**Life and Its Requirements**

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**Neil deGrasse Tyson, American Museum of Natural History**

"On this single planet called Earth, there co-exist (among countless other life forms), algae, beetles, sponges, jellyfish, snakes, condors, and giant sequoias. Imagine these seven living organisms lined up next to each other in one place. If you didn’t know better, you would be hard-pressed to believe that they all came from the same universe, much less the same planet."

The Search for Life begins with a deep question: What is life? Astro-biologists will tell you there is no easy answer …

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**The Importance of Defining Life**

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**Is a Definition of Life Possible?**

- Life is a self-sustained chemical system capable of undergoing Darwinian evolution (Joyce, 1994)
- Life is a self-replicating evolving system based on organic chemistry (Pace, 2002)
- System capable of evolution by natural selection (Sagan, 1970)
- Material system that undergoes Darwinian evolution (C. McKay)
- **Web definitions**
  - Period during which something is functional
  - Organic phenomenon that distinguishes living from non-living
  - Characteristic of organisms that exhibit biological processes

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**Is Life’s Definition Universal?**

- Any definition of life will necessarily be based on known properties of Earth and it’s life since that is the only life we know
- Is it possible to search for life on other planets without a definition of life?
  - Chemical equilibrium
  - Energy processes

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**What is Life? (The Astronomer’s Definition)**

- **Organized Chemistry**
  - Requires energy
  - Reproduces
  - Evolves

- **Liquid Environment**
  - Physical stability
  - Mobility
  - Close proximity
  - Contained structure
Characteristics of Earth Life
- Water is essential for active life
- Life exhibits order
- Life occurs in a micro-environment (cell)
- Life is Carbon-based
  - 4 primary elements: C, H, O, N 96% of all life
  - Others: Ca (1.5%), P (1.0%), K (0.4%), S (0.3%)
- Life uses energy, gives off waste
- Life replicates (reproduces)
- Life evolves (mutation & other mechanisms for acquiring genetic material and natural selection)

The Basis of Life?
“... Life must necessarily be based on C and H$_2$O, and have its higher forms metabolizing free oxygen”

[L. J. Henderson, 1912]

“I personally find this conclusion suspect, if only because L. Henderson was made of carbon and water and metabolized free oxygen. Henderson had a vested interest...”

[C. Sagan, 1973]

An Alternative Chemistry?
- Need to be able to make stable, complex molecules
  - Stability requires multiple covalent bonds
  - Bond in which one or more electrons are shared
- Require elements that are common
  - Li, Be and B are rare in nucleosynthesis

An Alternative Chemistry – Why Water?
- Water Characteristics
  - Water is the most likely volatile molecule from nucleosynthesis
  - Water remains liquid over a wide range of T
  - Other compounds with this property are liquid only at low T
- Low Temperature consequences
  - Chemical reactions slow down process slow down
  - Organic compounds (food) dissolve poorly at low T (except for Si compounds)

Chemical Composition of Humans

<table>
<thead>
<tr>
<th>Element</th>
<th>Earth’s Crust</th>
<th>Human Body</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium</td>
<td>3.4%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Silicon</td>
<td>25.7%</td>
<td>18%</td>
</tr>
<tr>
<td>Oxygen</td>
<td>49.5%</td>
<td>65%</td>
</tr>
<tr>
<td>Other</td>
<td>7.5%</td>
<td>Other</td>
</tr>
</tbody>
</table>

Other = Traces of boron, chromium, cobalt, copper, fluoride, iodine, iron, manganese, molybdenum, selenium, silicon, tin, vanadium, zinc and...<ref>

Why Carbon? Why H$_2$O?
- Carbon can link to 4 atoms at a time
  - Forms long complex structures
- Liquid water
  - Dense accumulation of matter
  - Carries waste/food
  - Heat regulation
  - This requires an atmosphere

Cosmic Abundances

<table>
<thead>
<tr>
<th>Element</th>
<th>Cosmic Abundance</th>
<th>Common Volatiles</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>1.000</td>
<td>H$_2$O</td>
</tr>
<tr>
<td>He</td>
<td>0.787</td>
<td></td>
</tr>
<tr>
<td>O</td>
<td>0.132</td>
<td>H$_2$O</td>
</tr>
<tr>
<td>N</td>
<td>0.104</td>
<td>HCN, HC$_2$N, NH$_3$, NO$_2$</td>
</tr>
<tr>
<td>C</td>
<td>0.087</td>
<td>CH$_4$, CO, CO$_2$</td>
</tr>
<tr>
<td>N</td>
<td>0.056</td>
<td>HCN, HC$_2$N, NH$_3$, NO$_2$</td>
</tr>
<tr>
<td>Si</td>
<td>0.046</td>
<td>SL$_4$</td>
</tr>
<tr>
<td>S</td>
<td>0.038</td>
<td>H$_2$S, N$_2$H, CS$_2$</td>
</tr>
<tr>
<td>Ar</td>
<td>0.023</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>0.007</td>
<td>PH$_3$</td>
</tr>
</tbody>
</table>
Silicon-Based Life?

