1 Origin of Life & Building Blocks of Life

1.1 What is life?

Astrobiology studies the origins, evolution, distribution, and future of life in the universe.

- 4.6 Gyr ago: Earth formation
- 3.5 Gyr ago: Evidence for life forms

The subject of our lecture today is what could have happened in the intervening period.

The very first hypothesis on the origin of life was spontaneous origin of life from “mud”. It was convincingly disproved by Luis Pasteur (1822-1895) who demonstrated that sterilized solution excluded from contact with microorganisms would remain sterile indefinitely.

A new, more difficult question was raised:

If all life comes from existing life, where did the first life come from?

Still, an inescapable and logical conclusion is that the very first life may have arisen from non-living materials present in the Universe.

Two key features indicate life:

- the capacity for self-replication
- the capacity to undergo Darwinian evolution (natural selection)

Some failures of the definition:

- A mule as an offspring of a donkey and a horse cannot breed and, thus, incapable of taking part in the process of self-replication and Darwinian evolution. Yet it is alive.
- etc.

1.2 Building blocks of life

Carbon

- The only element that can form large molecules
- It can form chemical bonds with many other atoms
- Many carbon compounds are readily dissolved in water which makes possible chemical reactions.
- Organic matter is the compounds based on carbon
- Most common elements of life H, O, C and N are the most abundant non-nobel gas elements in the Universe
- S and P are also important elements of life and are the 10th and 15th most abundant elements in the Universe
Water

Water is the major component of living organisms, generally accounting for 70% of their mass.

- Universal solvent
- Liquid at temperatures which are
  - not too cold to sustain biochemical reactions
  - not too hot to stop many organic bonds from forming

Water is a polar solvent:

The oxygen, being a stronger electron grabber than hydrogen, is able to pull the electrons shared with each hydrogen towards it. The result is an unequal sharing of the electrons.

This makes a water molecule polar, in that the oxygen end of the molecule has more electrons (a negative charge), while the hydrogen end has a slightly more positive end (as the electrons are found there less frequently). Having both a positive and negative end, water thus acts like an electromagnet. The positive end is able to attract negative ions or the negative end of other polar molecules. The negative end is able to attract positive ions or the positive end of other polar molecules. Because water does this very well, it is able to dissolve many substances, and it is thus called a universal solvent.

<table>
<thead>
<tr>
<th>Order</th>
<th>Universe</th>
<th>Whole Earth</th>
<th>Earth’s crust</th>
<th>Earth’s ocean</th>
<th>Humans</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>H</td>
<td>92714</td>
<td>O 48880</td>
<td>O 60425</td>
<td>H 66200</td>
</tr>
<tr>
<td>2</td>
<td>He</td>
<td>7185</td>
<td>Fe 18870</td>
<td>Si 20475</td>
<td>O 33100</td>
</tr>
<tr>
<td>3</td>
<td>O</td>
<td>50</td>
<td>Si 14000</td>
<td>Al 6251</td>
<td>Cl 340</td>
</tr>
<tr>
<td>4</td>
<td>Ne</td>
<td>20</td>
<td>Mg 12500</td>
<td>H 2882</td>
<td>Na 290</td>
</tr>
<tr>
<td>5</td>
<td>N</td>
<td>15</td>
<td>S 11400</td>
<td>Na 2155</td>
<td>Mg 34</td>
</tr>
<tr>
<td>6</td>
<td>C</td>
<td>8</td>
<td>Ni 1400</td>
<td>Ca 1878</td>
<td>S 17</td>
</tr>
<tr>
<td>7</td>
<td>Si</td>
<td>2.3</td>
<td>Al 1300</td>
<td>Fe 1858</td>
<td>Ca 6</td>
</tr>
<tr>
<td>8</td>
<td>Mg</td>
<td>2.1</td>
<td>Na 640</td>
<td>Mg 1784</td>
<td>K 6</td>
</tr>
<tr>
<td>9</td>
<td>Fe</td>
<td>1.4</td>
<td>Ca 460</td>
<td>K 1374</td>
<td>C 1.4</td>
</tr>
<tr>
<td>10</td>
<td>S</td>
<td>0.9</td>
<td>P 140</td>
<td>Ti 191</td>
<td>Si –</td>
</tr>
</tbody>
</table>
For instance, two water molecules can interact to form a hydrogen bond between the hydrogen of one water molecule and the oxygen of another molecule.

