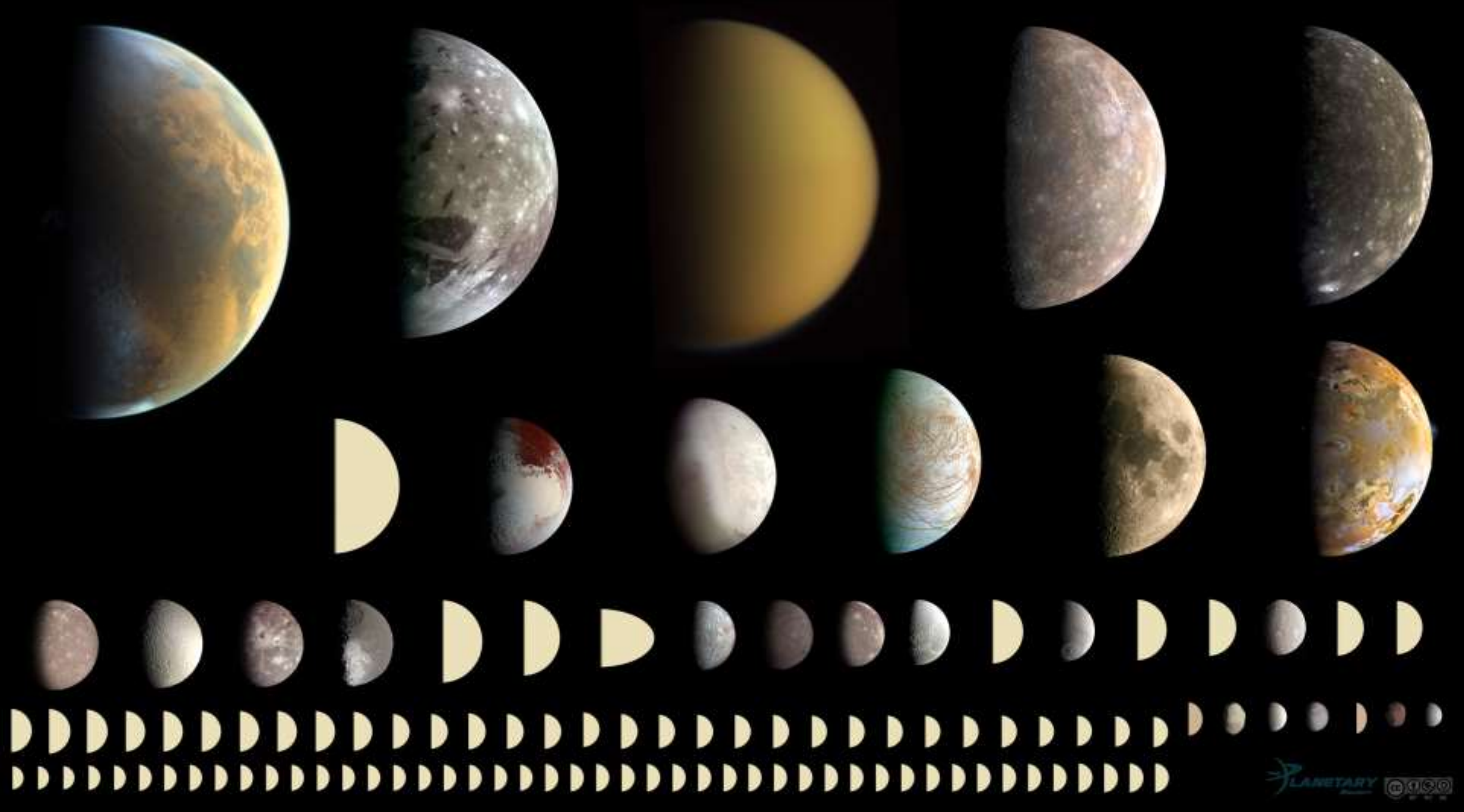


The word "planet" has proven similarly to define.



Credit: NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute

Small round objects of our solar system



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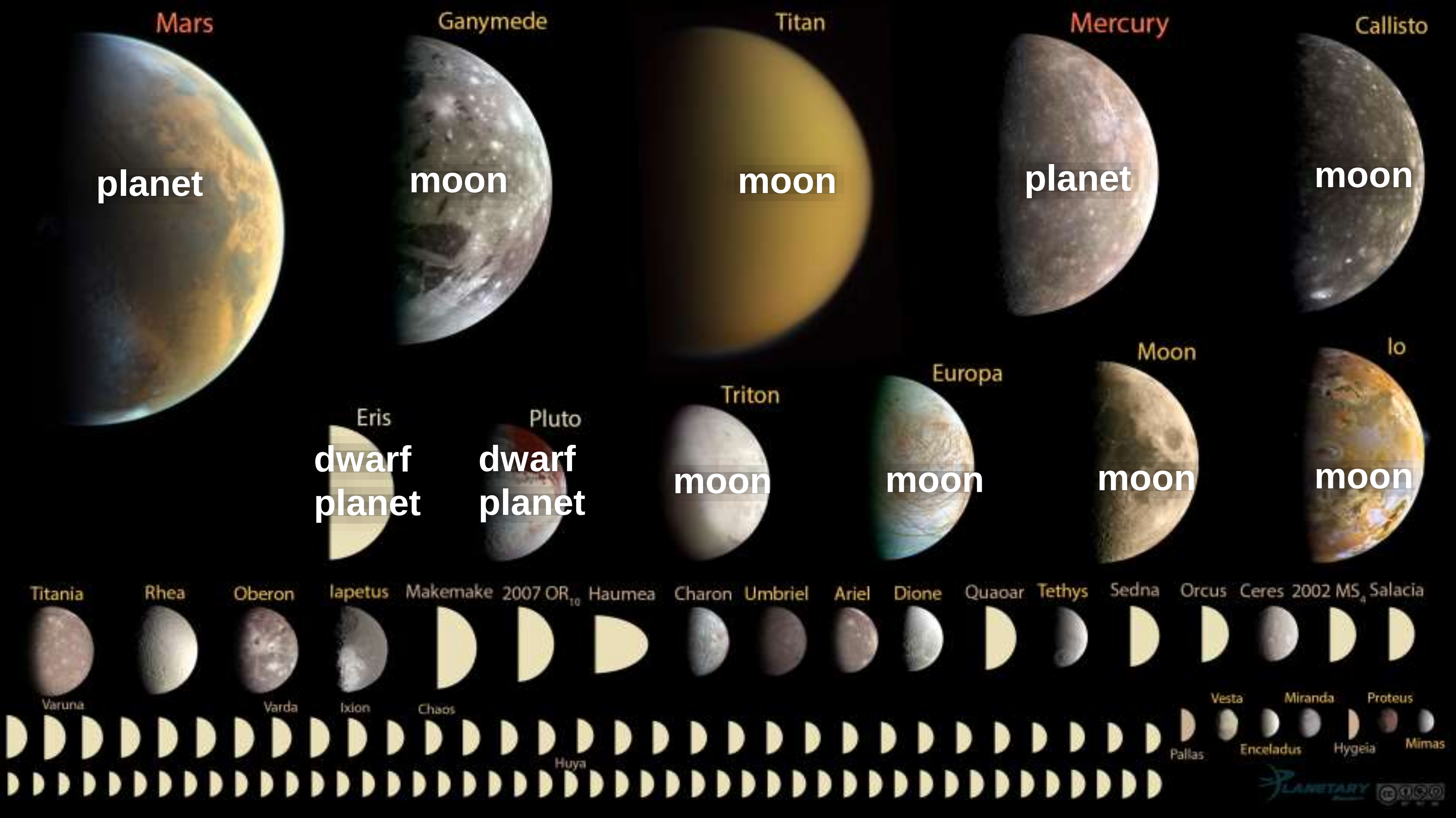
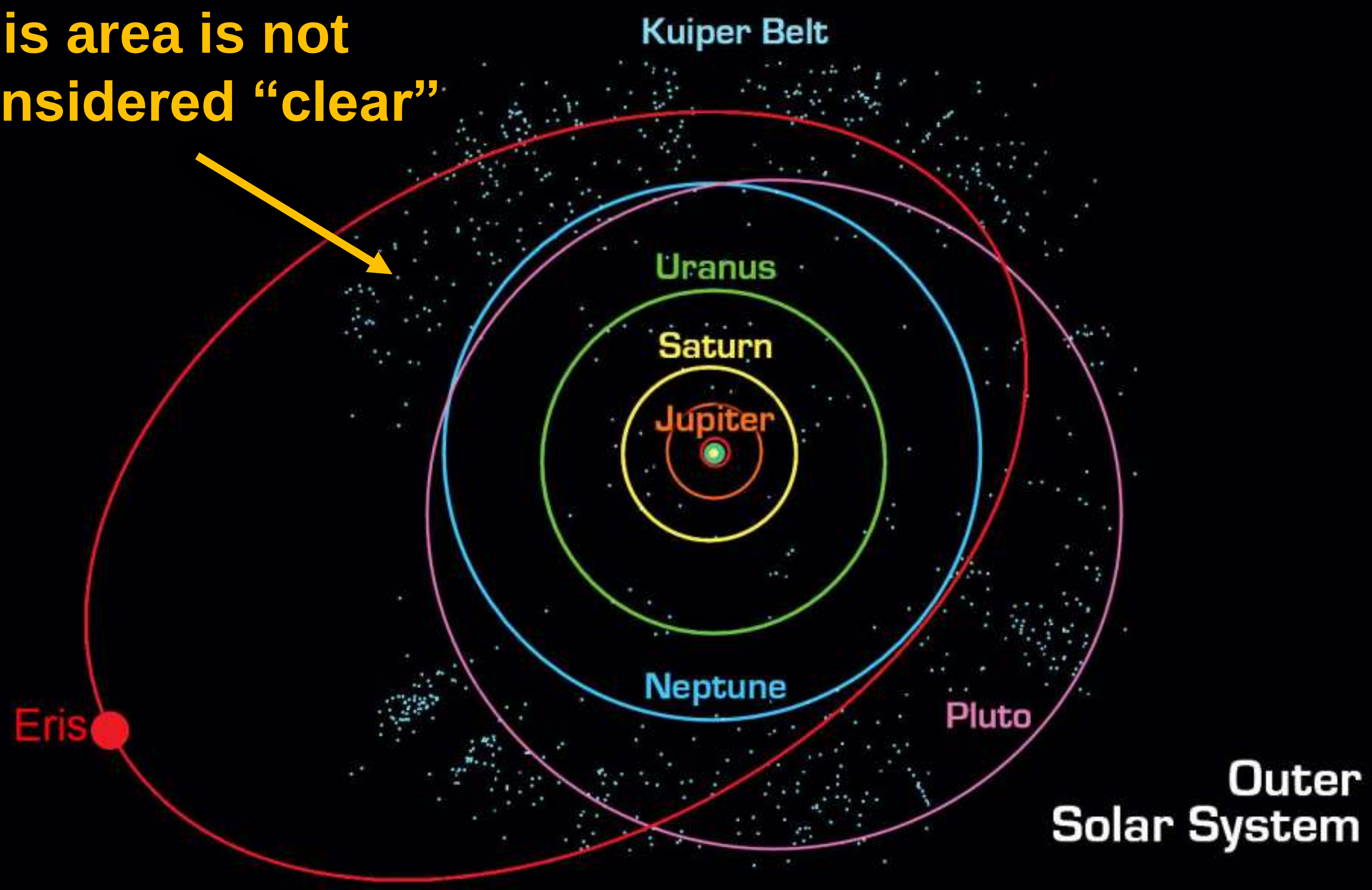


“A planet is a celestial body that:

a) is in orbit around the Sun,
b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, and
c) has cleared the neighbourhood around its orbit. ”

-IAU Resolution, 2006

This area is not considered "clear"



Credit: NASA

Credit: NASA/JHUAPL/SwRI

Credit: BennuBird

As with early definitions of “water” and the current definition of “planet”, current definitions of “life” are based on its characteristics.

"All living organisms share several key characteristics or functions: order, sensitivity or response to the environment, reproduction, adaptation, growth and development, regulation, homeostasis, energy processing, and evolution. When viewed together, **these nine characteristics serve to define life**."

– Rye et al., Biology, 2017

Note that most of these characteristics would be incredibly difficult to observe over interstellar distances.

“Life is a self-sustained chemical system capable of undergoing Darwinian evolution.”

– 1992 NASA Exobiology Program “working definition” of life

Concept Check

Can you think of something that you would definitely consider to be “life” which doesn’t satisfy the NASA exobiology definition?

In what way does the definition fail?

"Could there be a missing paradigm that would allow us to define "life" as simply as we define "water"?

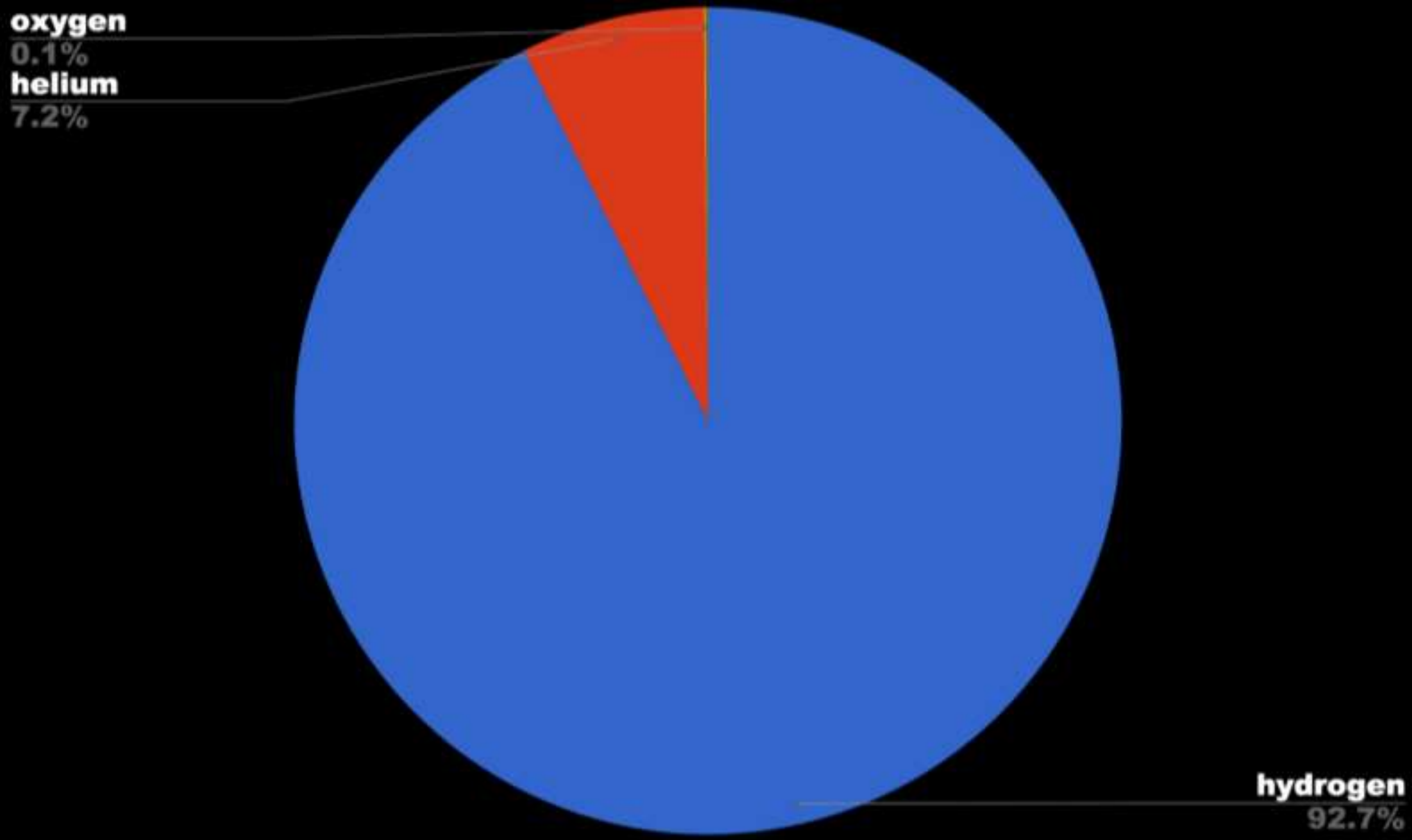
Entropy? Emergence? Complexity?

In this class, we will typically use the NASA exobiology definition of "life", but you should keep its limitations in mind.

