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Fundamentals of

EXOPLANETS & ASTROBIOLOGY

From the origin of the universe, stars and elements,
and the creation of solar systems and exoplanets,
to the arise and development of life

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Part 5: The origin, basic features, and development of life on Earth.

for lectures 2023, March 21 and 23.

Remark that part 5, in addition to these notes, includes separate scans from a book about the basic features of the biological cell. This information is also summarized in my powerpoint copies on page 50 to 55, but in particular if you were not attending the lectures and/or are not too familiar with the basic biological consepts, it is recommended to read also the scanned book text. Both the notes, the book scans and the power point copies are part of the syllabus.

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Life on Earth

1.1 The primordial soup

It is unknown what the chemical composition of the Earth's early atmosphere was. It might have been CO_2 dominated as the atmospheres of present-day Venus and Mars, and it might have been CH_4 dominated as present-day Titan. Organic reactions are much more efficient in a CH_4 dominated (i.e., strongly reducing) atmosphere than in a CO_2 dominated atmosphere (more neutral). One thing is, however, certain; it had no oxygen (i.e., it was not oxidising). This can be concluded from the fact that minerals in the oldest rocks formed on land are non-oxidised. For example, iron exist as Fe and not as FeO or Fe_2O_3.

The fact that there was no free oxygen in the atmosphere, also meant that there was only a sparse ozone-layer, or none at all. Therefore the solar UV radiation was passing almost un-affected to the surface of the Earth. UV radiation is energetic enough to break the chemical bond of small molecules like CH_4. Free atomic carbon has therefore been available for chemical reactions to form large organic molecules in the early atmosphere and ocean surface. Laboratory experiments (beginning with the famous Miller-Urey experiments in 1953) confirm that if the atmosphere was rich in CH_4, then the UV energy would indeed have caused the building up of complex organic molecules. As a result, the primitive ocean must have looked very different from the present-day ocean, having been abundant in free floating large organic molecules. We can get a rough estimate of the concentration of organic material in the primitive ocean by the following argument.

The solar constant, $f_\odot$, tells us how much energy reach each cm^2 of the surface of the Earth per time unit (outside the Earth's atmosphere). Its value is $f_\odot = 1.4 \cdot 10^6$ erg/cm^2/s. Approximately a fraction $f_{UV} = 10^{-4}$ of this is energetic enough to break the molecular bonds of e.g. CH_4 ($\lambda < 2000$ Å). Let us assume that a fraction $f_{abs} = 10^{-4}$ of these photons actually hit a molecule and broke a bond. This number is pretty arbitrarily chosen, but probably of the right order of magnitude, and good enough for the present purpose. It could be calculated from a detailed estimate of the absorption coefficient and corresponding calculation of the optical depth of CH_4 in the primordial atmosphere, for different assumptions about the atmospheric composition. Then the number of bond-braking photons n_{br} that hit each cm^2 of the Earth's surface per second is

$$n_{br} = f_\odot \; f_{UV} \; f_{abs} \; / \; E_{2000} = 1.4 \cdot 10^6 \cdot 10^{-4} \cdot 10^{-4} \cdot 10^{11} \;\approx\; 10^9 \mathrm{cm}^{-2}\mathrm{s}^{-1} \tag{1.1}$$

where we have used that the energy per photon with wavelength 2000 Å is $E_{2000} = h \cdot \nu = h \cdot c/\lambda = 6.2$ eV $= 10^{-11}$ erg, such that 1 erg $\sim 10^{11}$ photons.

Let's now assume that the ocean was on average $d \approx 3$ km $= 3 \cdot 10^5$ cm deep (as it is today), and covered most of the Earth's surface, and that organic material forming near the surface (from simple carbon containing molecules such as CO_2 mixed into the surface layers of the ocean, from CH_4 in the atmosphere just above the ocean, etc) was soon mixed downward where UV radiation would not destroy it again. After some time an UV blocking layer will probably have formed in the upper atmosphere. This could for example be an ozone layer from photo dissociated H_2O molecules, or it could be a layer of aerosols from CH_4. Let's assume that UV penetrated the atmosphere during the first $t \approx 500$ million years = $1.5 \cdot 10^{16}$ seconds and then stopped. Finally, we notice that the molar weight of carbon is 12. I.e., if we per bond-breaking photon produce approximately one carbon atom, then each bond-breaking photon will produce $m_\nu = 12/N_A \approx 2 \cdot 10^{-23}$ gram of free carbon which in principle could form the basis for building up more complex organic material. The concentration $f_{\rm organic}$ of organic material that was produced by the solar UV radiation in the primitive ocean can therefore have been

$$f_{\rm organic} = \frac{n_{br}}{d} \cdot m_\nu \cdot t \approx 10^{-3}\ {\rm g/cm^3} \tag{1.2}$$

In other words, in each m^3 of the ocean there can have been 1 kg of UV produced carbon available to form complex organic material (and 1 ton of water). A similar amount of organic material might have been added from comets, and a similar amount of organic material might have been produced by lightening. However, this is all inside the order of magnitude uncertainty in the above calculation, and the most important conclusion is that it is not unreasonable to envision that the primitive ocean can have been a diluted organic solution. It is what is often termed *the primordial soup*.