![Image of water molecule interactions]

**Apolar** (non-polar) molecules:
- compounds that do not have concentrations of positive or negative electric charge

“like dissolves like”
- polar solvents dissolve polar organic molecules
- apolar molecules do not readily dissolve in water

Two classes of organic molecules:
- **hydrophilic**: high affinity for water ⇒ water soluble
- **hydrophobic**: low affinity for water ⇒ water insoluble

Living systems exploit the hydrophobic and hydrophilic nature of different molecules to perform specific functions.

Most of molecules in a living system, except for water, are large organic molecules or “macromolecules”. They can be subdivided into four different types:
- lipids
- carbohydrates
- proteins
- nucleic acids
Lipids

A group of molecule with
- one end hydrophobic
- other end hydrophilic

Poorly soluble in water ⇒
- rarely found as individual molecules
- arrange themselves into weakly bonded aggregates that can be considered as macromolecules
- convenient and compact way to store chemical energy
- flexible because of the weak macromolecular bonds
- used in membranes

Carbohydrates

Molecules that have many hydroxyl (-OH) groups, which are polar
⇒ carbohydrates are soluble in water

Sugars are common carbohydrates:
- form ring-like structures when dissolved in water
- pentoses: sugars with 5 carbon atoms
- hexoses: sugars with 6 carbon atoms

Polysaccharides
- sugar monomers connected together
- polymerization: loss of water and formation of linear or branched network of sugars
- useful energy stores
- can provide structural support for organisms
Proteins

The most complex macromolecules found in living systems.
- long ‘trains’ of amino acids linked together
- polymerization: loss of water and formation of chains
- 20 different amino acids found in proteins of living systems
- particular sequence of amino acids gives a protein its function
- have many different functions:
  - provide structure
  - act as catalysts (digesting): enzymes
  - etc.

Nucleic acids

The largest macromolecules:
- a collection of individual nucleotides linked together in long linear polymers
- polymerization: loss of water

Nucleotides:
- a five-carbon sugar molecule (pentose)
- one or more phosphate groups
- nitrogenous base: a nitrogen-containing compound

Most famous nucleic acids:
- RNA: ribonucleic acid
- DNA: deoxyribonucleic acid
DNA contains four different nucleotides, each possessing identical sugar (deoxyribose) and phosphate groups but different bases:

- adenine: A
- guanine: G
- cytosine: C
- thymine: T

In 1953, J. Watson and F. Crick recognized that DNA consists of two long molecular strands that coil about each other to form a **double helix**:

- bonds connecting two helical strands consist of two nucleotides
- two nucleotides are connected via bases joined by weak hydrogen bonds
- the bases always match:
  - adenine is always paired with thymine (A–T)
  - guanine is always linked to cytosine (G–C)
- the sequence of bases on one strand strictly determines the base sequence on the other
- the bases are attached to their helical strands by sugar groups, which in turn are connected together along the exterior of the helix by phosphate groups

**Figure 1.7** (a) The structure of a nucleotide consisting of a phosphate group, sugar molecule and nitrogenous base (cytosine in this instance). (b) Nucleotides polymerize by simple reactions that involve the loss of water to form nucleic acids. (a) Zubay, 2000