The Chemistry of Life: Carbon

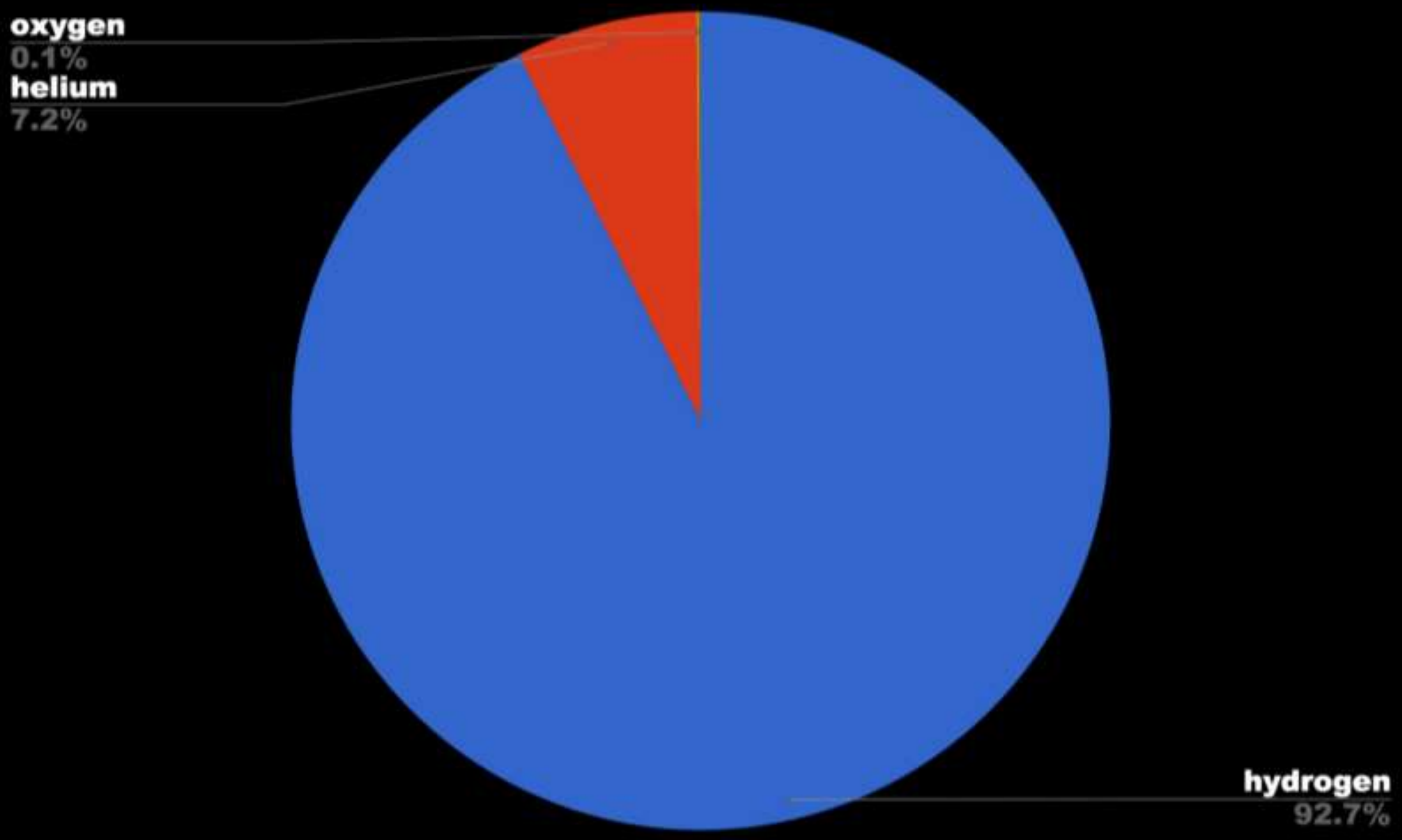
Why determined the chemical basis of life on Earth?

Abundance of Elements in the Universe



*Abundance by number of particles (Data from Wolfram Alpha)

Abundance of Elements in the Universe



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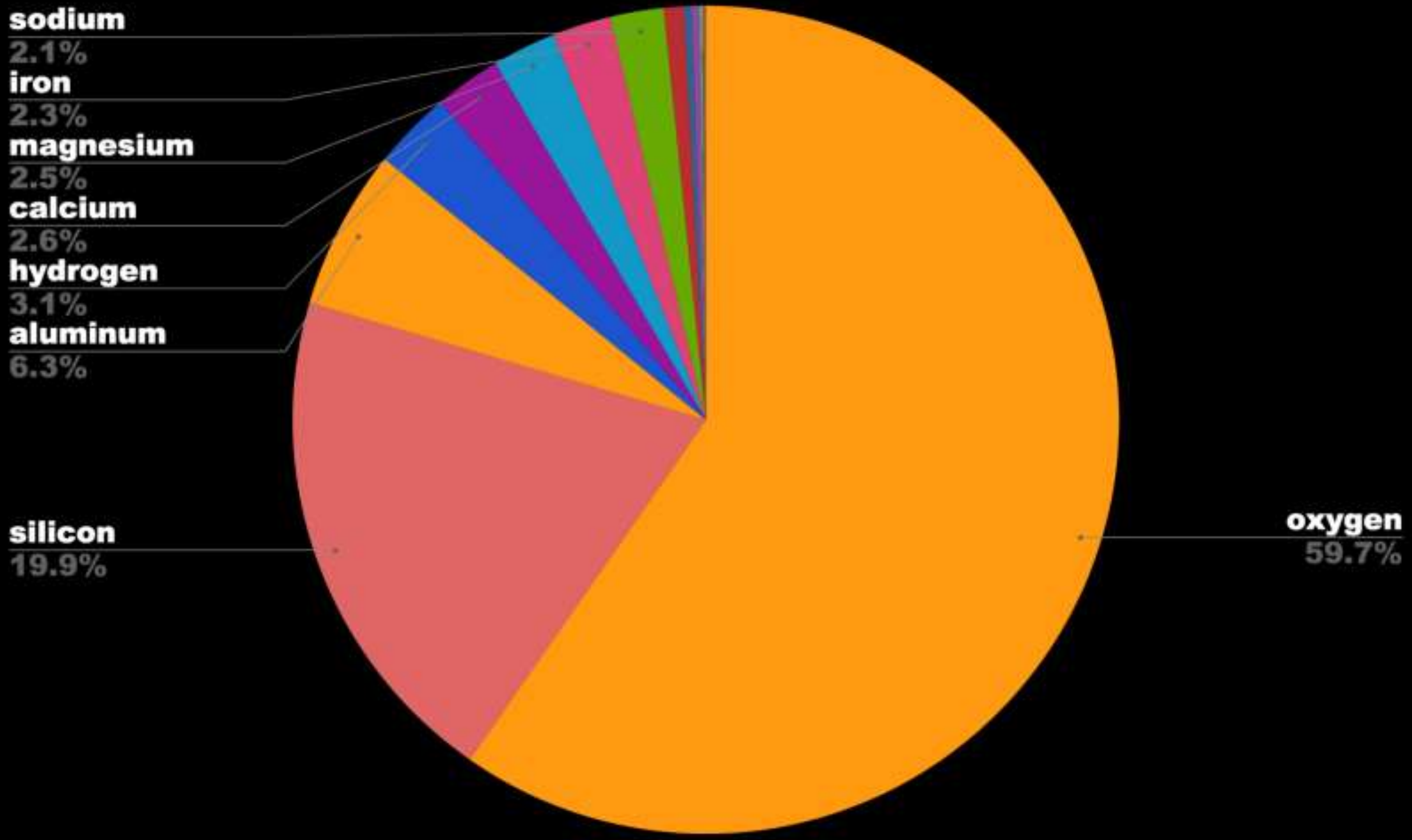
Abundance of Elements in Earth's Crust



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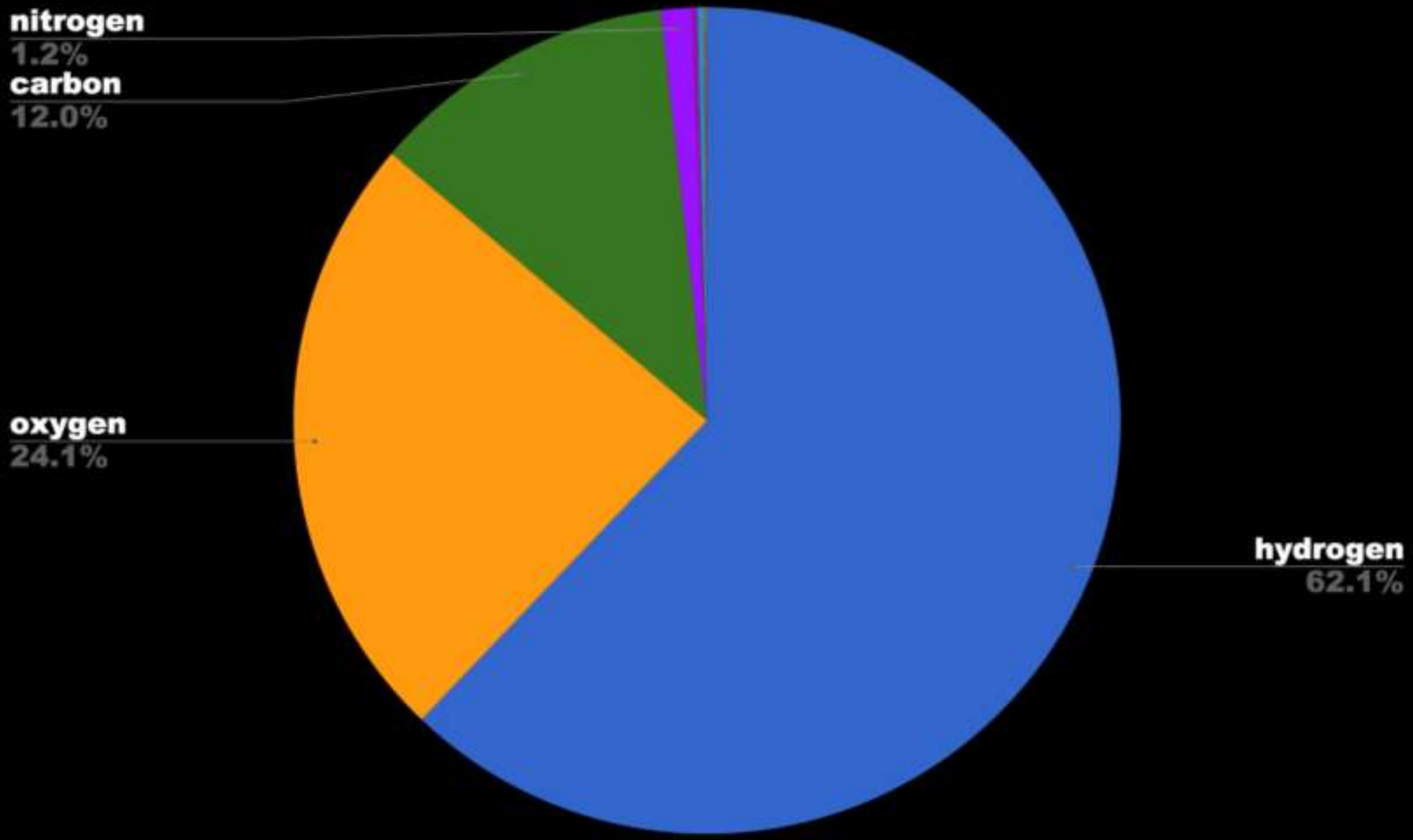
Abundance of Elements in Human Bodies



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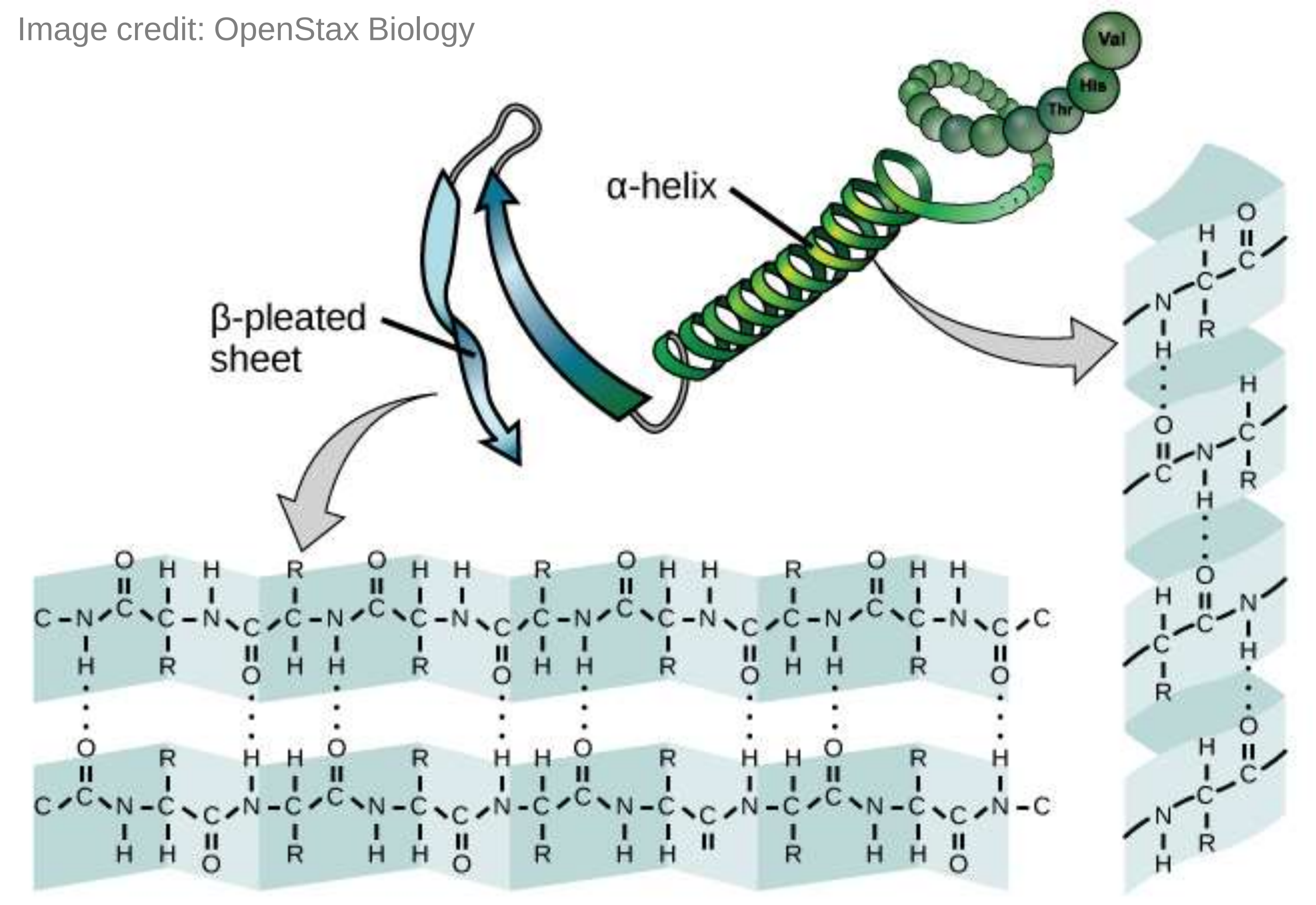
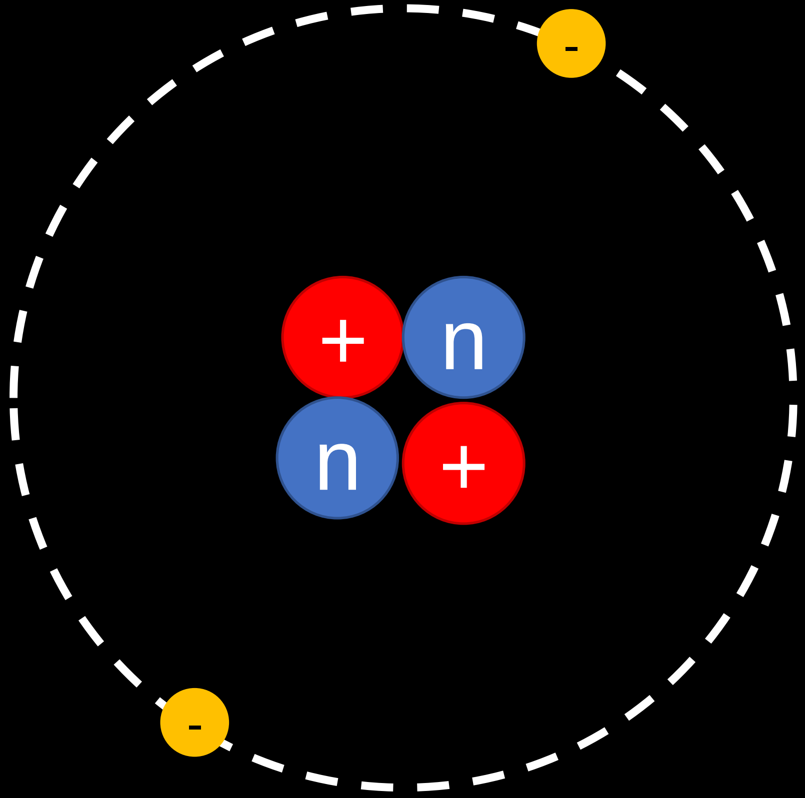


The proteins that compose all known life are based on carbon.