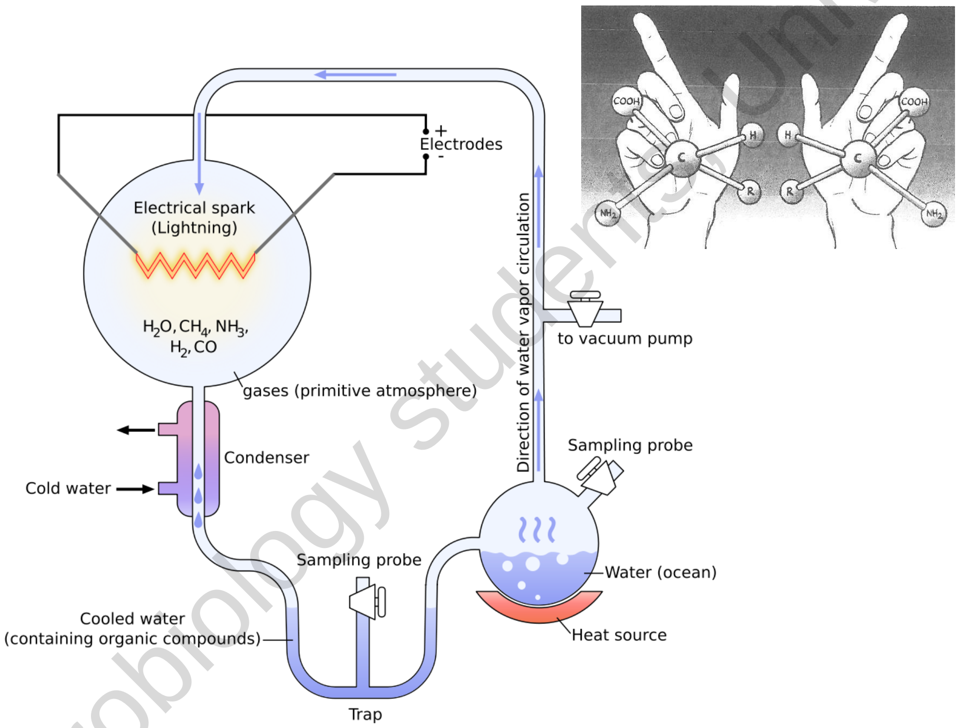


Figure 1.1. Spontaneous generation of complex organics may have taken place in the primitive ocean on Earth, Mars, and elsewhere in the solar system, but many of the complex organic building blocks can also have come from space with meteorites or comets. In laboratory experiments simulating the primitive ocean and atmosphere, many such molecules have been created, in particular if the simulated atmosphere is rich in CH_4 (methane). However, in cosmic material as well as synthetic material, the molecules are racemic, i.e. there are exactly 50% of each symmetry form of the molecule, illustrated here for an amino acid molecule. Life on Earth uses only the left symmetry form of the amino acids in the synthesis of proteins.

The organic material that is created spontaneously in the lab when simulations of the primitive atmosphere and ocean are exposed to lightening or UV radiation, include several amino acids, nucleotide bases, sugars, and other complex organic compounds of the kind that are also found inside primitive meteorites (primarily those that are expected to be part of comets, such as the Murchison and the Maribo meteorites). Of particular interest for astrobiology and the question of the origin of life, is that when various bases are present together with sugars and phosphates, then one of the most abundant molecules that is produced is the ATP molecule (adenosine-tri-phosphate; see Bennett & Shostak's notes p. 169 for an illustration). ATP must therefore have been an abundant part of the organic material in the primordial soup, independent of whether the bases and amino acids came from comets or were created in situ in the primitive ocean. Today exactly this molecule carries the energy around in the cells of all living organisms on the Earth. It is one of the indications that make us suspect that the first biological cells were created in the primordial soup, or at least in a chemically similar environment.

An organic cell is a very sensitive entity that can exist only within a limited temperature range. If the biological cell was a steam engine, it would be convenient to burn the hydrocarbon intake within our cells the same way we burn oil or coal. However, the temperature requirements of the organic cell, demands that the energy for the clipping and assembling of the right molecules for the growth of our cells, takes place by use of small energy units. The unit chosen by all living cells is the energy of the phosphate bond in the ATP molecule. In the primordial soup, ATP molecules were build up by reactions that took their energy from the UV light, and a convenient energy supply for organic reactions were therefore floating around in abundance in the surrounding ocean. Any organic entity that was able to use the ATP energy, had a big advantage in terms of energy supply security.

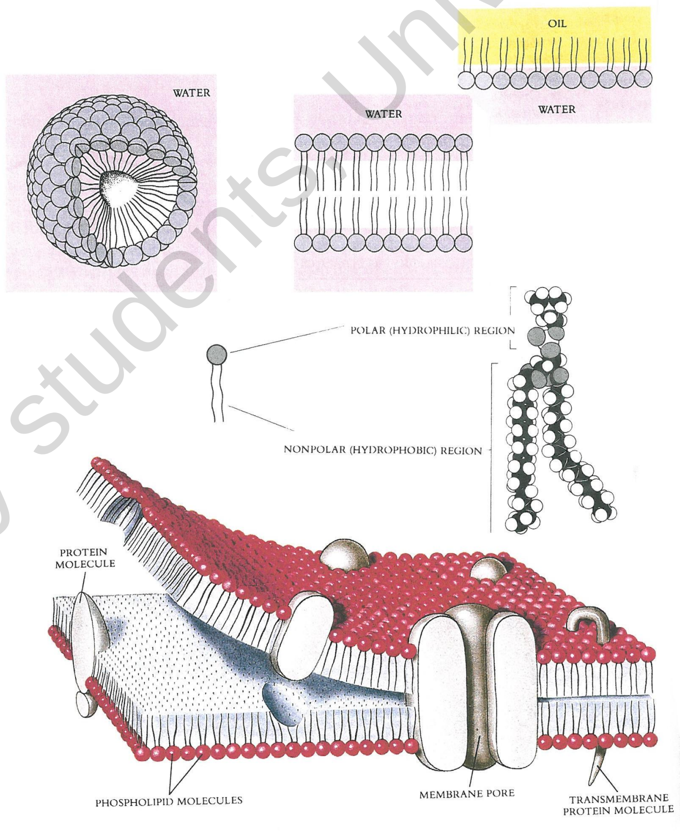


Figure 1.2. The lipid molecule and various simple lipid membranes. Also shown is a schematic drawing of a piece of the modern very complex cell membrane from our own body.