**Figure 1.8** The bases found in DNA.

**Figure 1.9** The DNA double helix. Note that the 'ribbons' are not real, but are there to illustrate the nature of the double helix.
DNA replication:
- special protein enzymes separate the strands of the double helix
- the single strands upgrade themselves with spare nucleotides present in the liquid surrounding the molecule
- each base in the unzipped strand catches its complementary base
- the sugar and phosphate groups of the newly acquired nucleotides then join together into helical strands
- two identical double-helix molecules are formed, exactly like the original

**Figure 1.10** DNA replication showing how one parent double helix ‘unzips’ and produces two identical daughter double helices. (Lowestain et al., 1998)

Different base sequences in DNA account for
- variations between individuals of the same species
- differences between species
- genetic code

RNA differs from DNA by sugar (ribose) and one base:
- adenine: $A$
- guanine: $G$
- cytosine: $C$
- uracil: $U$

When binding with DNA, uracil in RNA is always bound with adenine ($A$–$U$).

**Figure 1.12** An RNA nucleotide containing the sugar and base that makes RNA distinct from DNA.
DNA protein synthesis
- DNA helix unzips
- each of nucleotides searches for RNA nucleotides to produce a strand of messenger RNA (mRNA)
- the mRNA is released
- DNA helix zips itself together again
- mRNA carries the encoded DNA sequence into a region that contains free amino acids where molecular factories (ribosomes) use the mRNA to combine amino acids into long protein chains

The cell

A cell is a small bag of molecules that is separated from the outside world. It provides an environment in which biochemical processes can occur and genetic information can be stored.

Cell components:
- cytosol: salt water solution containing enzymes and ribosomes
- DNA devoted to storage and use of genetic information
- soft membrane consisting of lipids and proteins
- tough cell wall consisting of carbohydrate molecules and short chains of amino acids

Cells are the basic structural units of living organisms on the Earth. They vary in number, shape, size and function. For instance, bacteria are single-celled organisms, while humans contain around $10^{13}$ cells.

Biomarkers

- cellular remains
- textural fabrics in sediments that record the structure or function of biological communities
- biologically produced (biogenic) organic matter
- mineral whose deposition has been affected by biological processes
- stable isotope patterns that reflect biological activity
- atmospheric constituents whose relative concentrations require a biological source
1.3 Alternative biochemistries

Alternatives to carbon-based life:

Since 19\textsuperscript{th} century there has been speculation about whether some other element could replace carbon as a universal building block for life. B, N, Si, P, and S are other common non-metallic elements that are known to form heat-resistant polymers. It will be hard for any other element to match the complexity and versatility of carbon, but we have to keep in mind that

- the research on polymeric chemistry is carried out under Earth environmental conditions and many polymers that are stable below the freezing point or above the boiling point of water are unknown
- life may not in principle require any particular element to be as dominant as carbon is in terrestrial biochemistry. Chains composed of just one element may not be necessary; chains of alternating atoms constructed from two or more different elements may work just as well (e.g. sequential units of B-N or Si-O). Proteins and nucleic acids already provide examples of structures that incorporate other elements into their backbones, as described below. Furthermore, in some other variety of carbon-based life, many of the carbon atoms could be replaced by silicon.

Silicon as an alternative to carbon

Silicon is the most obvious potential substitute for carbon.

Table 5.6 Physical properties of carbon and silicon.

<table>
<thead>
<tr>
<th>Physical Properties</th>
<th>Carbon</th>
<th>Silicon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular Weight</td>
<td>12.011</td>
<td>28.086</td>
</tr>
<tr>
<td>Melting Point (in °C at 1 bar)</td>
<td>~3500</td>
<td>1414</td>
</tr>
<tr>
<td>Boiling Point (in °C at 1 bar)</td>
<td>~3900</td>
<td>3265</td>
</tr>
<tr>
<td>Density (g/cm\textsuperscript{3} at 20 °C)</td>
<td>2.27\textsuperscript{1}</td>
<td>2.34</td>
</tr>
<tr>
<td>Electronegativity</td>
<td>2.55</td>
<td>1.90</td>
</tr>
<tr>
<td>Single Bond Covalent Radius (pm)</td>
<td>77</td>
<td>118</td>
</tr>
<tr>
<td>Heat Capacity (J/g L at 25 °C)</td>
<td>0.709</td>
<td>0.705</td>
</tr>
<tr>
<td>Enthalpy of Fusion (kJ/mol)</td>
<td>0.00\textsuperscript{2}</td>
<td>50.6</td>
</tr>
<tr>
<td>Enthalpy of Vaporization (kJ/mol)</td>
<td>394\textsuperscript{3}</td>
<td>383</td>
</tr>
</tbody>
</table>