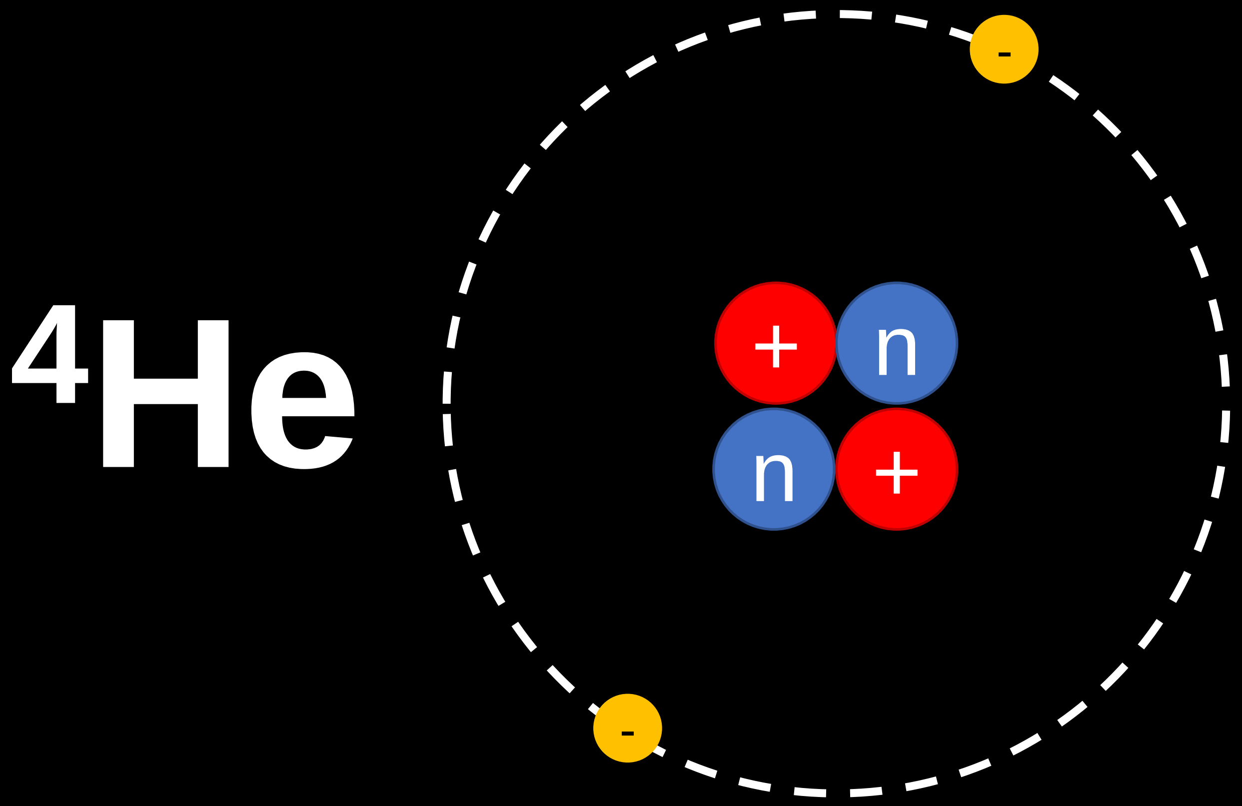
Critical astrobiological question:

Why carbon?

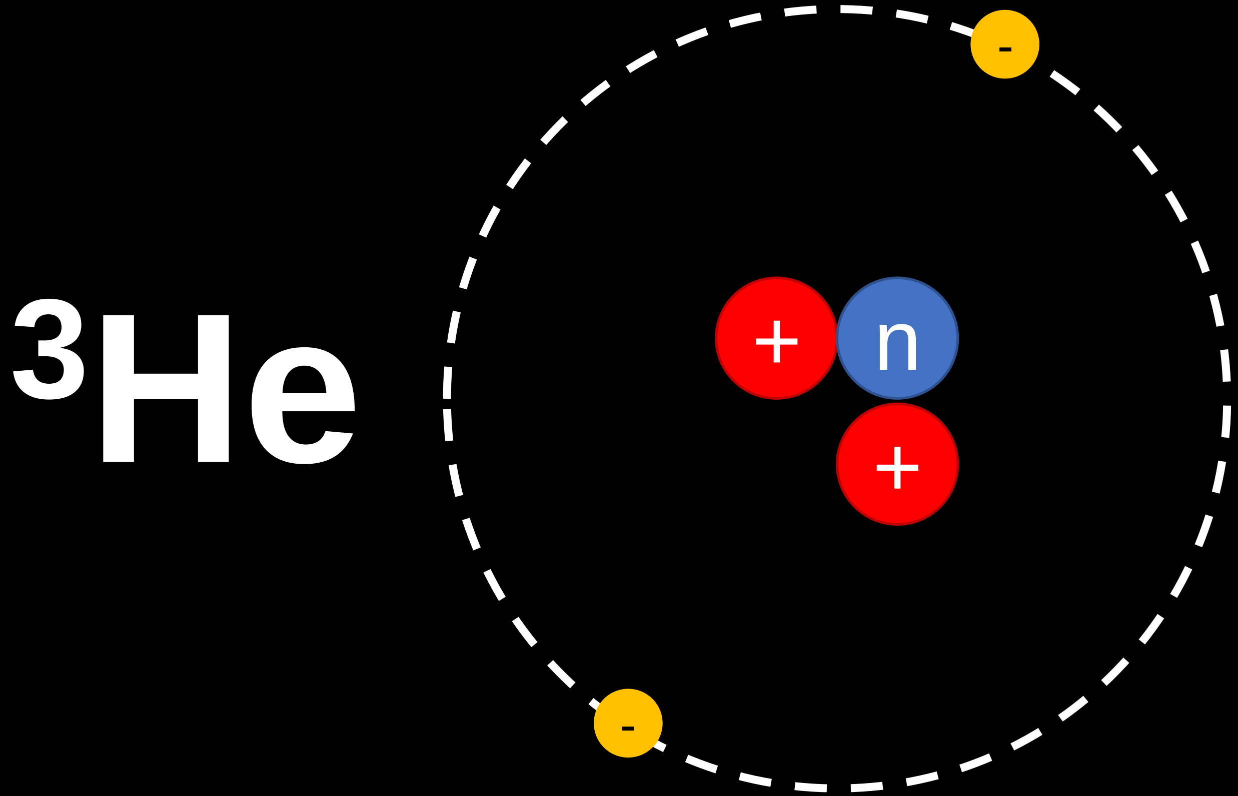
Atoms consist of protons (+), neutrons (n), and electrons (-). The protons and neutrons make up the **nucleus**, while the electrons orbit in **shells**.



Neutral helium-4 (2 protons, 2 neutrons, 2 electrons)

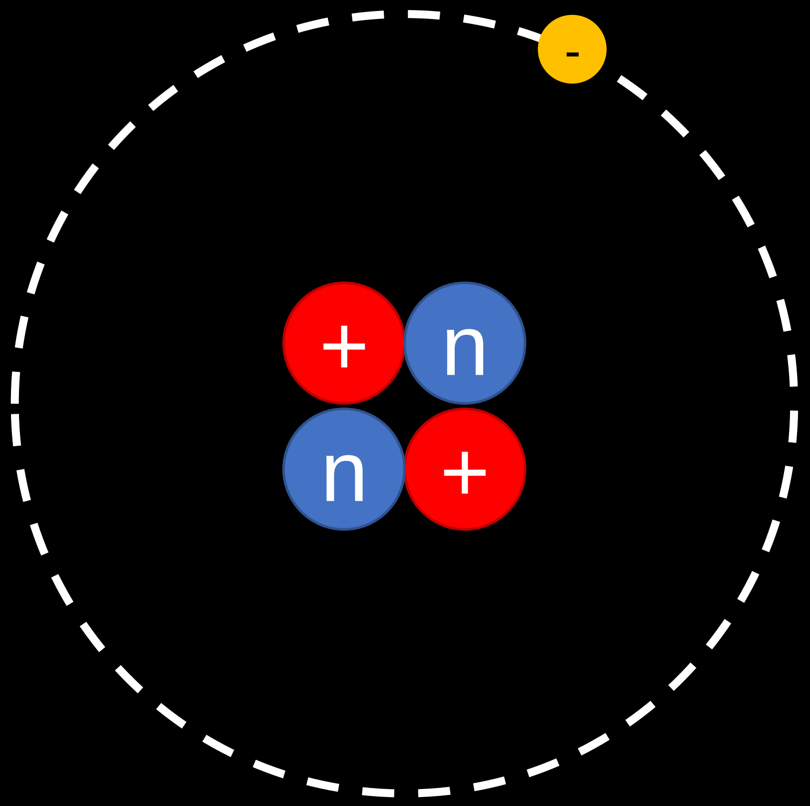


Neutral helium-4, an isotope of helium (2 protons,1 neutron, 2 electrons)



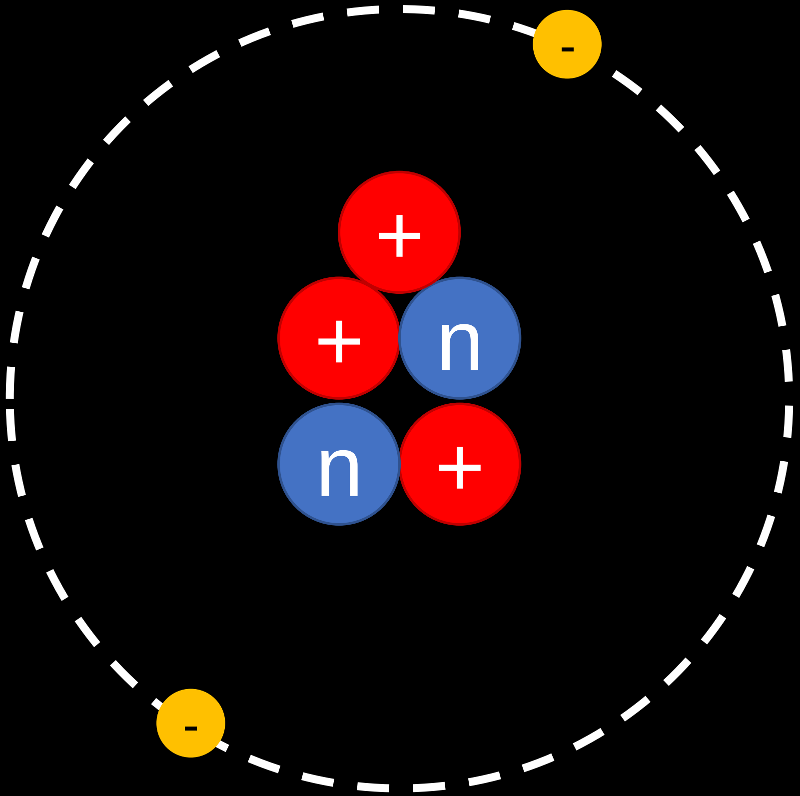
Ionized helium-4 (2 protons, 2 neutrons, 1 electron)

$^{4}He^{+}$



Ionized lithium-5 (3 protons, 2 neutrons, 2 electrons)

$^{5}Li^{+}$



Concept Check

The identity of a chemical element is determined by number of _____ it contains?

A. electrons
B. neutrons
C. protons
D. isotopes
E. ions

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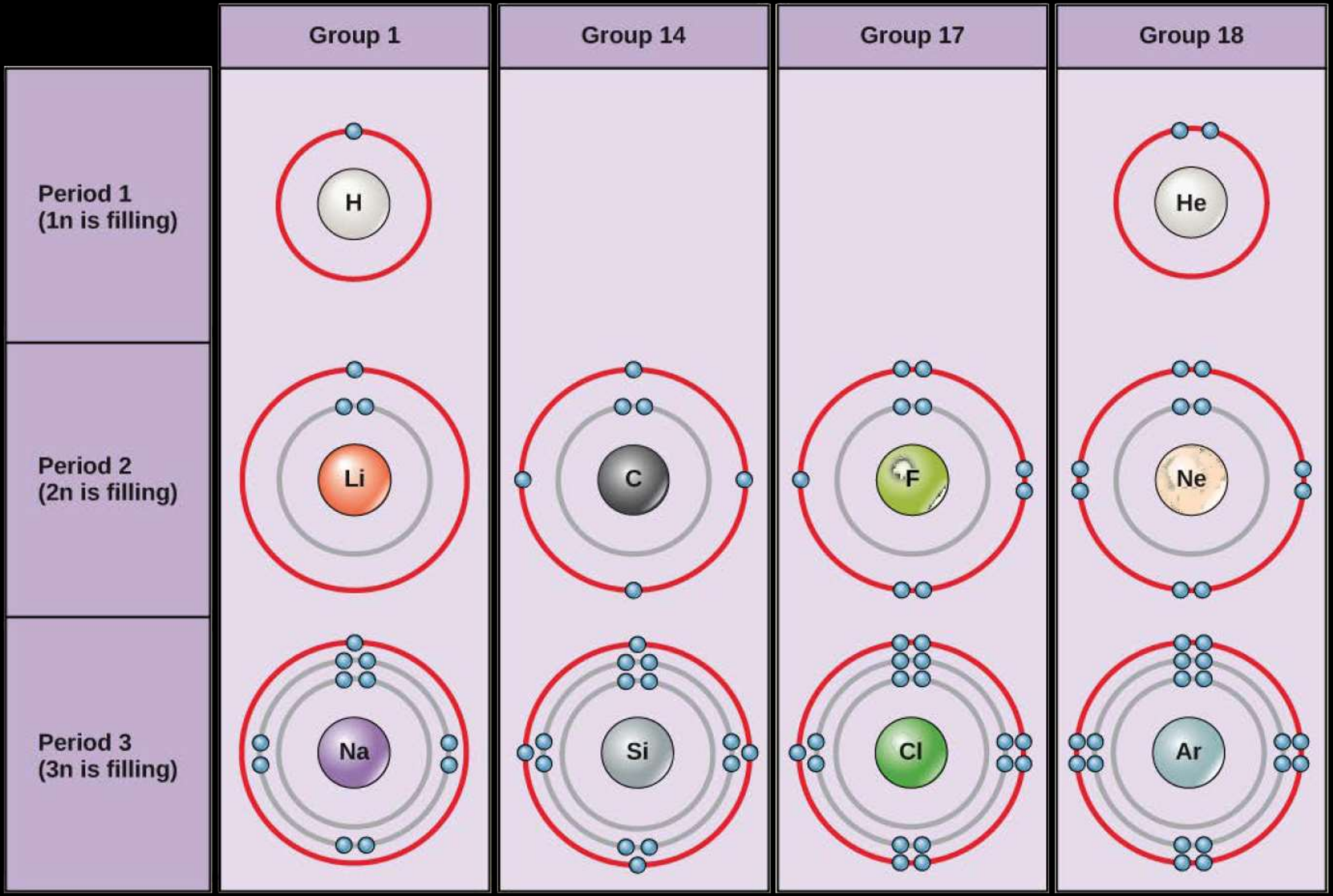


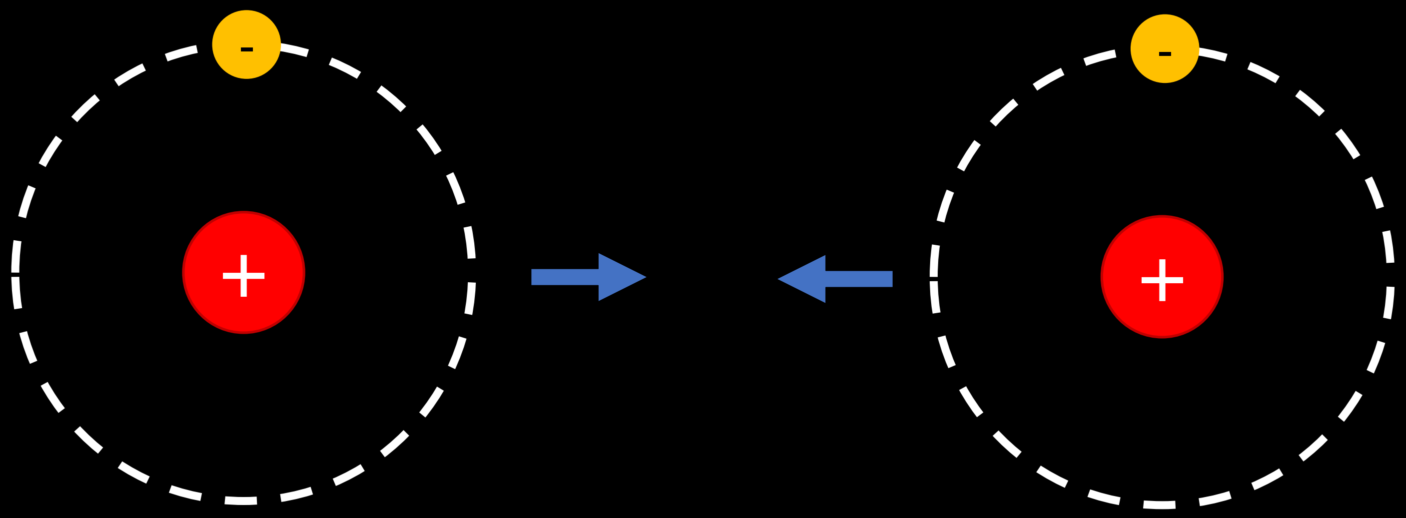
Credit: Rye et al., *Biology*

Atoms are most stable when their shells are full of electrons.