A fundamental part of any organic cell, is the cell wall. It is the material that divides the cell interior from the surroundings. It is made primarily from lipid molecules ("fat"). It is not a simple sack, but a complex membrane which is able to let certain molecules pass one way through the cell wall (e.g. from outside and in) but block them from passing the other way through the membrane, just like e.g. a modern rain coat, which is able to preventing the water molecules from the rain to pass from outside and in through the rain coat material (the membrane), but which willingly let the water molecules from the sweat pass from the inside of the membrane and out. The biological cell membrane therefore assures an excess of certain molecules relative to the surroundings, and assures that molecules of waste products of the life supporting processes inside the cell can be expelled. Lipid molecules will automatically form a simple membrane when they are exposed to water, because the head of a lipid molecule is hydrophilic ("likes water"), while the tail is hydrophobic ("afraid of water"). In water, lipid molecules will therefore line up to form a closed double layer structure with the heads toward the water and the tails toward one another, shielded from the water. The lipid cell membrane in all life we know of, thus, only exist when it is surrounded by water. This is a major reason why searches for extraterrestrial life always start with the question of the existence of places where liquid water can exist. The cell structure itself is not an entity in itself, but an interaction with the surrounding water. On top of this, water is also the solvent that allow transportation of all the relevant pieces around the body. We could therefore with some right claim that chemically we are a walking concentration of fat resolved in water, even though it may not be the most romantic way to describe ourselves, and may not be the way we usually think of ourselves.

If we pour a little bit of oil into water, we will see it spontaneously form tiny droplets. These are the lipid cells. In the primordial soup, lipid molecules will have been created spontaneously by the interaction of UV light, and the molecules will have formed such closed microscopic cells. Lipid cell membranes that had the ability to let ATP molecules into their interior and block them from getting out again, will have had an abundant energy source available for building up complex organic molecules inside the cell. If they were also able to let organic molecules in that could be assembled by the ATP energy, they would be well on their way to build up a growing cell. The cell that had the best structure to grow would use a larger fraction of the available organic material than less efficient cells would, and soon they would therefore dominate among the growing cells. This is somehow the darwinistic principle of "survival of the fittest" all the way down to the pre-biologic chemical level in the primordial soup.

When the cells grew large enough it would be energetically favourable to divide in two, just as a soap bobble would do it. Only when information about how to grow and divide was transfered from the original cell to the two new cells during the division, would we begin to think about calling it a living organism. Cells that could transfer a bit of information about efficiency just sometimes would have a big advantage over some that were completely unable to do so. In this way there may not have been any sharp transition from non-living cells to living cells. We don't know, however, whether life started this way, but it could have done, and it would be one way of making sense out of why all cells use ATP as their energy source. It was abundantly available at the time when UV sunlight formed large organic molecules in the ocean, and stored some of it in the phosphate bindings in ATP molecules.

Once the UV radiation stopped penetrating the atmosphere, the organic material in the primordial ocean must slowly have been used up by the growing cells. Those that could produce some of the organic material themselves, would have had an increasing advantage over those that relied on the existing molecules from the ocean. One of these cells was the predecessor of the modern cyanobacteria. It had developed the photosynthesis, which made it possible for it to produce the sugar in situ in the cell, thereby becoming independent of the original existence of sugar in the primitive ocean. Photosynthesis use the energy of visual light to combine water and $\mathrm{CO_2}$ into sugar ($\mathrm{C_6H_{12}O_6}$) and oxygen by

$$6\,CO_2 + 6\,H_2O + \text{visual light} \rightarrow C_6H_{12}O_6 + 6\,O_2 \tag{1.3}$$

Sugar is an important part of the biological material we are made of; e.g. sugar and phosphate constitutes the backbone of the DNA molecule.

In daily life, sugar is probably more well known for giving energy ("calories") to our body. In plant cells the chemical energy in the sugar (which is eventually the stored solar energy from Eq. 1.3) is released to the cell via the interaction of ATP molecules. In plant-cells 2 ATP bonds participate in fermentation of the sugar, thereby producing 4 new ATP bonds. In total, 2 ATP energy units for use in the cell is therefore produced per sugar molecule. The waste product of the process is alcohol. This process is, of course, also well known from fermentation of sugar in order to produce alcohol, where it is also well known that the process has to be performed anaerobe – without contact with oxygen, in order to end with alcohol. In the aerobic cell (the one that uses oxygen, like our own cell) the consumption of sugar starts in the same way as in the anaerobic cell, by fermentation (producing net 2 ATP bonds of energy per sugar molecule), but then it continues with breaking down the alcohol to water and CO_2, thereby gaining additionally 34 ATP bond units. This combined process of fermentation followed by breaking down the alcohol by use of oxygen, is called respiration. It is what happens when we breathe.

$$C_6H_{12}O_6 + 6\,O_2 \rightarrow 6\,CO_2 + 6\,H_2O + \text{energy} \tag{1.4}$$

Living organisms that are able to use oxygen in their energy production therefore have a much more effective metabolism.