Similarities of silicon to carbon:

- element of group IV, just below carbon in the periodic table.
- four electrons in its outer shell ⇒ somewhat similar physical properties
- very high melting and boiling points
- solids at standard temperatures and pressures (298 K, 105 Pa)
- both are semi-metallic
- both form tetrahedral structures in many of their compounds
Differences between silicon and carbon:

- Silicon has a larger radius and therefore forms relatively weak bonds with the light abundant elements ⇒ reduces chance of forming complex compounds.
- The Si-Si bond strength is lower than the C-C bond strength, thus carbon is much more likely to bond with itself than silicon.
- Silicon rarely forms any double or triple bonds, which are common and of great biological significance for carbon.
- Due to silicon’s strong bond enthalpy with oxygen, it will be oxidized if oxygen is present. The high abundance of silicates on many of the rocky planets is caused by the bonding of silicon with oxygen when the planets formed.
- **The fully oxidized** form of silicon, SiO$_2$, forms four single bonds with four oxygen atoms resulting in a relatively inert mineral, while the fully oxidized form of carbon, CO$_2$, forms double bonds with two oxygen atoms, resulting in a reactive gas.
- **The fully reduced** form of silicon, silane SiH$_4$, a compound analogous to methane CH$_4$ in the carbon system. Silane is much more reactive than methane and burn spontaneously when in contact with oxygen to form a silicate and molecular hydrogen. Silane decomposes in the presence of water vapor to SiO$_2$, which explains why no SiH$_4$ has been detected in the hydrogen-rich atmosphere of Jupiter even though it has been detected in the interstellar medium.
- The affinity of silicon to oxygen is so strong that if silicon is placed in water, it will form a silica shell, stripping the oxygen from the water. Thus, water is not a compatible solvent for silicon-based compounds. Methane, ethane, or any compounds that contain methyl groups are more compatible solvents for a silicon-based system.

<table>
<thead>
<tr>
<th>Property</th>
<th>CH$_4$</th>
<th>CO$_2$</th>
<th>SiH$_4$</th>
<th>SiO$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular Weight</td>
<td>16.04</td>
<td>44.01</td>
<td>32.12</td>
<td>60.09</td>
</tr>
<tr>
<td>Melting Point (°C)</td>
<td>−182.5</td>
<td>−56.6</td>
<td>−185</td>
<td>1713$^2$</td>
</tr>
<tr>
<td>Boiling Point (°C)</td>
<td>−161.5</td>
<td>−75$^1$</td>
<td>−112</td>
<td>2950</td>
</tr>
<tr>
<td>Density (g/cm$^3$) (at −164 °C)</td>
<td>0.424</td>
<td>1.03</td>
<td>0.68</td>
<td>2.65</td>
</tr>
<tr>
<td></td>
<td>(at −20 °C, 19.7 bar)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 5.2** Some physical properties of the fully reduced and fully oxidized forms of carbon and silicon.