The first three shells have 2, 8, and, 8 spaces for electrons.*

*We are using simplified chemical rules here. Consult a first-year chemistry textbook for more details.

Atoms bond by exchanging electrons in various ways to try to fill their outermost shells (“valence” shells).



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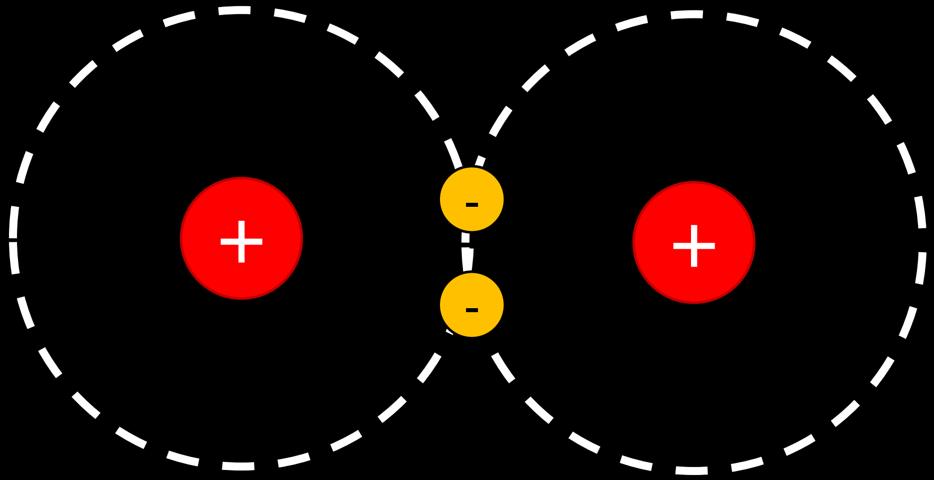
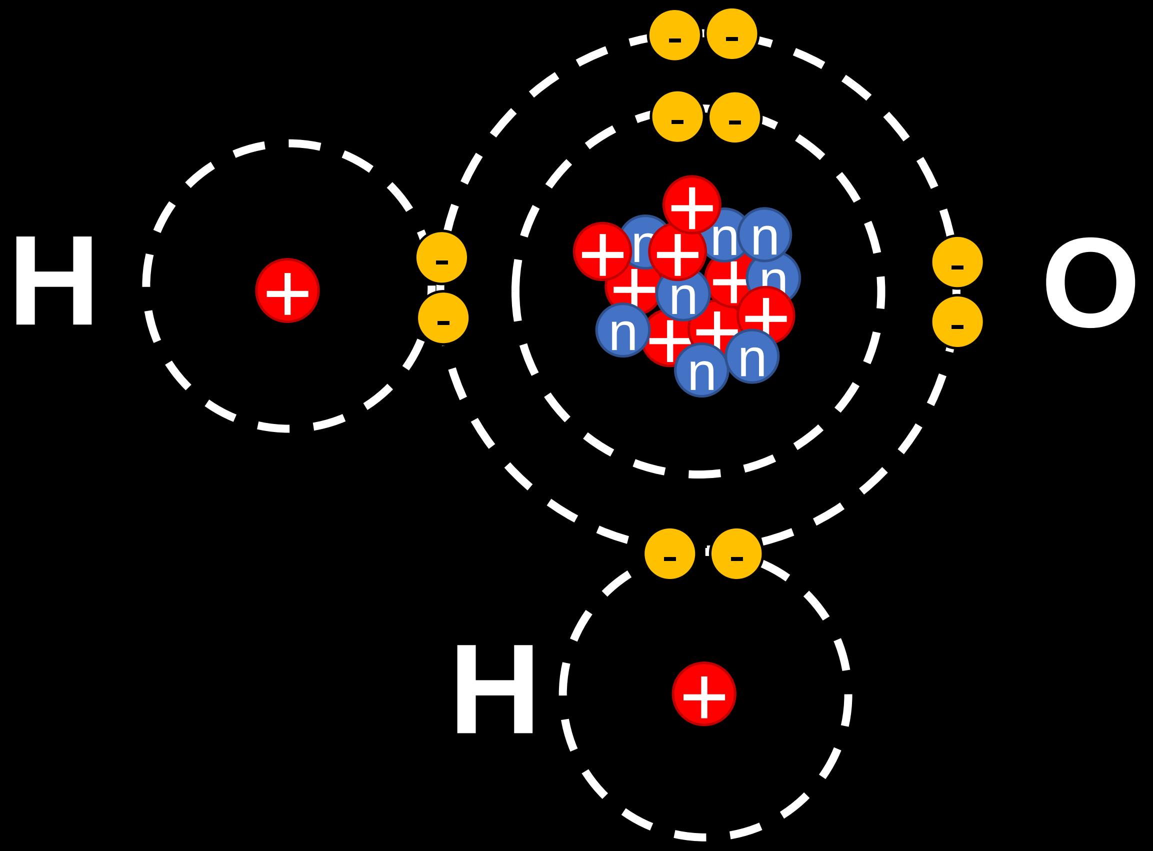
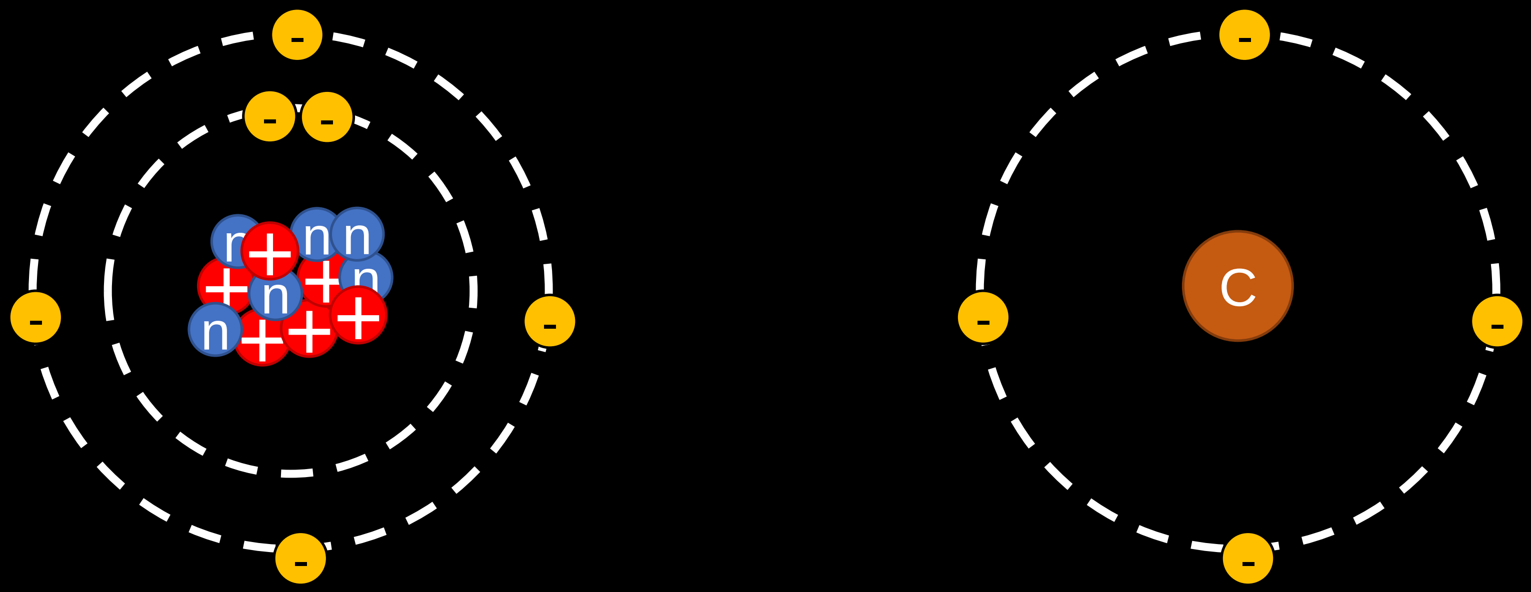


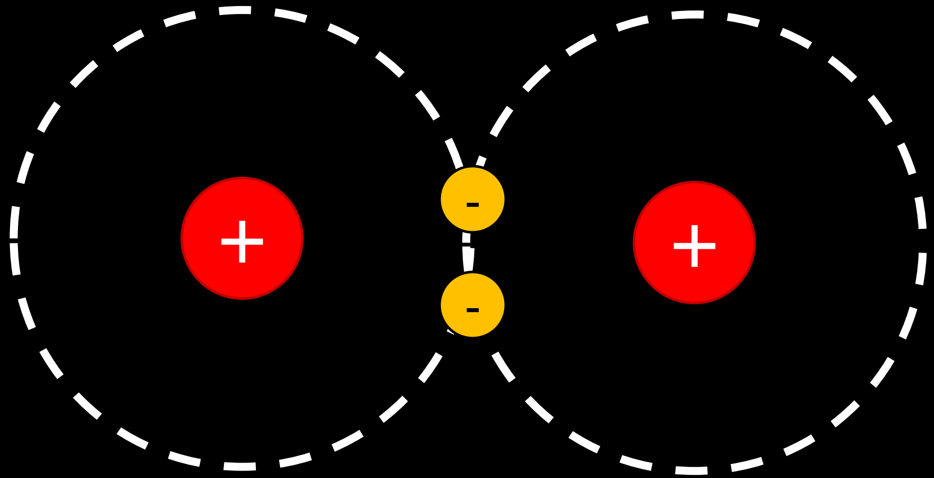
They can do this either by gaining or losing electrons. Here oxygen (6 valence electrons) is sharing 1 electron with each of two H atoms (1 electron each), so that every atom has a filled valence shell.



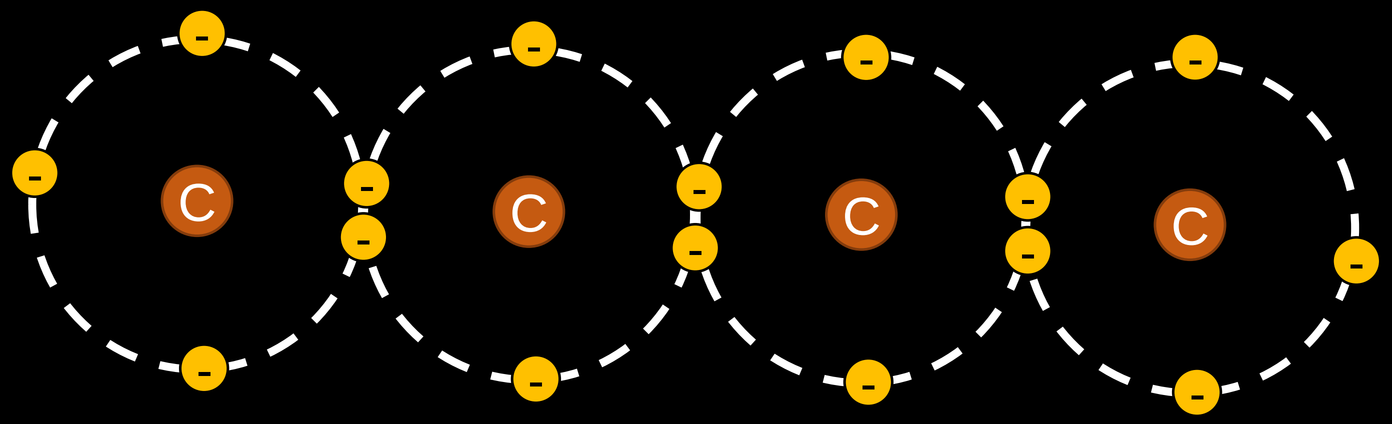
Carbon is special because it has 4 valence electrons (and it wants 8).



You can't make complicated biomolecules based on H because H can only bond with one atom at a time.



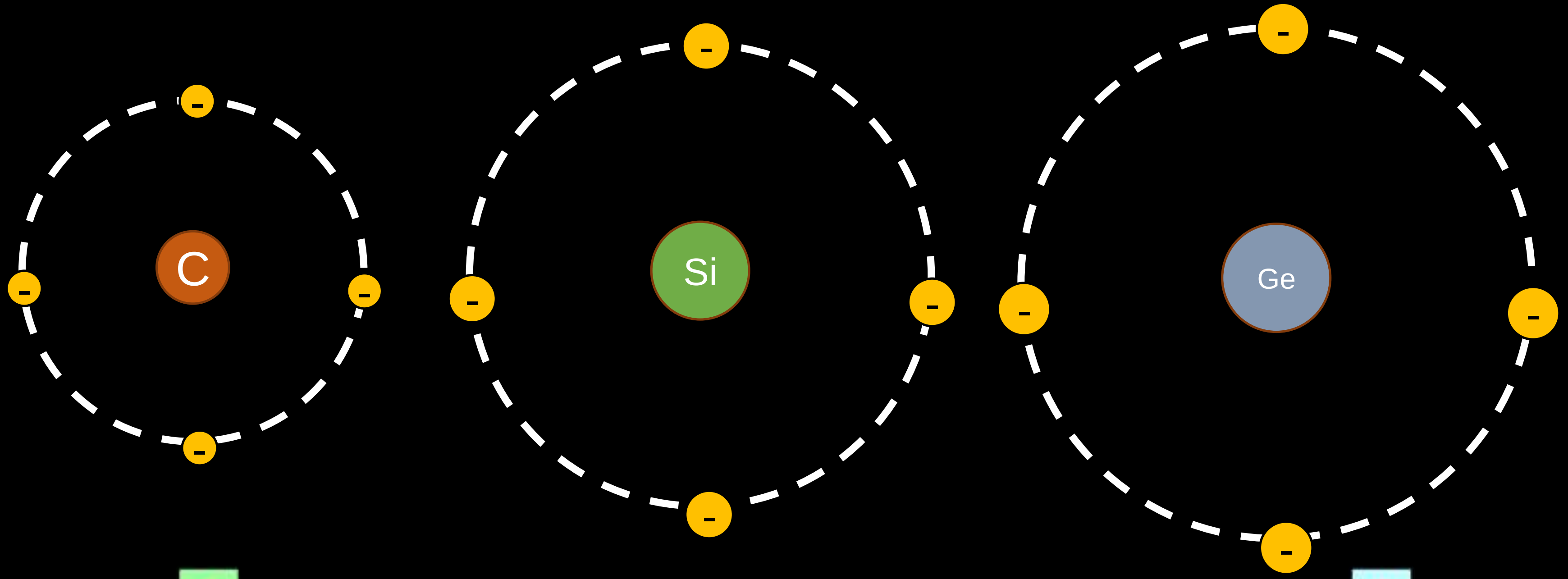
Carbon's 4-way bonding ability allows it to form complicated chains and structures.