The planets and the animals are seen to be in an ecological dependence of one another, but not (as is often erroneously postulated) in an ecological balance with one another (see below). The plants store the solar energy in sugar molecules and produce O_2, and the animals use the sugar and the O_2 and produce H_2O and CO_2 in almost the amount that is needed to keep the process running in a balanced circle. If future evolution, or evolution on another planet in our Galaxy, developed an organism that was able to perform both processes in a closed loop, then probably both plants and animals would die out, and this hypothetical organism would live from transforming directly the (low-entropic) solar light into biological molecules and (high-entropic) heath.

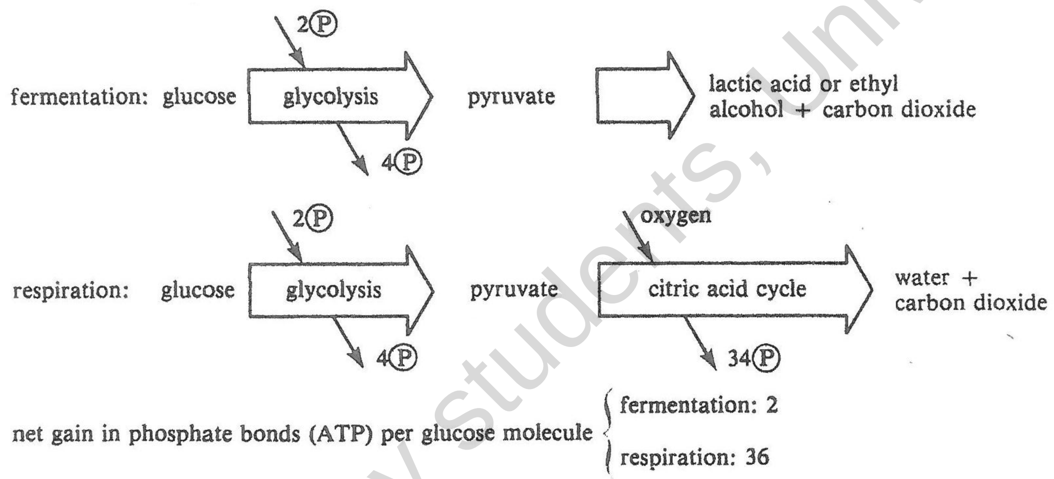


Figure 1.3. Fermentation uses two ATP bonds and produce 4 in the breaking down off a sugar molecule to alcohol. The anaerobic "digestion" of sugar therefore produce a net of 2 units of ATP bond energy that can be used for building up the cell. Aerobic respiration starts with anaerobic fermentation (gaining 2 ATP bonds per sugar molecule), but continues with breaking down the alcohol into CO_2 and water, which produces additionally 34 ATP bond units of available energy for the growth of the cell. Respiration therefore gives 18 times more energy per sugar molecule than fermentation.

For the anaerobic cells in the primitive ocean it has been important to get rid of the oxygen as quickly as possible, otherwise the very reactive oxygen would react with the organic material of the cell and destroy it. For the first 2 billion years of Earth's history the released oxygen from the cyanobacteria reacted with free iron resolved in the ocean water and formed FeO ("rust"). The rust will have sedimented to the ocean bottom. Only when almost all of the free iron finally had disappeared from the ocean water, the released oxygen from the photosynthesis will have started to find its way into the atmosphere. Geological land-formations from before this time show non-oxidised minerals in the soil, while the oxidation state of soil from younger geological formations show that the abundance of oxygen in the atmosphere must have been $\approx 0.2\%$ 2 Gyr ago ($\sim$ the first explosion of new life forms on Earth), was $\approx 2\%$ 1.5 Gyr ago ($\sim$ the first appearance of multi-cellular organisms), and was $\approx 15\%$ 200 Myr ago ($\sim$ tree burns to form char-coal). Today it is 21% and either the photosynthesising organisms have to reduce in abundance or the respirating organisms have to increase in abundance in order that we shall avoid reaching the critical 25% oxygen abundance that will make organic material self-igniting. The planets and the animals are almost in ecological balance on short time scales, but completely out of balance with one another on geological time scales.

1.2 What is life ?

The basic unit of life is the cell. We have discussed in the previous chapter ("the primordal soup" and associated photocopies) how the cell is structured and how it functions. Although there are still open questions to be answered, we have a well founded solid knowledge about the basic principles of the cell. In this chapter we will discuss how it can have originated in the first place and how life developed from a simple one-cell unit to a complex assemble of billions of individual cells with each their specialised task in a complex interaction that we call "a higher organism", such as ourself. This development has taken place in an intricate interaction between life itself and its environment. It is well known that life has completely changed the Earth's atmosphere, and still does, but controversial issues today include such central questions as whether the formation of the continents was a consequence of the existence of life, and whether life manipulates the global environment as response to changes in the Earth's cosmic surroundings.

How closely was the origin of life on Earth connected to the initial physical conditions on Earth? Was the development of life on Earth, determined also by remote conditions in the rest of the solar system, such as the mass and the orbit of Jupiter? Is life as we know it on Earth today so closely connected to detailed conditions and stochastic events in our solar system that we can never find any other civilisation in the vast universe that we could, even in theory, expect to be able to have a meaningful conversation with?

We will discuss in this chapter the origin and evolution of life on Earth, and later the possibilities of finding life elsewhere in the Universe, outside the Earth. We will discuss the interaction between life and its environment, the development of intelligence, and the possibility that the first life on Earth came together with the first water from comets. However, we have first to recall the unpleasant fact that none of us really know what life is – a fact that becomes more clear than anywhere else when we start asking whether "this thing" (life) exist outside the Earth itself.