<table>
<thead>
<tr>
<th>Atoms</th>
<th>with Carbon</th>
<th>with Silicon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>435</td>
<td>393</td>
</tr>
<tr>
<td>Oxygen</td>
<td>~360</td>
<td>452</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>~305</td>
<td>322</td>
</tr>
<tr>
<td>Chloride</td>
<td>351</td>
<td>381</td>
</tr>
<tr>
<td>Carbon</td>
<td>368</td>
<td>360</td>
</tr>
<tr>
<td>Silicon</td>
<td>360</td>
<td>340</td>
</tr>
</tbody>
</table>

**Table:** Typical bond energies for carbon and silicon with some other elements, as enthalpy of bond formation (kJ/mol).

Pure carbon-based and pure silicon-based forms of life may merely be the limiting cases, with a variety of transitional alternatives in between. Some recent work on proteins and nucleic acids, where C atoms are replaced by Si atoms but functionality is attained, seem to support that assertion.
Silicon is not the basis for life on Earth, but it is still a very important component of living organisms:

- Plants use silicon as silica within the walls of the stems to provide rigidity
- In the animal kingdom, silicic acid is a major constituent of the cells of the connective tissue where it is found in hair, nails, and the epidermis.

Polymeric chemistry of silicon

Silicon hydrides or silanes have the generic chemical composition

\[ \text{Si}_n\text{H}_{2n+2} \]

Silanes occur both as branched and unbranched chains. They form direct analogs to hydrocarbons in the carbon-based world.

\[
\begin{align*}
 & \text{H} \quad \text{a.} \quad \text{H} & \text{b.} \quad \text{H} \\
 & \text{H} \quad \text{H} & \text{H} \quad \text{H} \\
 & \text{H - Si - H} & \text{H - C - C - H} \\
 & \text{H} & \text{H} \\
\end{align*}
\]

For example, a ring of six silicon atoms is called a cyclohexasilane, which has a direct analogy to a ring of six carbon atoms. However, because the silicon atom is larger than the carbon, silanes do not form benzene analogs.

Because the bond energy between hydrogen and silicon is relatively weak compared to the bond energy to oxygen, silanes are much more reactive than their corresponding carbon compounds, and are readily oxidized into silicates in the presence of oxygen.

Polysilanes are not stable at the temperature and pressure conditions of Earth’s surface (with the exception of silane), but are fairly stable at low temperatures, especially at higher pressures.

Life Based on Silane?

Based on the previous discussion, the prospect of silicon-based life under any conditions resembling those on Earth does not appear encouraging. If silanes could be a basis for life as hydrocarbons are for carbon-based life, it would not be under the conditions found on present-day Earth, where silanes turn instantly into a silicate rock.

Minimum conditions for silane-based life

- Little or no atmospheric or lithospheric oxygen
- Little or no water in liquid form
- Low temperature (at least below 0°C) and or high pressure
- Solvent suitable for silane-based complex chemistry
- Restricted abundance of carbon
Alternative solvents

Several potential candidates could replace water as a polar solvent on other worlds. For example:

- sulfuric acid (H₂SO₄) as a possibility for Venus
- ammonia (NH₃) as a possibility for Jupiter.

Most of the potential solvent candidates are liquids at lower temperatures than water. Chemical reactions occurring within these solvents would proceed at a much slower pace than on Earth, typically by a factor of 2 for every 10°C decrease in temperature. However, the key to developing a suitable chemistry at a given temperature lies in selecting chemical reactions suited to that temperature. For example, those reactions involving unstable and highly reactive free radicals have very low activation energies and would be suited for low temperature organisms.

Many planetary bodies even within our solar system have much colder surface temperatures than Earth, and planets and moons at these temperature ranges may be much more common than Earth-type bodies in the universe. In order to qualify as a suitable candidate for a polar solvent, the solvent has to be easily available and plentiful, as well as suitable for at least a hypothetical scheme that could lead to prebiotic chemistry.

Ammonia

Ammonia is analogous to water and could be a solvent for building proteins, nucleic acids, and polypeptides.