- Elements in same column of the periodic table – 4 valence electrons
  - Can combine (share e⁻) with 4 other atoms
  - Allows for complex molecules
  - DNA – most complex – 100,000’s of atoms
  - C is mobile in environment as CO₂
- Si 2nd most abundant element in Earth’s crust
  - Can also combine with 4 other atoms
  - Largest naturally occurring Si molecule has 6 silicon atoms

Other Basis of life?

- Problems with Silicon
  - Si forms rocks when combined with O and isn’t mobile
  - Hard to get energy to break a Si-O bond
  - Si-H bonds are less stable than C-H bonds
  - Silicon life would have to “eat rocks and shit bricks”
- Other column IV Elements
  - Ge (Germanium) – abundance in Earth in ~ 1 ppm
  - Sn (Tin) – abundance ~ 2 ppm

Respiration – Chlorine Rather Than Oxygen?

- Poisonous
  - Chlorine to us → yes
  - Life on early earth → O₂ was the poison
- Life now
  - Breaks water or CO₂ to make CHON compounds
- Alternate chemistry?
  - Break apart salts to get alkali metals and release chlorine
  - Energetically expensive

Polar Molecules

- Water is a bent molecule
  - Electrons spend more time orbiting the O atoms than H
  - This causes a charge separation in the molecule
- Hydrogen Bond
  - Attractive force between the H attached to an electronegative atom and an electronegative atom of another molecule
  - Bond strength 5-10% covalent bond
- Hydrogen Bonds in Water
  - Each H₂O molecule can bond with 4 others
  - High boiling point is because of the large number of H-bonds and low molecular weight

Special Properties of Water

- High freezing point
- Heat of vaporization
  - Amount of heat needed to turn into a gas
  - Basis for a cooling system for plants/animals – H₂O evaporating uses up heat
- Specific heat
  - Amount of heat needed to raise 1 gm by 1°C
  - Cells are buffered against environmental T change
- Cohesion (sticking together)
  - Polar bonds
  - Gives high tensile strength (resistance to being pulled apart)
- Density upon freezing
  - Important for habitability
- Dissociation
  - Makes for Acids and bases

Acids & Bases

- Water dissociates into H⁺ and OH⁻ (and sometimes then H₂O⁺)
- Acid: Any substance that gives an H⁺ into water (solution)
- Base: decreases the concentration of H⁺ ions
- pH Scale
  - In 1 litre H₂O there are s.oxmo g mole H⁺ and OH⁻, written as
  - pH = -log[H⁺]
  - Pure water has pH = 7
  - Concentration of H⁺ and OH⁻ in water is equal.
**Organic Compounds**
- Early definition: “living matter”
  - Usually not CO, CO₂ but simplest is CH₄
  - Carbon bonded to H, but may contain others
- Unique Characteristics
  - **Wide stability** (T, P)
  - **Strong covalent bonds** – share 2 or more e-
  - **Aromaticity** – compound where 2 = structures (resonant) can be drawn
    - e shared by 3 or more atoms
    - Compounds are very reactive – easily form more complex molecules
  - **Stereoisomerism** – same atoms, different arrangement
    - Chiral molecules – mirror images
    - Chemically identical
    - Biologically – complex molecules only interact with one enantiomer
- **Complexity**

**Organic Structural Complexity**
- C can form compounds with straight chains, branched chains, rings: many isomers
- Isomer – same atomic composition, arranged differently (different chemical behavior)
- \( \text{C}_{20}\text{H}_{42} \) 300,000 isomers!
- **Monomer** – basic molecule unit that can repeat in long chains
- **Polymers** – strings of monomeric molecules

**Chiral Molecules**
- **Enantiomers**: Mirror images not superimposable
  - Life is L-left handed
- **Using chirality to search for life**
  - Search for enantiomeric excess
- **Testing for Chirality**: a chiral test
  - Circular dichroic spectrum
  - Diff between absorption from L&B circularly polarized light

**Evidence of Life in Ice?**
- **Clathrates** - Cage of water
  - form to minimize interaction of non-polar molecule with polar water
- **Same for Biomolecules**:
  - In living cells, 5% of the water is tightly coupled to the biological molecules
  - How does ice form around living molecules
  - Is this detectable spectroscopically?