We all have an intuitive understanding of what life is.... Or rather: We all think we know what we mean when we say "it's alive" or "it's a living creature". But try to explain what you mean, and you will realize that it is not easy, maybe even impossible. Is this because the concept of "life" is a man-made division of nature that doesn't exist in reality, or do we just have to try harder? Try the following postulates and questions:

1 "Life are such things that move around". Do you mean that a tree is not alive, but the dry leaves that are blown around by the wind are alive ?

2 "Life is a system that is capable of moving by its own force". Do you mean that grass is not alive, but that your car is ?

3 "Life is an entity that is able to reproduce itself". Do you mean that a salt crystal and self-reproducing computer programs are alive, but a mule isn't ?

4 "Life is a self-sustaining chemical entity with encoded information that it can transfer to construct a new entity of the same kind". Now we excluded the computer program, but we still have the problem with the salt crystal and the mule, and we (still) have the more tricky question left of whether a virus is alive. A virus cannot reproduce itself by itself, but only by injecting its DNA material into a "real living" cell like one of the living cells in our body, and "confuse" this cell to replicate the virus.

Nobody has been able to give a definition of life which cannot be shown to be "wrong" by being confronted with counter-examples and questions of the type above. However, whatever life is, it seems that from basic physics we cannot avoid to somehow include the second law of thermodynamics and the concept of entropy in our understanding of it, and from basic biology we need to include the concept of the cell, metabolism, reproduction and evolution.

1.3 Entropy and the second law of thermodynamics.

The most basic understanding of the difference between living and non-living material, the conceptual understanding of what is meant by *life*, is intimately connected to the second law of thermodynamics and the concept of entropy.

The second law of thermodynamics states that whenever energy flows from one system to another, some of the energy must become heat. Hence, the relative fraction of energy that is in the form of heat, in the sum of all systems, will always increase. Since heat is just random motion of the molecules, heat is the ”lowest” or most ”disordered” form of energy. We can therefore express the second law as saying that ”the sum of higher forms of (i.e., available or free) energy in interacting systems will always (i.e., when time pass) transform itself toward lower forms of energy (eventually to the lowest form: heat)”. Since heat is a disordered (i.e., a result of disorder or random movements of the particles in the system) form of energy, we could equally well had said that ”the total amount of disorder in the sum of all the interacting systems will always increase when time pass”. In this formulation, the second law of thermodynamics include the concept of disorder (and time), which is more precisely expressed by the concept of entropy. The more disorder, the higher the value of the entropy.

Entropy is a real physical quantity, just like temperature, mass, and energy. But there exist no entropy-meter like a thermometer or a ”mass-meter” (a balance), and we do not sense it with any of our senses, and it therefore often feels as something very alien. However, entropy is zero at zero Kelvin, just like the absolute temperature, and the amount of entropy, dS, added to the system when its temperature is increased, is the amount of added energy, dQ, divided with the temperature, T,

$$dS = dQ/T \tag{1.5}$$

Hence, the total amount of entropy in the system is

$$S(T) = \int dS = \int_{\widetilde{T}=0}^{\widetilde{T}=T} dQ(\widetilde{T})/\widetilde{T} \tag{1.6}$$

When H_2O is in the form of an ice crystal, or even more obvious in the beautifully ordered fractal form as a snowflake, the order of the molecules relative to one another is high, i.e., the entropy of the snowflake (or ice crystal) is low. It takes 80 times more energy, dQ, to heat a snowflake one degree from its snowflake form at $-0.5°$C to its water droplet form at +0.5°C, than it does to heat a water droplet one degree from, say, +0.5°C to +1.5°C. Obviously, water has an entropy barrier at the phase transition temperature, or expressed in a more popular way, an ”energy-absorption-buffer” barrier. A water droplet is hence a much more disordered, i.e. higher-entropy, system than a snow flake.

We could also compare the water droplet and the snowflake by introducing statistics, considering the molecules as identical particles which can be placed in different configurations. Then we would ask how high the probability is that the molecules will arrange themselves into the snowflake structure, and how high is the probability to form the random oriented droplet structure. The famous Austrian physicist Ludwig Boltzmann was able to quantify this way of reasoning with the entropy concept of Eq. 1.6 to express the entropy, S, of a system in terms of the probability, P, of its structure,

$$S = k(ln\, P) \tag{1.7}$$

where the constant k is Boltzmann’s constant, k = 1.38 10^{-16} erg/K, entering many thermodynamical problems, such as for example the ideal gas law.

A third way of getting a feeling of the concept of entropy, would be to think of it as the lack of information in the system. The more organised (i.e. with low entropy) the system is, the more information it requires to describe the organisation. It requires much more information to describe the organisation of the water molecules in a snowflake than in a water droplet. The molecules in the water droplet are described by simple thermodynamic equations (a distribution of random and spatially symmetric motions of the molecules), whereas a description of the snowflake in addition at least requires information about the orientation and the fractal shape (disregarding in both cases the macroscopic effect on the form, tension, collective velocity, etc, due to collective motion in a medium and/or a gravitational field). In analogue to the amount of order, we would say that the description of the snowflake requires more information than the description of the droplet; or in a more sloppy use of the language we will often say that the information content of the snowflake is higher than that of the droplet. We see that the entropy, S, and the information content, I, are inversely related,

$$S \propto 1/I \tag{1.8}$$

Whereas Eq. 1.6 historically arrived from analysis of the efficiency of energy transformation in steam engines, the entropy described as a function of information in Eq. 1.8 arises from studies of the efficiency to transfer telephone signals. Claude Shannon at Bell Telephone Laboratories realized that when a signal is transfered in a wire, information is unavoidably lost. The information content of the signal will always decrease with time. It was the computer pioneer John von Neumann who eventually suggested Shannon to call this *information loss* for *entropy gain*. If the two concepts of entropy (Eq. 1.6 and 1.8, and for that matter also Eq. 1.7) are really identical, then they relate the information content of a system with its thermodynamical state, with interesting possibilities of getting deeper into the understanding of the concept of life.