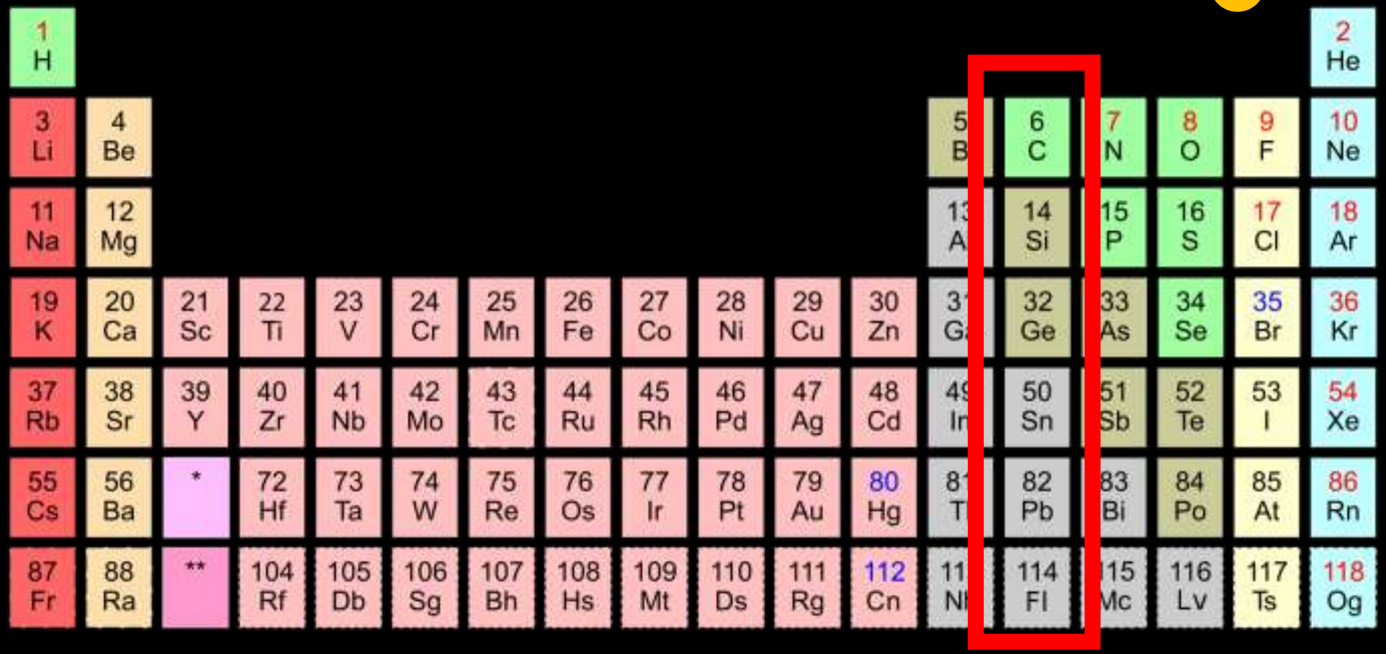


Four bonds is the practical limit for most common elements.

There are exceptions, and it’s possible for some elements to form 5 or more bonds (e.g. SF_6) but it’s not common among highly abundant elements.

Carbon is not the only element that can form long-chain molecules (polymers).





Credit: Wikimedia Commons

So why is Earth life carbon-based?

Carbon does have some properties that seem to make it work a bit better than silicon.

Atoms	Bond Strength (kJ/mol)
C - C	346
C = C	602
C - O	358
C - H	411
C - P	264
C - N	305

Carbon can form medium-strength bonds with itself and many other common atoms.

This means they can be assembled and disassembled easily.

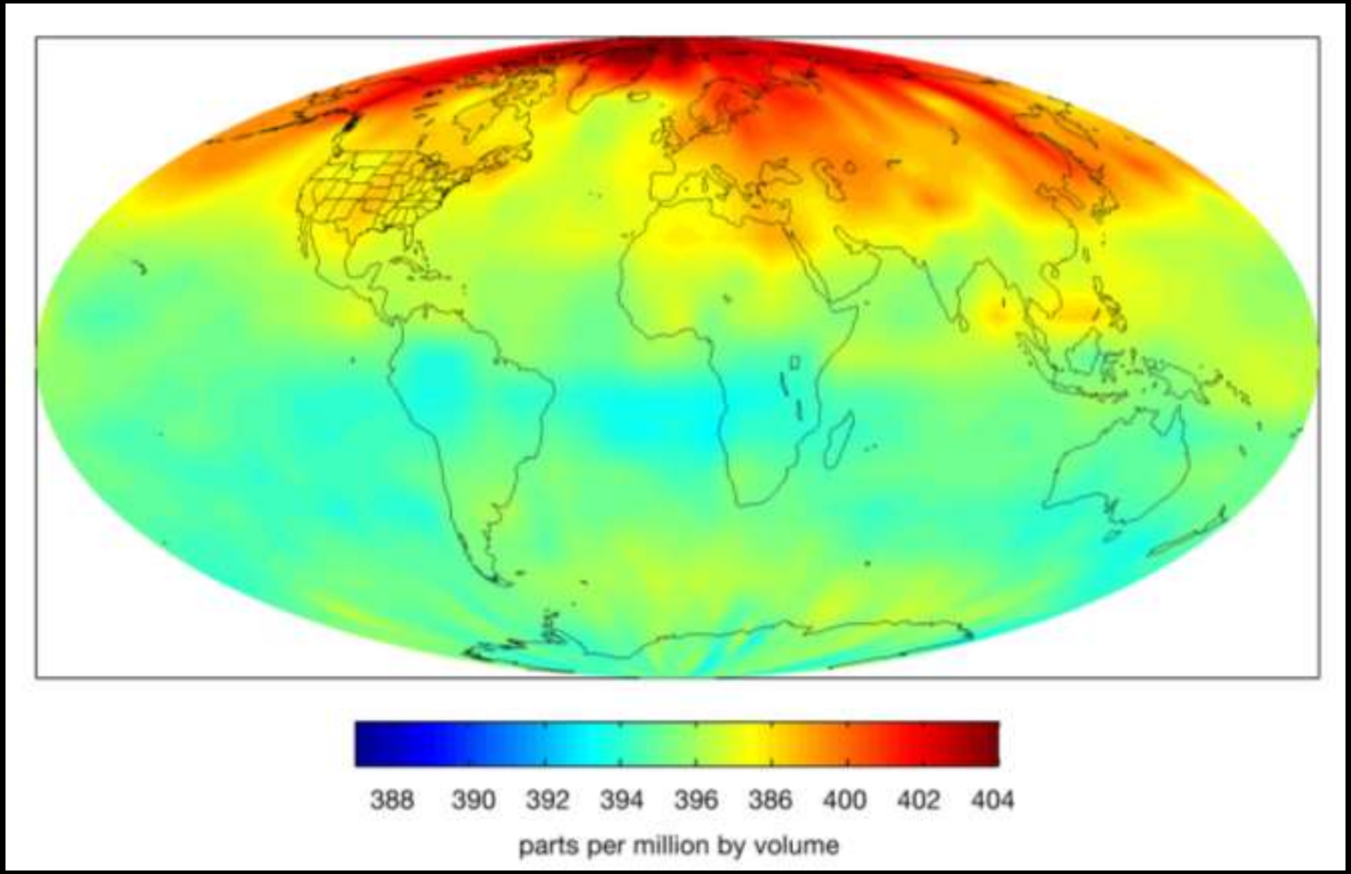
Atoms	Bond Strength (kJ/mol)
C - C	346
C = C	602
C - O	358
C - H	411
C - P	264
C - N	305

It can also form extra-strong double or triple bonds with itself when needed. This ability is used extensively in the chemistry of living organisms.

Atoms	Bond Strength (kJ/mol)
Si - Si	222
Si = Si	???
Si - O	452
Si - H	395
Si - P	215
Si - N	355

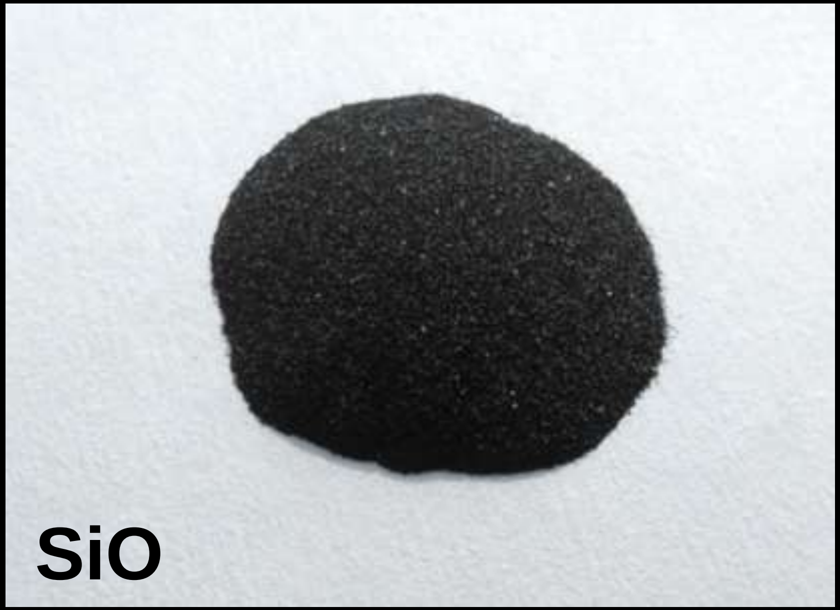
Silicon doesn’t bond as strongly with itself as carbon and it is difficult to get it to double-bond.

When C and O bond, you get CO or CO_2, which are gases at conditions prevailing on Earth’s surface. So, they remain highly available for reactions with living organisms.



Map of CO_2 in Earth’s atmosphere

Credit: NASA/JPL



When Si and O bond, they become SiO or SiO_2. Both are solids, which makes the Si much less bio-available.

Credit: Wikimedia Commons user Leiem & James St. John

Are other chemistries possible?

Is silicon-based life possible under some other environmental conditions?

The Chemistry of Life: Water

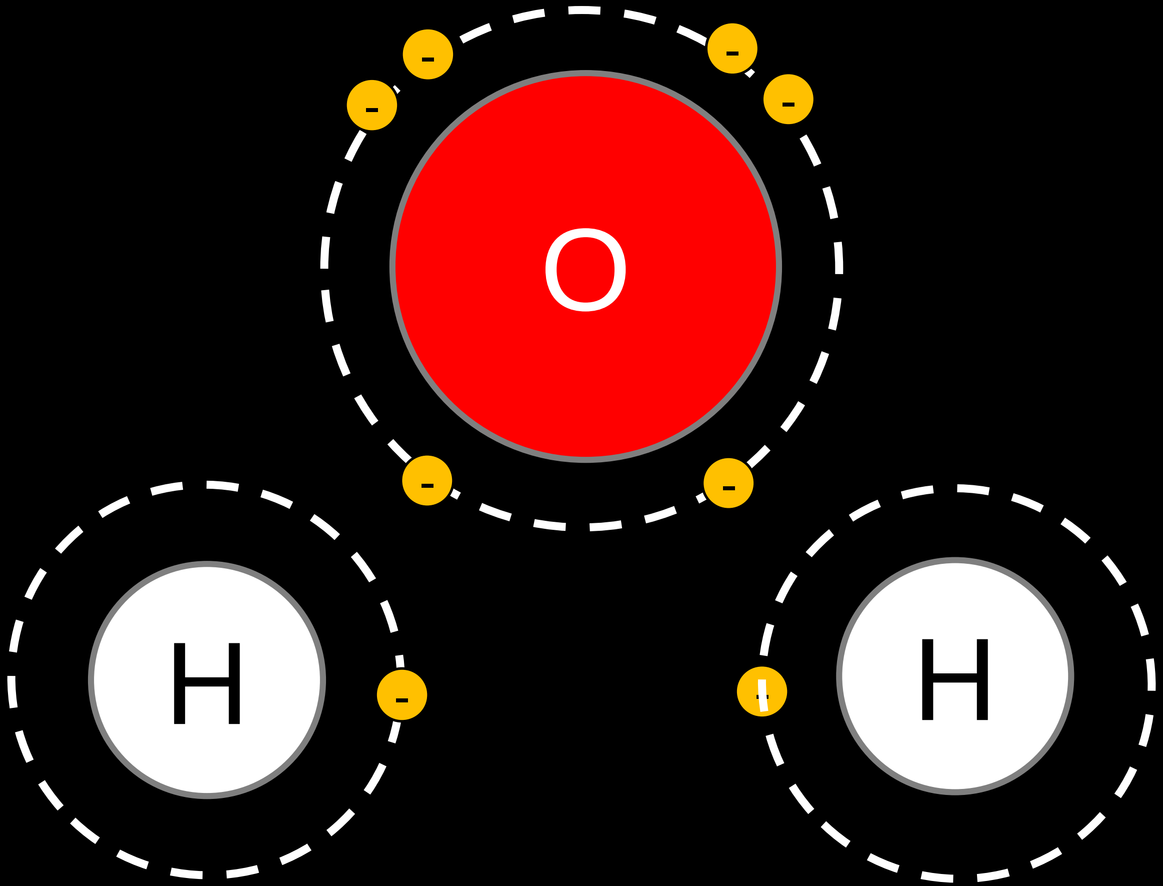
Second critical astrobiological question:

Why water?

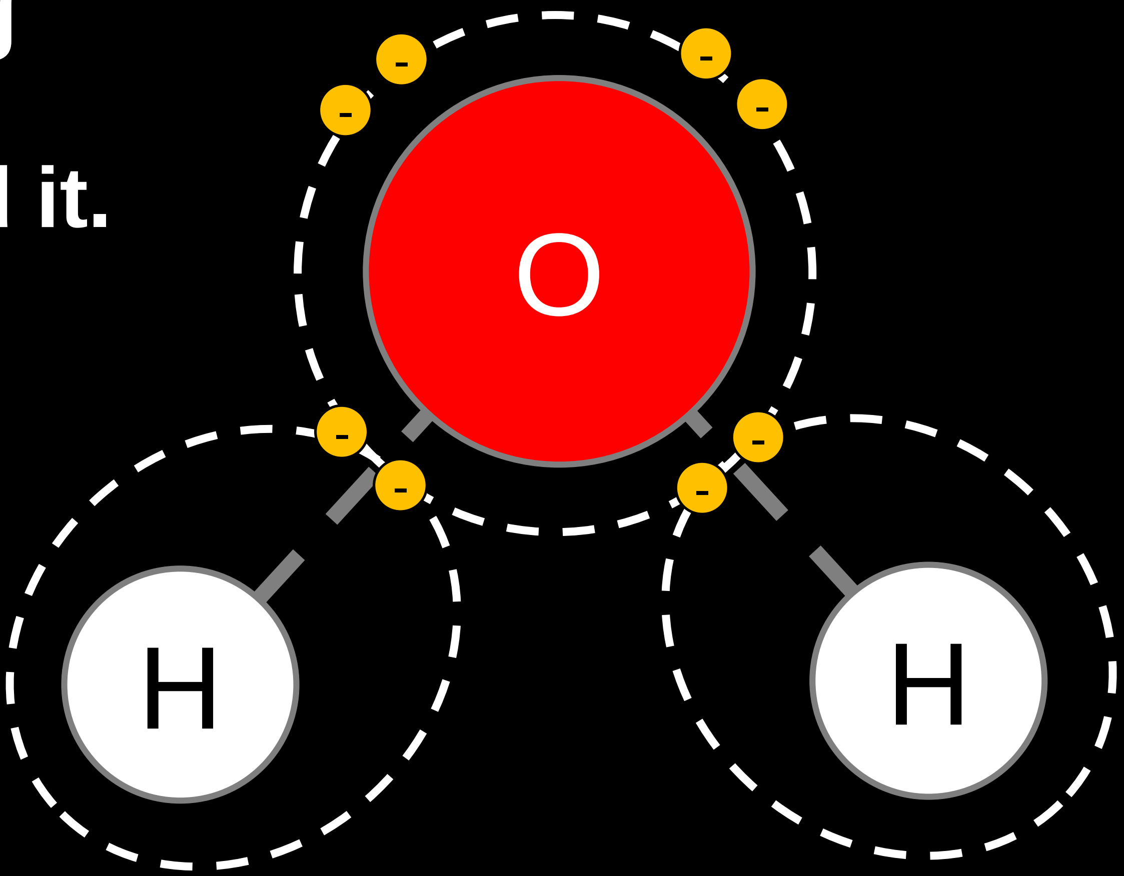
To develop chemistry sufficiently complex to form life-like-us, it must be possible for molecules to react freely.