Synthesis of proteins from amino acids through a peptide bond with ammonia as a solvent. In a water system two glycine molecules combine with the release of water:
If reaction this would take place in a water-ammonia mixture the COOH group would be replaced with a CONH$_2$ group and the following reaction would be the result:

\[
\text{H}_2\text{N}-\text{C}-\text{C}-\text{O}-\text{H} + \text{H}_2\text{O} \rightarrow \text{H}_2\text{N}-\text{C}-\text{C}-\text{O}-\text{H} + \text{H}_2\text{O}
\]

In this reaction the peptide bond is preserved and ammonia is released instead of water.

In a pure ammonia solvent without the presence of oxygen, the carboxyl group could be replaced with a -CH(NH$_2$)NH$_2$-group and the peptide bond with a -CH(NH$_2$)-NH- group. Similar analogs can be shown for the phosphate bonds in the nucleic acids.

**Disadvantages for ammonia-based life**

- liquid at very low temperatures
- has a smaller range in which it stays liquid, thus life would have to adapt to a smaller temperature window to survive on such a world
- chemical reactions (and evolution!) would progress at a slower pace
- has a lower dipole moment and is thus less efficient at dissolving polarized compounds.
- its heat of vaporization and heat of fusion are lower than those of water. Thus, ammonia is not as good at moderating temperature as water, but is still sufficient to have a stabilizing effect on climatic conditions.
- surface tension is only about one third that of water; thus ammonia is not likely to concentrate organic macromolecules in microscopic interfaces as well as water.
- dissociates into nitrogen and hydrogen, and does not afford any protection from UV light when compared to the dissociation of water. Thus any origin of life in ammonia would have to occur in some kind of protected environment.
- solid ammonia is more dense than liquid one that makes it unlikely that multicellular organisms could survive in such an environment.
- liquid ammonia cannot co-exist with free oxygen, thus aerobic metabolism would be inconsistent with ammonia as a solvent.
Advantages for ammonia-based life

- dissolves alkali metals without reaction, which is of biological relevance because alkali metals can act as catalysts
- salt solutions in liquid ammonia have usually a greater electrical conductivity than an aqueous solution of the same salt
- four times less viscous than water, thus dissolved particles

Other solvents

![Temperature ranges for solvent candidates to occur in the liquid state (at 1 bar).](image)

1.4 Assembling living organisms

The mechanisms by which organic molecules could have been assembled into complex living organisms are poorly understood. We consider here possible fundamental steps.

Creating polymers and macromolecules

Simple molecules would eventually have to be polymerized into macromolecules. This occurs via forming a bond between two molecules with the release of water molecule:

Sugars: combining two –OH groups

Amino acids: combining the –NH₂ and –COOH groups
Formation of boundary layers

On the prebiotic Earth there were no large molecules like nucleic acids and proteins available to control the assembly processes. So the first forms of life must have arisen through a self-assembly process.

Amphiphiles (e.g. lipids)
- one end is polar hydrophilic
- the other end is hydrophobic

If amphiphilic molecules are added to water, they tend to sit at the surface with hydrophilic heads in the water and the hydrophobic tails in the air. In this way they create a single layer of molecules – a monolayer, which represents a two-dimensional surface, or membrane.

Figure 1.27 A lipid monolayer – a single layer of lipid molecules with hydrophilic ends in the water and hydrophobic ends in the air.

If the water surface is shaking and amphiphilic molecules get into the water, they tend to form small spherical structures where hydrophilic heads face the water while the hydrophobic ends are tucked inside, shielded from the water. These spherical structures are called micells.

Figure 1.28 A lipid micell – spherical collections of lipids with hydrophilic heads on the exterior and hydrophobic tails in the interior.
Lager collections of amphiphilic molecules can form a double-layer structure. This arrangement is called **bilayer**.

A spherical form of the double layer molecules is called **bilayer vesicle**.

![Image](https://example.com/image.png)

**Figure 1.29** (a) A lipid bilayer and (b) bilayer vesicle.

Many types of organisms use the bilayer type of membrane to preserve the integrity of their cells.