1.4 Life as a low-entropy entity.

A living organism is low in entropy, in terms of Eq. 1.7 and 1.8. The probability of randomly arranging the molecules the way they are in a living organism is low, and the information content is high. According to Eq. 1.6 this also implies that the integral of dQ/T is low. We can now try a thermodynamical description of life:

5 "Life is a non-equilibrium, self-organising chemical entity which is capable of lowering the total entropy content of the entity, by transforming low-entropy material from the surroundings to high-entropy products in the surroundings"

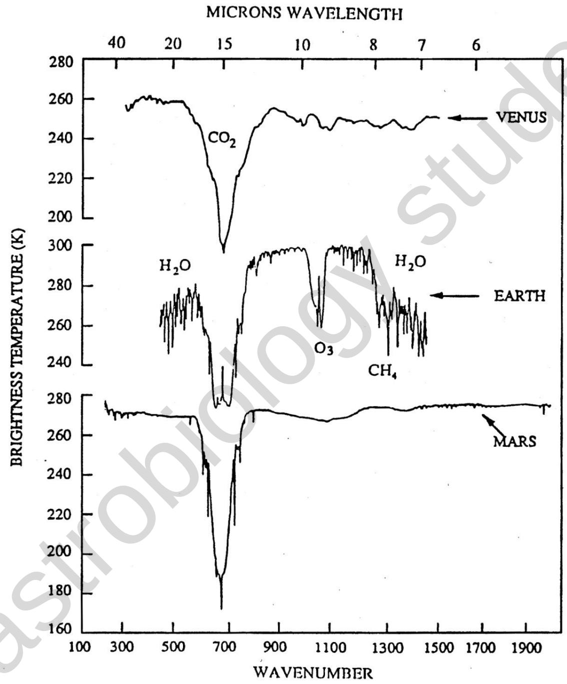


Figure 1.4. The infrared spectra of Venus, Mars, and the Earth. While the two former reflects a chemistry in equilibrium (i.e., a high entropy state), the Earth's spectrum shows chemistry out of equilibrium (i.e., a low-entropy system).

This statement, and the whole enterprise of the attempt, can seem very atheistic. However, one has to have in mind, that all we try to clarify is how does life differ from non-life. Not why and from where did it come, or who or what made it; just the simple question: "how do we identify that something is alive". Where are the pitfalls in this question? In order to ask ourselves for example the question "is there life elsewhere in the Universe, outside the Earth?", we need to know what we mean by life; we need to know what precisely we are looking for, before we can expect to possibly find it. This was one of the major problems and big surprises in the famous search for life on Mars by the two Viking missions in 1976. The questions the robotic laboratories on-board Viking were programmed to ask in the analysis of the Martian surface soil, were not focused enough on what the mission thought they were looking for, and the answers were therefore not clear either – were there life on Mars? NASA's official answer to this question was never more precise than to say that the Viking mission gave no clear evidence for the existence of life on Mars.

Another common pitfall in the interpretation of life, is the belief that it is contradicting the second law of thermodynamics. This common misunderstanding arise from forgetting that the second law is an idealised law. It strictly applies only to one system in the Universe: the whole Universe itself. It is often forgotten that the second law says that *in a closed system* the entropy will always increase. Strictly speaking there are no other closed systems than the Universe itself. Therefore attempt (5) above for a definition of life, takes into account that an organism can only be alive when it is interacting with its surroundings. Decrease of the entropy in a closed system (one that doesn't interact with its surroundings) would have been in conflict with the second law of thermodynamics, but local decrease of the entropy in an open system (i.e., one that interacts with its surroundings) is not in conflict with the second law of thermodynamics, as long as the sum of the entropy in all the interacting systems is increasing. Think for example of yourself being sealed into a closed box with no exchange of energy, air, food, and other substances, with the surroundings. You would not continue to be a living entity for long, in complete agreement with the description of closed systems by the second law of thermodynamics.

Definition (5) above is not sufficient for describing life. Statements about metabolism, evolution and reproductions are all likely additional requirements, but definition (5) does contain fundamental physical properties of life that the previous 4 statements don't, and it is likely to touch on some of the most fundamental aspects of life that are necessary for us in order to look for it outside the Earth.

When I think of a living organism in terms of entropy, I envision for my eye a kind of a generalised water-mill where energy is flowing from higher forms to lower forms (i.e., entropy is growing), and during the flow the mill-wheel is turning, producing negative entropy for the mill. The mill is the living organism; the turning wheel the mechanism that makes is work (i.e. reduce its entropy, or live). As long as energy flows through the mill-wheel, it produces life (i.e. negative entropy, or information content). We live basically on the flow of energetic photons (visual light with a low entropy content) from the Sun which we slowly transform to lower energy photons (i.e. infrared radiation with a higher entropy content). The plants build up high-energetic molecules like sugar and oxygen from the solar energy (and CO_2) it absorbs, and manages the total entropy budget by radiating heat. Animals gain energy from using (eating, breathing) the high-energetic products produced by the plants (i.e., using the solar energy, or low entropy, stored by the plants) and releasing it as high-entropy infrared radiation (heat) from their bodies and high-entropy waste products (stools and exhaust gases, methane and CO_2). The generalised water-mill (life) is therefore powered by the stream of energy transformation toward higher and higher entropy forms of energy (and not by consumption of energy as food declarations erroneously try to convince us; the total amount of energy we take in is always equal to the total amount of energy we give away; only the entropy changes in the process). When we search for potential places with extraterrestrial life, we therefore need to have in mind that it is not energy that has to be available, it is (negative) entropy.