They can’t be trapped in solids or stuck to surfaces.

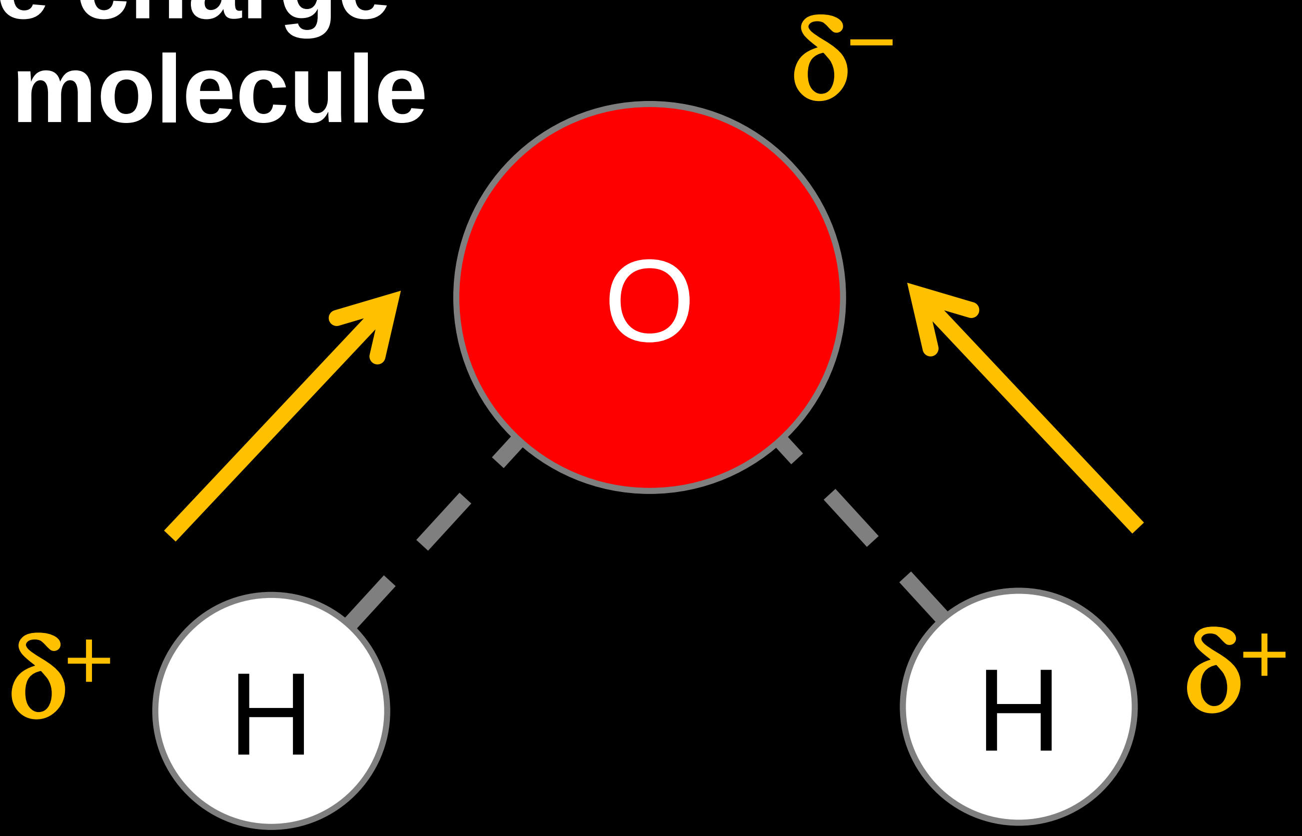
Water has unusual chemical properties that make it a very good solvent for organic molecules.

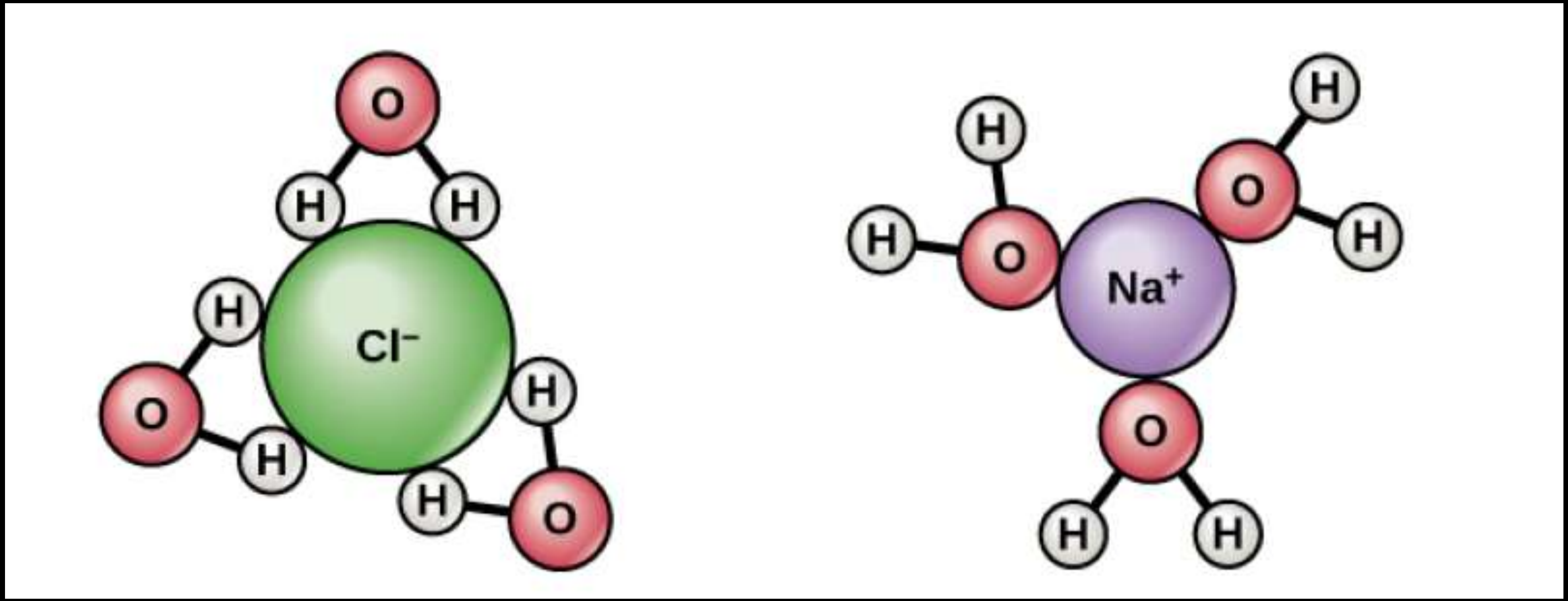

O
H
H

Oxygen is strongly electronegative, meaning that it really pulls the H valence electrons toward it.



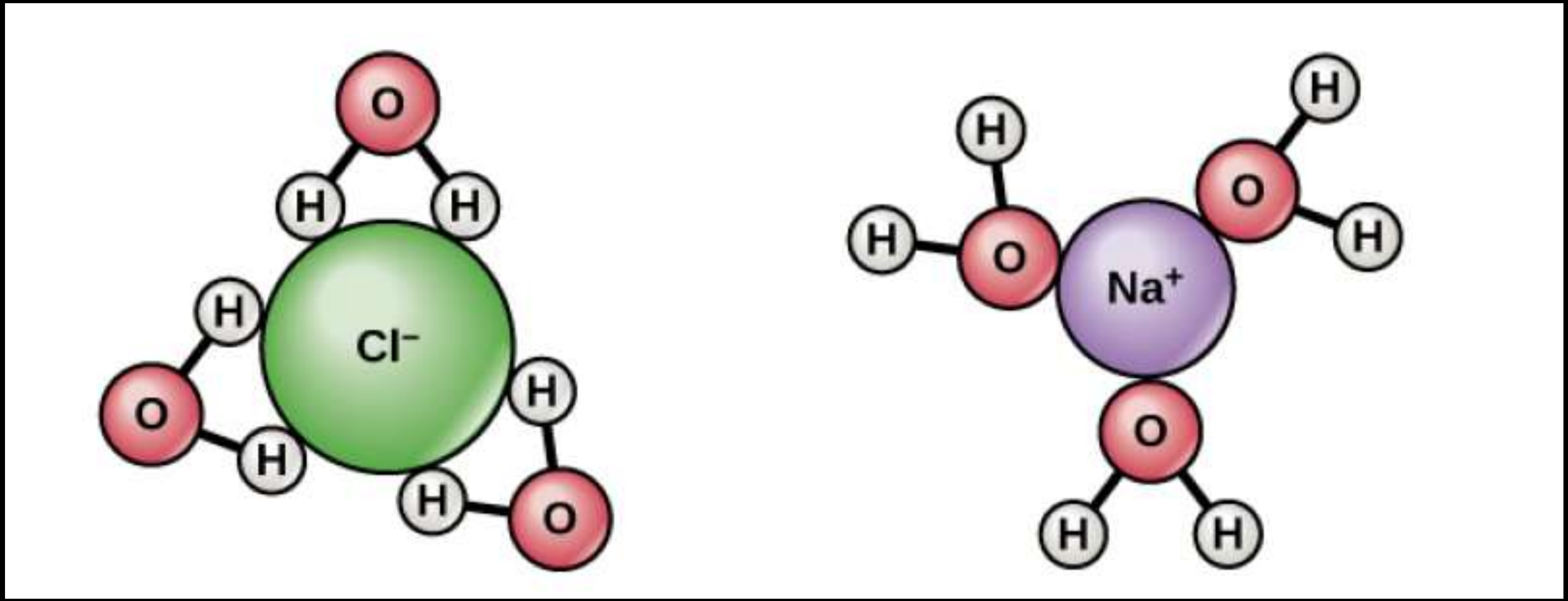
This means that the charge distribution in this molecule is uneven or polar.





The strong polarity of water molecules means that they can "overpower" inter-atomic bonds in other molecules and snap them.

Credit: OpenStax Biology

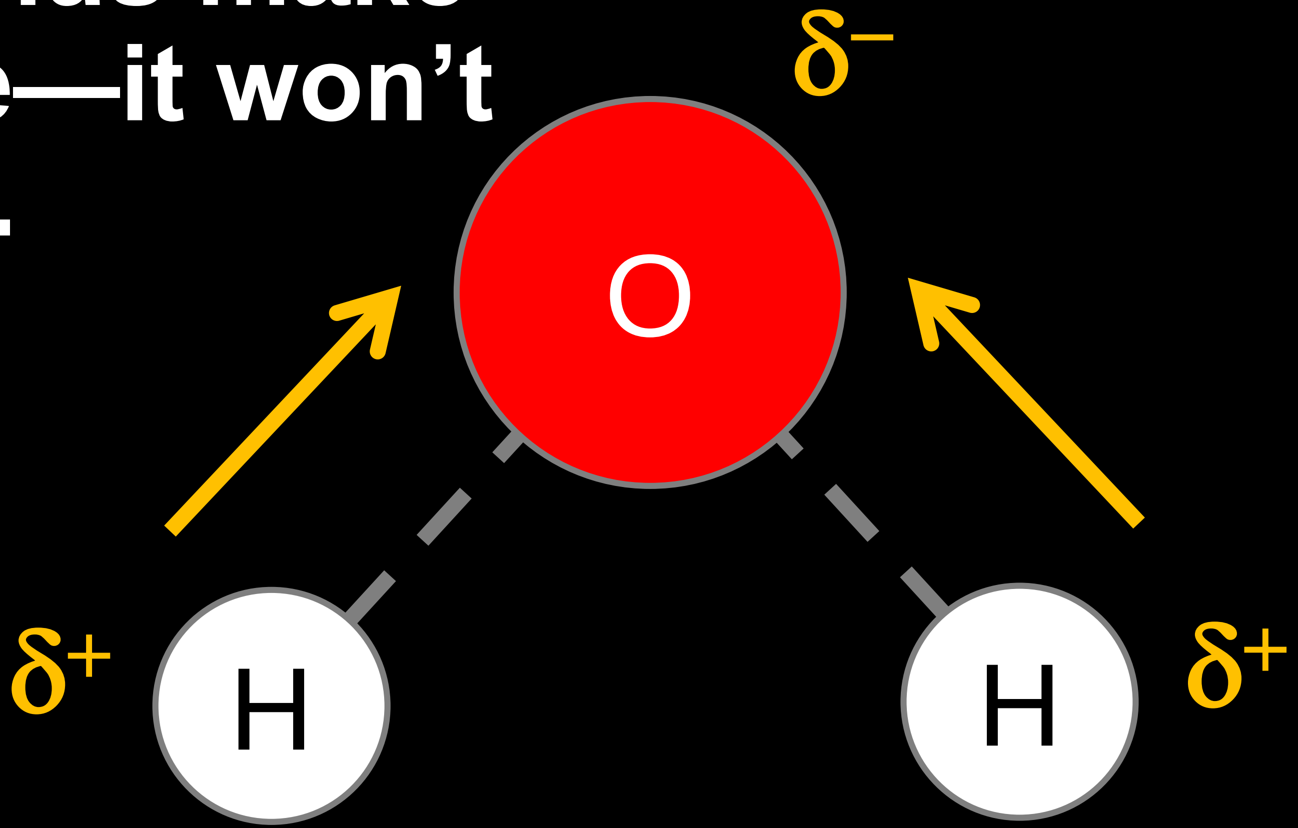


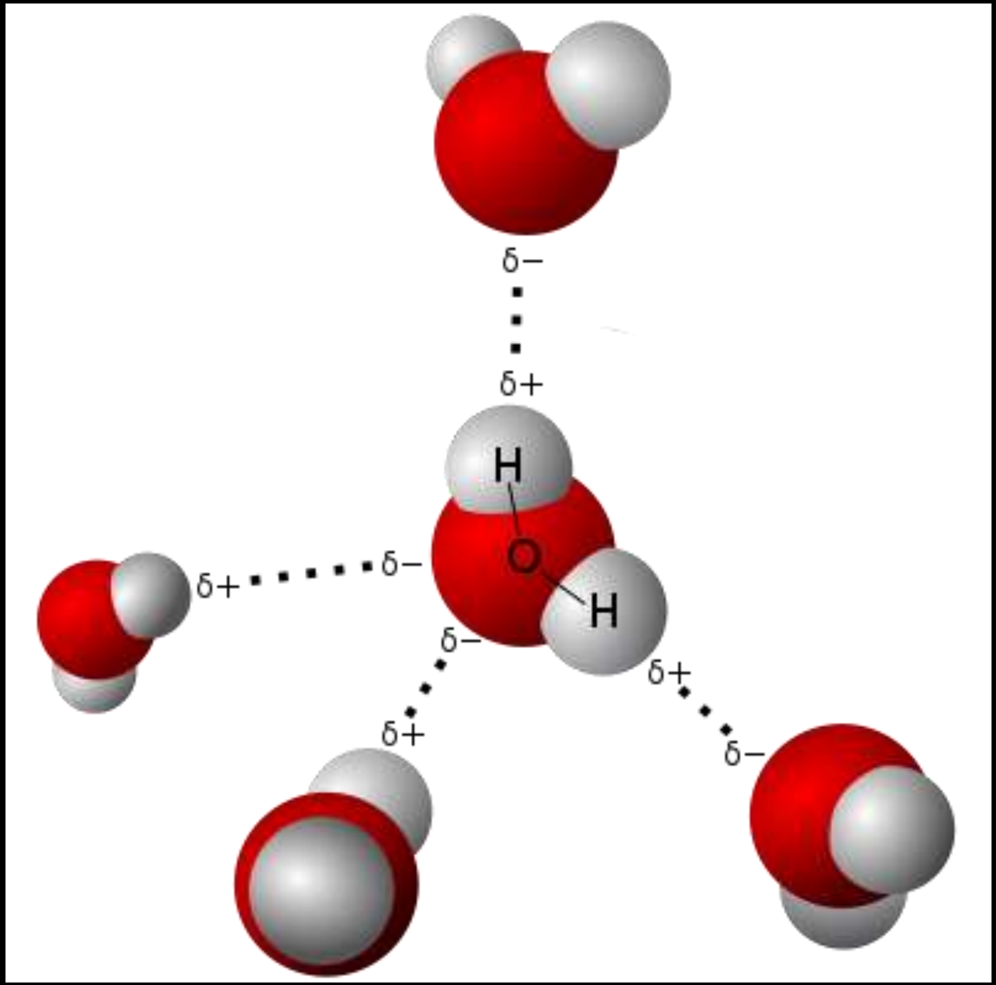
This is why water is such a good solvent for many chemicals, including salt, NaCl.