Monolayers, micells, bilayers and bilayer vesicles are structures that form spontaneously and perhaps provided the original membrane-bounded environment required for cellular life begin.

**Experimental investigations:**

1924: Alexander Oparin (1894-1980)
- proteins, when added to water, group together to form droplets, called **coacervates**
- the same property is common to nucleic acids and polysaccharides
- many substances can be incorporated into droplets
- this provides a means by which prebiotic chemical factories could have been constructed

1958: Sidney Fox
- heated dry mixture of amino acids results in polymerization with products resembling proteins, called **proteinoids**
- when proteinoids are dissolved in hot water and the solution is then cooled, they form small spheres about 2 µm in diameter, called **microspheres**
- microspheres displayed a double wall resembling a biological membrane and could shrink or swell, depending on salt concentration
- if left for several weeks, the microspheres absorbed more proteinoid material from the solution
- they could produce buds which occasionally separated to form second generation microspheres
1985: David Deamer
- considered that amphiphilic molecules might have been delivered to the early Earth
- extracted organic material from Murchison meteorite and added it to water
- the Murchison molecules formed membrane-bound bubbles
- provided strong evidence that on the early Earth mixture of abiotic organic compounds could have helped to form membranes for primitive cellular life

![Bilayers generated from the Murchison meteorite organic matter. (Dr. David Deamer)](image)

**Possible development of primitive cells:**
- membranes are mixed with a collection of molecules
- a mixture is dehydrated in hotter environment
- when hydrated again, molecules are incorporated into membranes
- chemical factories may have developed into primitive cells.

**Concentration mechanisms:**
- marine lagoons or tidal pools provide a means of concentrating dilute solutions via temporary isolation and evaporation
- freezing solution increases organic concentration as water freezes first
- minerals can trap organic matter on their surfaces
- clays can accommodate organic molecules within their structure

![The dehydration and incorporation of molecules, and rehydration of membranes.](image)
The role of minerals

Four key roles that minerals could have played in the origin of life:

- **protection**
  - air pockets in volcanic rock
  - hosts for assembling chemical systems
- **support**
  - accumulating molecules on the surface
  - supporting polymerization
- **selection**
  - mirrored crystal faces bond selectively left- and right-hand amino acids
  - protein-like chains form exclusively from one type of molecules
- **catalysis**
  - unreactive N₂ gas together with H₂ could be used to generate ammonia on the surface of FeS
  - this may have occur in hydrothermal vents

From chemical to biological systems

To sustain the biological system

- DNA stores genetic information
- RNA carries information into a cell

Paradox:

- nucleic acids need proteins to catalyse the reaction
- proteins need nucleic acids to reproduce

Which of these three key molecules (DNA, RNA and protein enzymes) could have exist without other two?

The RNA world


- RNA molecules can have catalytic properties similar to enzymes needed for replications
- these are called ribozymes
- they would make proteins unnecessary for simple life

A simpler RNA world may have preceded the DNA-plus-protein world of today:

- the nucleotides in RNA are more readily synthesized than the nucleotides in DNA
- perhaps, DNA evolved from RNA and then, on account of its greater stability, DNA took over the RNA role
- RNA is likely to have evolved before proteins because no proteins can replicate in the absence of RNA

Eventually, the evolving RNA organisms began transcribing DNA, which was a much more efficient replicator. Natural selection then saw it that the more proficient DNA-plus-protein world outcompeted its parent RNA.
1.5 Energy sources for life

Primitive biochemistries

Life forms capture the energy and utilize it via metabolic processes.

- The main energy source available for life is sunlight. This energy is captured by a process called photosynthesis. Mainly UV and the optical wavelengths are absorbed.

Photosynthesis is the production of carbohydrates from water and carbon dioxide.