1.5 The search for low-entropy systems outside Earth.

The experience from Viking taught us that in order to look for alien life, we will have to look for a more fundamental feature of life than the metabolic processes Viking was testing for in the Martian soil. The now canceled Darwin and TPF missions (sci.esa.int/home/darwin/ and planetquest.jpl.nasa.gov/TPF/) would have looked for large scale low-entropy features on planets around other stars, as signs of life, and the coming E-ELT (http://www.eso.org/public/teles-instr/e-elt) and other next-generation giant telescopes will do the same from the ground. Table 1.1 compares the atmospheric composition, surface temperature, and atmospheric pressure (at the surface) of the planets Venus and Mars, the moon Titan, and the Earth (including one estimate of what these quantities would have been if there had been no life on Earth). These are the (only) four solid

	Venus	Mars	Titan	Earth with life	Earth without life
CO_2	96.5%	95%	0.01 ppm	0.03%	98%
N_2	3.5%	2.7%	82-99%	79%	1.9%
O_2	traces	0.13%	0.0%	21%	0.0%
Ar	0.007%	1.6%	$< 1 - 6\%$	0.9%	0.1%
CH_4	0.0%	0.0%	1-6%	1.7 ppm	0.0%
H_2O	0.01%	0.006%	0.0%	1%	
$T_{surface}$[°C]	456	-53	-179	13	240-340
$P_{surface}$[atm]	90	0.007	1.5	1	60

Table 1.1. The relative abundance of common gases in the atmospheres of Earth, Venus, Mars, and the Saturn-moon Titan, as well as the temperature and gas pressure at their surfaces. For the Earth is given the present, measured values as well as one estimate of how the atmosphere could have looked like if there were no biological activity on the planet.

bodies in our solar system with an atmosphere. Fig. 1.4 shows the corresponding near-infrared spectrum of the three planets. It is seen from the table and the figure, that Venus and Mars have an atmosphere in chemical equilibrium – a high-entropy atmosphere in the most probable state of chemical composition. The Earth, on the other hand, has a non-equilibrium chemical composition of its atmosphere – i.e., a very unlikely chemical composition, or an atmosphere in low-entropy state according to Eq. 1.7. The Earth reflects a planet affected by widespread life according to definition (5) above of what life is (or a living planet if one wants to take the definition very literally).

If an atmosphere with the composition of the Earth was left to itself, it would soon reach a chemical equilibrium where the oxygen would disappear, due to reactions with the solid surface, and where the methane (CH_4) was gone too, due to the chemical reaction

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{1.9}$$

In order for the Earth to contain the measured amount of methane listed in Table 1.1, it is necessary to pump 10^9 tons of methane into the atmosphere per year. The non-equilibrium CH_4 content says nothing about the process that produced the CH_4, as we will discuss further in connection with possible life on Mars, but on Earth it is mainly CH_4 producing bacteria that are responsible for the non-equilibrium pumping of CH_4 into the atmosphere.

1.6 The possible role of comets for the first life on Earth.

Life as a concept is intimately connected to entropy and the second law of thermodynamics, and life as we know it on Earth is intimately connected to the existence of water. It is therefore now a general belief that the two basic chemical conditions we want to look for when we search for life outside the Earth, are:

- Do we see traces of large-scale chemically non-equilibrium processes ?
- Do we see indications of the existence of liquid water ?

We have already discussed the first item above, and we also discussed why water is essential for life as we know it, for example that the biological cell membrane cannot exist without water inside and outside the cell. Although the membrane is a double layer of lipid molecules, you cannot take it in your hand and look at it like any commercial membrane; it is an interaction between the lipid molecules and the water on both sides of the wall. If the water was gone, also the membrane would be gone. If we can obtain good infrared spectra of planets outside our solar system, we will be able to judge whether the atmosphere is in a state of chemical non-equilibrium, and we will be able to judge whether water is abundant on these planets.

However trivial and common knowledge it is for all of us that oceans, rivers, and rain exist on Earth, it is somewhat surprising that non of us know where it came from. It is therfore also not know how common water is on Earth-like exoplanets, or whether it exist at all, and we do not know whether life came to the Earth together with the water (i.e., had a cosmic, extra-terrestrial origin) or it originated in the water on the Earth (i.e., had a terrestrial origin). It is very puzzling that in the region where water can exist in liquid form on the planetary surfaces (the terrestrial region) water cannot condense out of the proto-planetary nebula to become part of the original planetary environment, while in the region where water can condense and become an intrinsic part of the planets and moons (i.e. in the region of the gas-planets), it is too cold for water to exist in liquid form on the surface – and yet life seems to be intimately connected to the existence of liquid water.