**Complexity**
- **Cellulose, a polymer of glucose**

**Organic Bases**
- Organic compound with properties of a base
- Examples – building blocks of life
- **Purine** – double ringed crystalline organic base
  - Guanine \( \text{C}_{5}\text{H}_{5}\text{N}_{3}\text{O} \)
  - Adenine \( \text{C}_{5}\text{H}_{5}\text{N}_{5} \)
- **Pyrimidine** – single ringed organic base:
  - Cytosine \( \text{C}_{4}\text{H}_{4}\text{N}_{2}\text{O} \)
  - Thymine \( \text{C}_{5}\text{H}_{4}\text{N}_{2}\text{O}_{2} \)
  - Uracil \( \text{C}_{4}\text{H}_{4}\text{N}_{2}\text{O}_{2} \)

**Amino acids** – monomeric building blocks of life
- Containing an amino group (NH, NH₃) and a carboxyl group (COOH)
- 20 are found in Earth life

**Proteins** – long chains (polymers) of amino acids

**Enzymes**
- proteins which control rate of life chemical reactions (catalysts) without being destroyed
- Chemical matchmaker

2 examples of amino acids
- L-serine
- L-histidine
RNA & DNA

• **RNA**
  - Long polymer – single stranded chain
  - phosphates, sugars and bases (AGC & U)
  - Performs critical functions such as protein synthesis
  - Other functions: help translate genetic information to assemble amino acids

• **DNA**
  - Nucleic acid capable of self replication
  - Carries genetic information
  - Structure – 2 long chains of nucleotides in a twisted helix

What is a Cell?

• **Cells**
  - house the biochemical basis of life
  - Genes, enzymes, machinery of E production
  - Encased in a thin membrane

• **Large molecular components of Cells**
  - **Lipids**
    - substance such as fat or oil
    - Used in energy storage, membrane structures
  - **Carbohydrates**
    - Provide energy, make cell structure
  - **Proteins**
    - Structural elements, enzymes
  - **Nucleic Acids**
    - Hereditary molecule

Basic Cell types

• **Prokaryotes**
  - simple non-nucleated cells (bacteria, archaea)

• **Eukaryotes**
  - complex cells with a nucleus

Phylogeny – Evolutionary Relatedness

• Ideally – we compare whole genomes to determine life relationships – Not yet feasible

• Must substitute a phylogenetic marker: a gene who’s sequence is used to infer relationships among microbes

• **Ribosomes**
  - Molecular machines that make protein in cells
  - Sites of protein synthesis (~10,000 to 20,000 ribosomes per cell)
  - occupy 25% of cell volume and use 90% of the cell’s energy

• **Ribosomal RNA and taxonomy**
  -Ribosomes critical to cell function, so structural RNAs should not evolve rapidly – a sequence change may disable the ribosome
  - 16S rRNA – conserved
    - Possessed by all cellular life
    - Doesn’t change much over time

Genes – Basic Units of Heredity

• **Nucleotide** – Basic building block of DNA & RNA
  - consists of sugars, phosphates, and a base with N
  - Adenine (A), guanine, (G) cytosine, (C) thymine, (T)

• **Gene** – Basic unit of heredity
  - A portion of DNA that carries functional information
  - Functional unity of heredity
  - Sequences of bases which provide instruction for cell function

• **Genome** – complete set of an organisms’ genes

Lipids & Membranes

• **Hydrogen bonds** – negative end of 1 molecule orients toward + end of another

• **Hydrophilic** – possesses a dipole moment (charge separation) – polar molecules
  - Water loving – able to bond with H in water

• **Non-polar** – no charge separation; hydrophobic
  - Cluster together in water – do not dissolve (e.g. oil)

• Lipids have a hydrophobic group (tail) and a hydrophilic group
  - Hydrophobic ends come together – making a membrane

Domains of Earth Life

• **Early Classifications**
  - Pre Darwin: plants & animals
  - 1866: protists
  - 1958: bacteria
  - 1959: fungi

• **Now: biochemical & genetic classes**
  - Classification made on the basis of RNA
  - Mostly made of microbes
  - Domains
    - **Archaea** – non-nucleated single celled microbes
    - **Bacteria** – non-nucleated single celled microbes (different evolution than archaea)
    - **Eukarya** – possess cells in which chromosomes are packaged in a nucleus (more closely related to archaea than bacteria)
Energy Utilization

- **Oxidation-Reduction Reactions**
  - Oxidation
    - Atom or molecule loses electrons
  - Reduction
    - Atom or molecule gains electrons

- **Metabolism**
  - Energy to power cells – from enzyme-speeded breakdown of food
  - Without the cell the chemistry would occur too slowly to be useful for life.
  - Requirements: raw materials (C source), energy
  - All cells use the molecule **ATP** to store and release E
    - ATP releases E when gives up 3rd phosphate group
    - No reason another molecule couldn’t do this
    - Suggests that life formed from a common ancestor

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Metabolic Sources: Energy for Life

- **Heterotrophs** — feeders
  - Currency of energy: ATP
    - $13\text{O}_2, 2\text{C}, 6\text{H}_2, 5\text{N}_2, 3\text{P}$
    - O-P bond break $\rightarrow$ E release

- **Autotrophs** — produce food
  - Photosynthesis
    - Converts CO$_2$, water & sunlight to sugar (glucose) and O$_2$
    - $6\text{CO}_2 + 6\text{H}_2\text{O} + hf \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2$

- **Chemoautotrophs**
  - Get energy from food (us)

- **Chemoautotrophs** — make energy from chemicals
  - Sulfate reducing
  - Methanogenic
  - Fe oxidizers (deep biosphere)