Low energy barrier reaction is based on sulfur:

\[ n\text{CO}_2 + n\text{H}_2\text{S} + hv \rightarrow (\text{CH}_2\text{O})_n + n\text{H}_2\text{O} + n\text{S} \]

However, the reaction most commonly used by plants today is based on water:

\[ n\text{CO}_2 + n\text{H}_2\text{O} + hv \rightarrow (\text{CH}_2\text{O})_n + n\text{O}_2 \]

In the absence of sunlight, the organisms can synthesize organic matter via process called chemosynthesis.

- deep-sea hydrothermal vents (T~400°C)
- hydrothermal systems in the Earth’s crust, called ‘deep hot biosphere’

Organisms that utilize photosynthesis and chemosynthesis to generate organic compounds from energy and simple inorganic substances are called autotrophs (from the Greek auto meaning ‘self’ and troph meaning ‘feed’).

Organisms sustaining their existence by consuming autotrophs are called heterotrophs.

Metabolism is the biochemical modification of chemical compounds in living organisms and cells. This includes the biosynthesis of complex organic molecules and their breakdown.

An important biosynthesis process is the generation of energy-rich phosphate bonds from carbohydrates, e.g. from glucose.

Two most common forms of metabolism on the Earth today:

- fermentation
  - transformation of glucose \((\text{C}_6\text{H}_{12}\text{O}_6)\) into both \(\text{CO}_2\) and ethanol \((\text{CH}_3\text{CH}_2\text{OH})\), or into lactic acid \((\text{C}_3\text{H}_6\text{O}_3)\)
  - a net gain of 2 energy-rich phosphate bonds

- respiration
  - use of the free oxygen in the Earth’s atmosphere
  - glucose is transformed into \(\text{CO}_2\) and \(\text{H}_2\text{O}\)
  - a net gain of 36 energy-rich phosphate bonds
1.6 Extrapolating back in time: Molecular phylogeny

Another approach to understand the origin of life is to extrapolate as far back as we can by using information contained in the Earth’s extant biology.

Life on Earth has a history that extends back over almost 4 Gyr. It is believed that it started with a single and simple common ancestor.

Life seems to build on top what was done before. The biological record of this continuous addition and modification is present in genetic material, namely the sequence of nucleotides in RNA and DNA. Examining similar molecules in different creatures allows us to construct so-called genetically based phylogenetic trees.

One of the more useful trees is built on the genetic information obtained from small sub-units of ribosomal RNA. It reveals a hierarchy of evolutionary innovations.

Three clear domains are evident:
- Bacteria
- Archaea
- Eukarya

Within the three domains, the species are more closely related to each other than to other branch on the tree.

It is the root of this phylogenetic tree that interests us the most:
- the organisms closest to the center of the tree are heat-loving microscopic organisms (thermophiles and hyperthermophiles)
  ⇒ the course of evolution was from high to low temperatures
- the majority of the deepest branching organisms do not use light as an energy source
  ⇒ the photosynthesis may be a later development than chemosynthesis
The phylogenetic tree seems to be telling us that our **last common ancestor** may have been similar to heat-loving chemosynthetic organisms that populate hydrothermal vents today. This was not necessarily the first organism on Earth.
Summary on the origin of life

- Earth formation
- generation of a prebiotic soup aided by the influx of organic matter from extraterrestrial objects
- first living organisms are created using minerals as catalysts and templates
- generation of biotic world with self-replication and Darwinian evolution
  - RNA world: RNA acts as both the store of genetic information and the catalysts for replication
  - DNA world: the labour of life is shared by three molecules, DNA, RNA and proteins
- the last common ancestor was probably a heat-loving organism similar to those found today at deep-sea hydrothermal vents

Figure 1.38 A synthesis of information from our bottom-up and top-down approaches to the origin of life. (Lahav, 1999)
Has life originated outside Earth?

- Sharov & Gordon (2013) argued that the growth of life complexity follows Moore’s law of the exponential growth.
- If extrapolated back in time, “life” or first nucleotides could have originated 9 Ba ago, well before the Earth was formed.