Credit: OpenStax Biology

Water also has physical properties that make it a very good environment for living organisms.

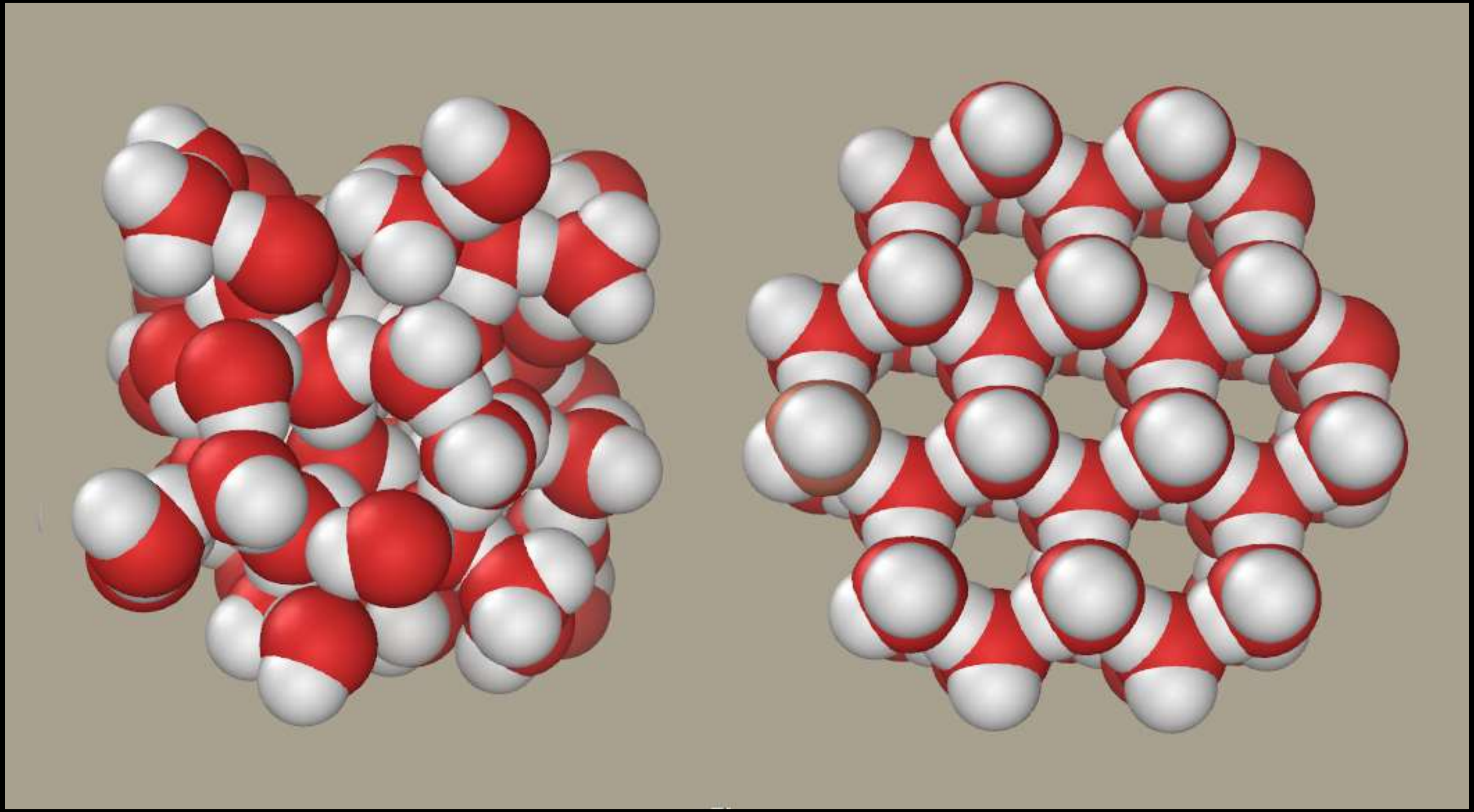
These strong bonds make water very stable—it won't dissociate easily.





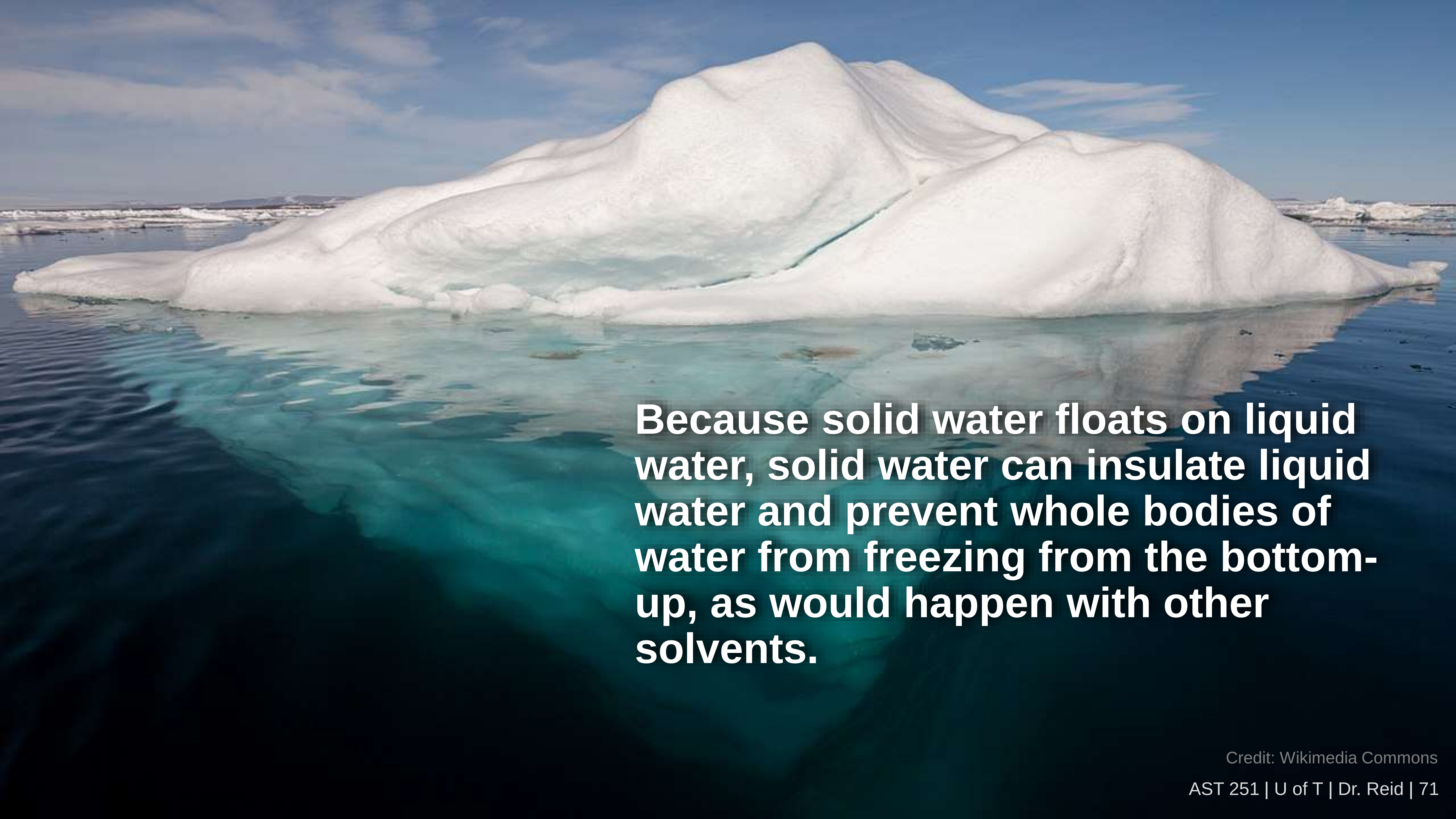
The polarity of the molecules allows them to form strong **hydrogen bonds** between molecules.

Credit: Wikimedia Commons



When water freezes, the molecules form a lattice with large open spaces.

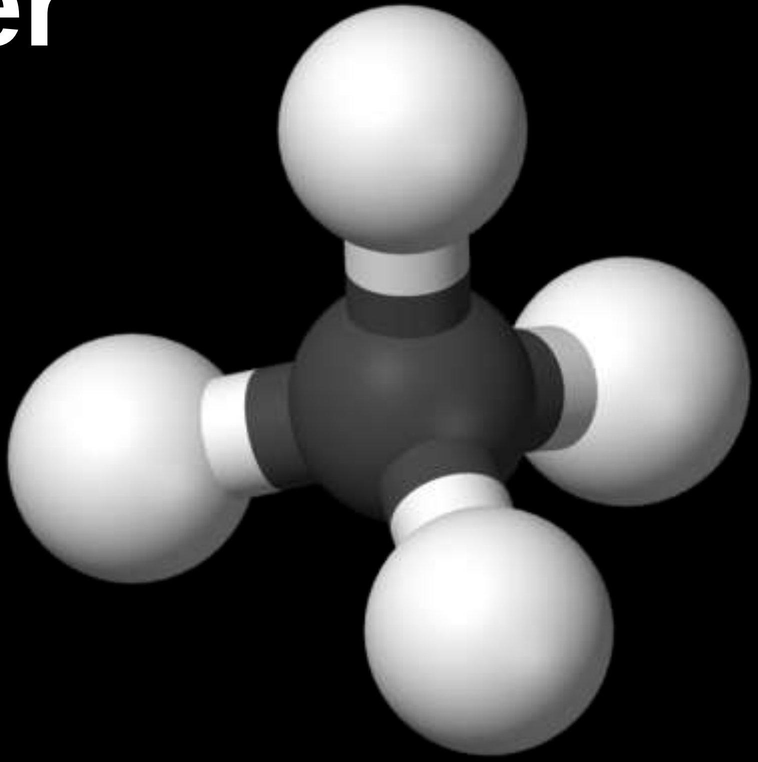
Credit: Wikimedia Commons



Because solid water floats on liquid water, solid water can insulate liquid water and prevent whole bodies of water from freezing from the bottom-up, as would happen with other solvents.

Credit: Wikimedia Commons

Contrast water with methane, CH_4, another abundant solvent.



Credit: Wikimedia Commons

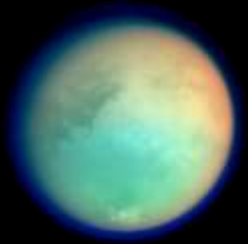
H_2O	CH_4
Polar	Non-polar
Melts at 0ºC Boils at 100ºC	Melts at -183ºC Boils at -162ºC
Forms strong H bonds that tend to tear apart organic molecules.	Doesn’t form strong H bonds, so gentler on organic molecules.

Worlds of our solar system, categorized by the composition of their oceans (past or present):

Water

+?

Methane



Credit: NASA

A fundamental question for astrobiology:

If life can have other chemistries than carbon+water, why did they not occur on Earth?

Or did they?

Would we recognize life based on a totally different chemistry than our own?

Some have proposed that there might be a "shadow biosphere" representing a second genesis on Earth.

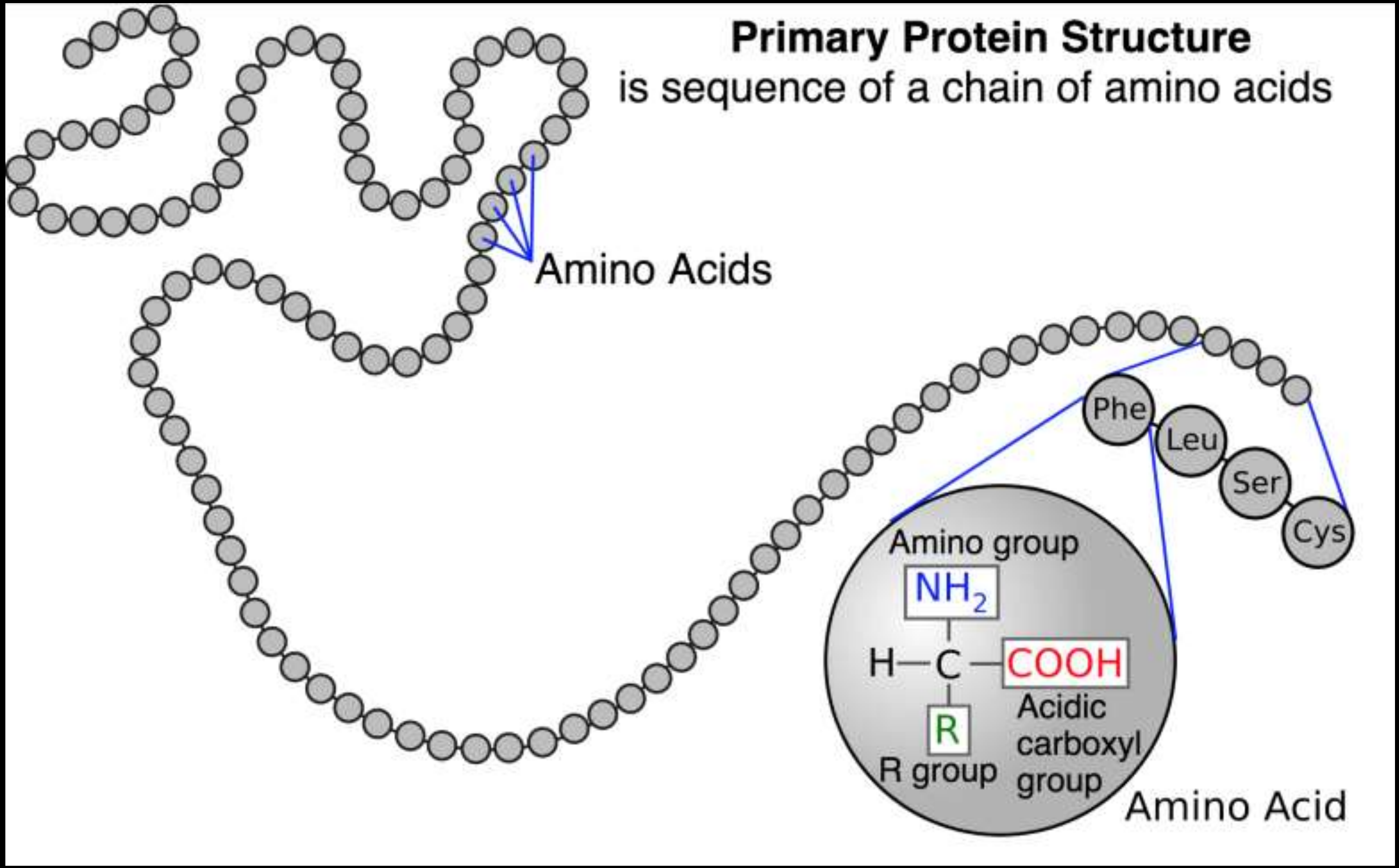
Desert varnish is sometimes suggested as a candidate, though this is not widely accepted. (e.g. Cleland, 2007)

Image Credit: Encyclopedia of Geobiology

Extremophiles and the Limits of the Biospace

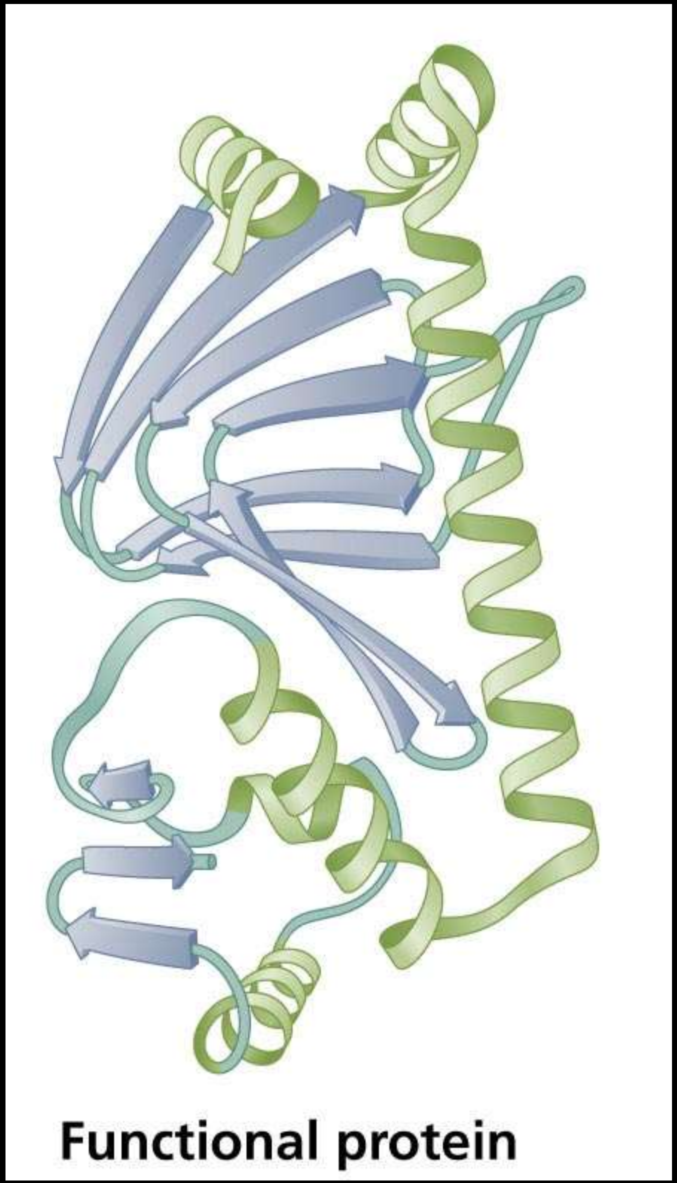
The particular chemical basis of Earth life imposes limits on the conditions it can endure.

Let’s consider temperature.



Life-like-us is made of proteins, which are long chains of amino acids.

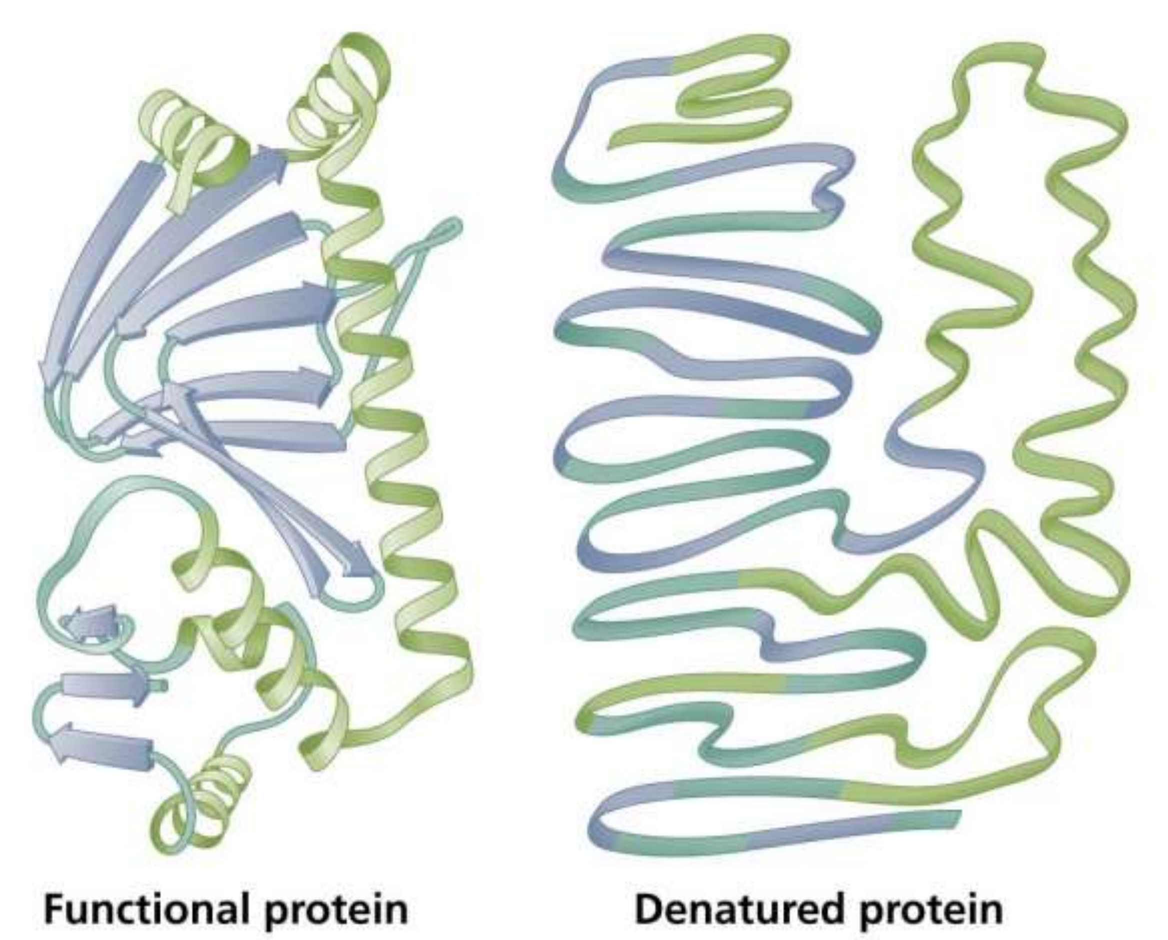
Credit: National Human Genome Research Institute



The precise way that a protein is folded in an organism determines its function.

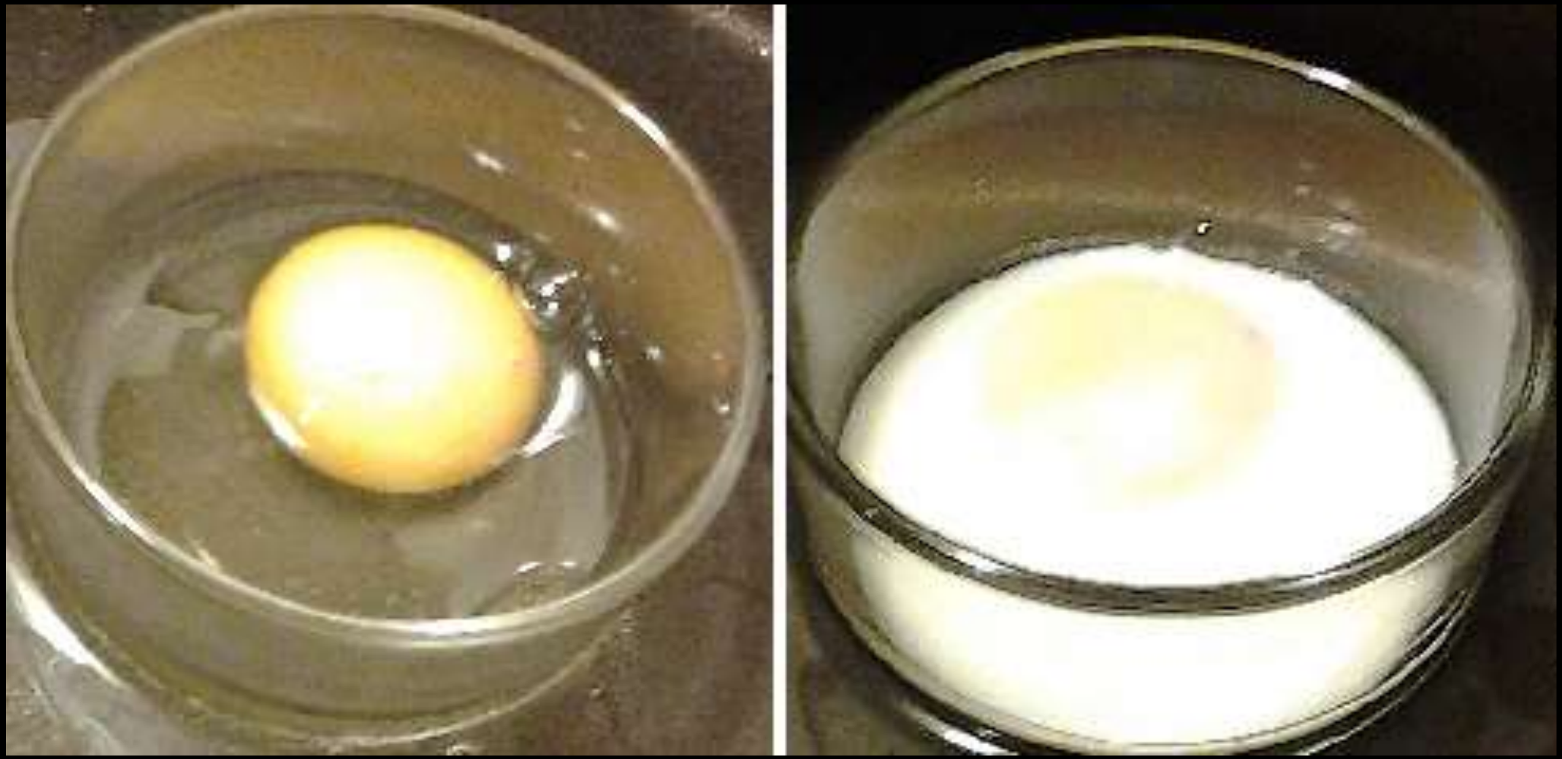
Misfolded proteins can lead to disease or death.

Credit: Pearson Education



Heating a protein breaks some of the bonds that hold it in its precisely folded shape, destroying its biological function. This is called denaturing the protein.

Credit: Pearson Education



Cooking an egg is a familiar example of denaturing a protein with heat.

Credit: RMADLA

The Old Wisdom:

$$0^{o}C < T < 100^{o}C$$

Organism freezes; proteins are immobilized and structures rupture.

Proteins denature; function destroyed.

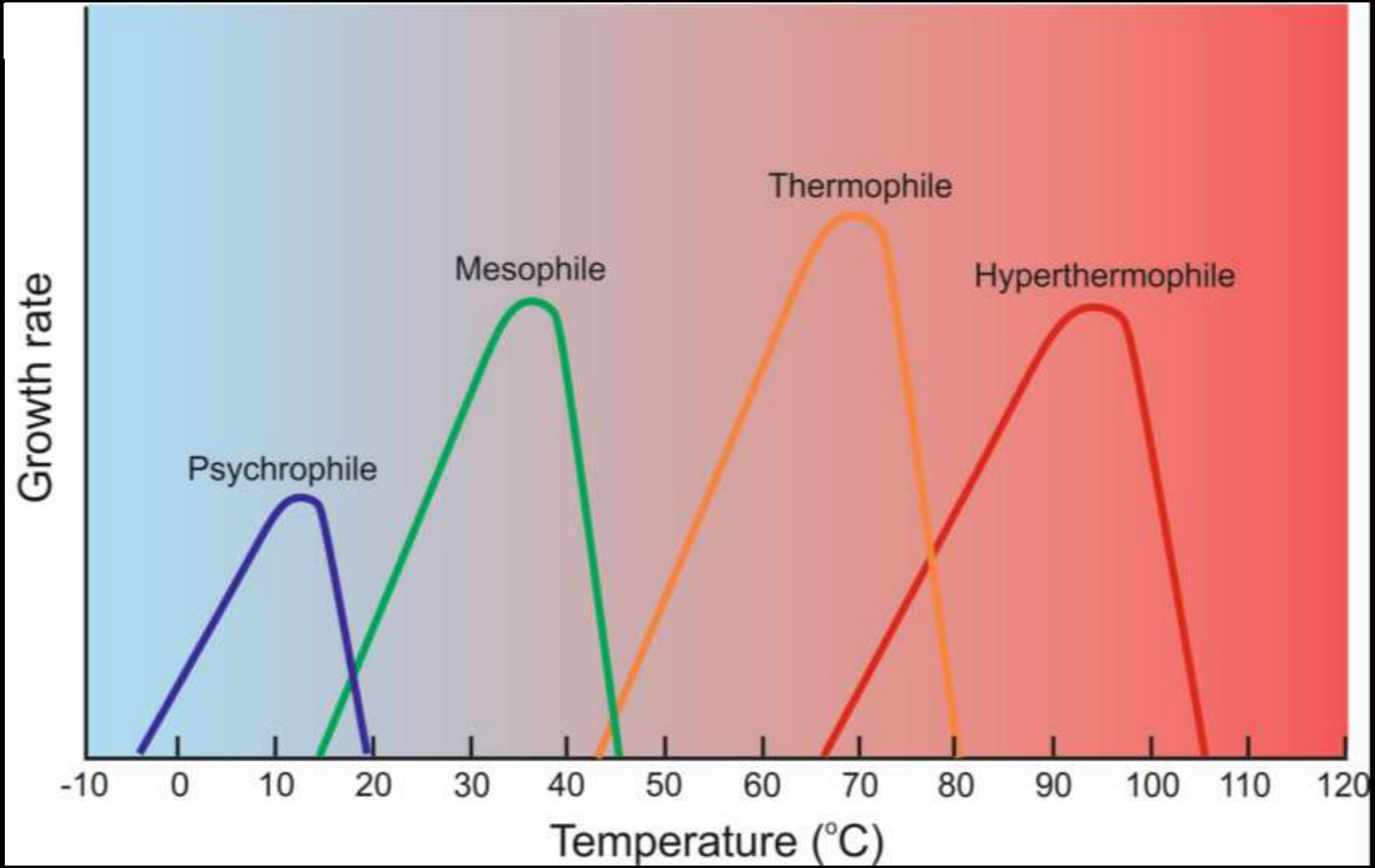
As our understanding of the complexity of Earth's biosphere grew, we realized that life has adapted to live and even *thrive* well beyond the narrow limits we once believed.

Black Smokers & Hot Vent Creatures at Endeavour Ridge (2190m)

8 October 2010:
Specially adapted tubeworms, scale worms and limpets thrive in the hot sulfide-laced waters of Grotto Hydrothermal Vent.

Credit: Ocean Networks Canada

Many organisms have evolved to *prefer* the > 100ºC temperatures around deep-ocean hydrothermal vents. We call these organisms thermophiles or hyperthermophiles.



Organisms grouped by temperature preference.

Credit: Charles Cockell

Many thermophiles have adapted to use stronger bonds to preserve their folded state.

Others can re-fold denatured proteins.

More broadly, organisms that have evolved to thrive in “extreme” environments are called extremophiles.

Many of the hyperthermophiles are archaea, among the earliest forms of life on Earth, suggesting that life may have *begun* in hot thermal vents.

Maybe *we* are the true extremophiles!

Table 1 Classification and examples of extremophiles

Environmental parameter	Type	Definition	Examples
Temperature	Hyperthermophile	Growth >80 °C	*Pyrolobus fumarii*, 113 °C
	Thermophile	Growth 60–80 °C	*Synechococcus lividis*
	Mesophile	15–60 °C	*Homo sapiens*
	Psychrophile	<15 °C	*Psychrobacter*, some insects
Radiation			*Deinococcus radiodurans*
Pressure	Barophile	Weight-loving	Unknown
	Piezophile	Pressure-loving	For microbe, 130 MPa
Gravity	Hypergravity	>1*g*	None known
	Hypogravity	<1*g*	None known
Vacuum		Tolerates vacuum (space devoid of matter)	Tardigrades, insects, microbes, seeds
Desiccation	Xerophiles	Anhydrobiotic	*Artemia salina*; nematodes, microbes, fungi, lichens
Salinity	Halophile	Salt-loving (2–5 M NaCl)	Halobacteriaceae, *Dunaliella salina*

Credit: Rothschild and Mancinelli, Nature, 2001

pH	Alkaliphile	pH > 9	*Natronobacterium*, *Bacillus firmus* OF4, *Spirulina* spp. (all pH 10.5)
	Acidophile	low pH-loving	*Cyanidium caldarium*, *Ferroplasma* sp. (both pH 0)
Oxygen tension	Anaerobe	Cannot tolerate O_2	*Methanococcus jannaschii*
	Microaerophile	Tolerates some O_2	*Clostridium*
	Aerobe	Requires O_2	*H. sapiens*
Chemical extremes	Gases		*C. caldarium* (pure CO_2)
	Metals	Can tolerate high concentrations of metal (metalotolerant)	*Ferroplasma acidarmanus* (Cu, As, Cd, Zn); *Ralstonia* sp. CH34 (Zn, Co, Cd, Hg, Pb)

Credit: Rothschild and Mancinelli, Nature, 2001

Even some non-extremophiles have the ability to *survive* in conditions well beyond the human range.