We have already seen in the chapter about the origin of the solar system, that the inner part of the proto-solar nebula where the Earth accumulated material, was too hot for water to condense into solid material; and hence too hot for water to become part of the planet Earth. We also see today that water (in the form of hydrated minerals) only exist in the bodies in the outer asteroid belt (the C-type asteroids), and not in the inner belt (the S-type asteroids). Liquid/solid water by itself can form only at Jupiter's distance and beyond. The major part of the solid core of Jupiter is water-ice, and as large a fraction as 50% or more of several of the moons of the outer planets (Jupiter, Saturn, Uranus, and Neptune) in our solar system, is water-ice. The bodies further out (comets) are mainly ice. We do understand why these bodies contain so much water (just simply because the water molecule is very abundant in cosmos, so as soon as the physical conditions are right for it to condense and form solid particles, it will be a major fraction of solid bodies), and we do understand why the inner planets practically do not have water. We do not, however, understand why the Earth have some water, even though it compared to the objects in the outer parts of the solar system is a very small fraction (only 0.02% of the Earth's mass is water, in spite of water being one of the most abundant molecules in the Universe). Where did it come from, when it could not condense out of the cloud that the rest of the Earth condensed out of ?

It is very difficult to answer this question by looking at the Earth itself, because the huge level of geological and biological activity the Earth harbours in itself erases the evidences related to the Earth's early history. Fortunately, the Earth has a geologically and biologically inactive appendage – the Moon – which contain extensive information about our (the Earth and Moon) common early history – a huge source of information that has yet only been scratched over the surface (one simple example: it is likely that coming expeditions to the Moon will find kicked off pieces of the Earth from regions that no longer exist on the Earth itself, potentially even from regions as old as 4 billion years or more).

From theoretical considerations that we discussed in the chapter about the solar system formation, we expect that the planetesimals in the Earth's region of the proto-solar nebula fairly quickly grew to lunar size bodies. At this size there were no more dust to accumulate inside the Hill sphere each planetesimal could accrete material from. There must have been 100 or more such bodies in the region of the present Earth, and gravitational interaction must slowly have made their orbits more elliptic, and with time (some tens of millions of years) they must have collided and thereby formed the Earth. It is believed that the Moon was created from the mantle and crust of the Earth, due to a collision between the Earth and a Mars-sized object. The reason that we believe that the Moon formed in this way, and not just represent one of the leftover lunar sized planetesimals, is that the Moon does not have the same composition as the bulk of the Earth (as we would expect if it was one of those planetesimals that the Earth is made of). Instead it has a composition very close to the Earth's mantle, apart from being depleted in volatiles. We can understand these similarities and differences between the Earth and the Moon, if the collision took place after the core-mantle separation in the Earth had taken place, such that it was mantle material that was expelled at the collision, and the disrupted material was heated such that the volatiles disappeared into space before the pieces had re-assembled to form the Moon. The water must have come to the Earth after this collision, because water near the surface would have evaporated, and possible water prior to core separation at $\sim$4.4 Gyr – 4.5 Gyr ago would have been destroyed by reaction with the hot metallic iron by

$$Fe + H_2O \rightarrow FeO + H_2 \tag{1.10}$$

The Moon is covered with craters, so the Earth-Mars-like collision cannot have been the last collision that took place. The same kind of objects that formed the lunar craters must have formed craters on the Earth during the same period, but on our active Earth none of these craters remain today. Knowledge about these collisions may hold the key to understand the origin of the water on Earth, and hence may also hold important information about the origin of life on Earth. However, it is not as straightforward to figure out what caused the lunar craters as one should maybe think. Was it leftover pieces from the solar system formation process? Was it the last pieces from the assembling of the Moon after the Earth-Mars-like collision? Or was it a later event decoupled from the planetary formation itself, and in that cases was it then (dry) asteroids or (water-rich) comets?

We can with good probability exclude that it was a terrestrial phenomenon, alone because we see a quite similar crater distribution on the Moon, on Mars, and on Mercury (and on Venus when one takes into consideration the effect of the dense atmosphere). In principle one should be able to figure out whether the craters were associated to the formation of the solar system or to a later event just by dating them. The Apollo mission did this, but gave us a very unexpected answer: All the craters have the same age – very close to 3.9 billion years (say, between 3.95 and 3.80 Gyr). However, the Apollo missions also showed us that the upper 200 km of the Moon melted after the first lunar solidification, and formed a liquid magma-ocean of ferroan anorthosite, which we now see as an almost homogeneous composition of the solid lunar surface down to this depth. The oldest powder-like material we find on the lunar surface is 4.42 Gyrs old and of this composition. Obviously, there was a very heavy bombardment prior to 4.42 Gyrs ago, which melted the upper part of the Moon, but 4.42 Gyrs ago it had weakened enough in intensity that the outer most crust could again solidify.

The astronauts did not find impact melts older than 3.95 Gyr, so none of the craters are older than this age. Therefore either the bombardment before 3.9 billion years was so heavy that no whole-rock is left from that period; no single piece of rock, but only the 4.42 billion years old "powder" of pulverised regolith that the astronauts found lots of. Or, alternatively, the craters we see today are the result of a *Late Heavy Bombardment* that took place in the period from 3.95 to 3.8 billion years ago with asteroids and/or comets, long after the original bombardment had decayed away.

It is easiest to understand the Earth's oceans as water from comets if there was a late heavy bombardment. Models inspired by our knowledge of migration of giant exoplanets have shown that if Jupiter and Saturn migrates over a resonance, it would disturbed the whole population of comets in the outer solar system, thereby perturbing thousands or millions of gigantic ice-blocks on collision course with the inner planets. One can estimate the amount of collisions with Earth by counting the number, $N(r,t)$, of craters on the Moon as function of age and size. If we assume that the size distribution of crater formation is independent of time and we assume that the total impact rate declines exponentially with time, then

$$N(r,t) = N_0(t_0)\, r^{-\alpha}\, exp[-(t-t_0)/\tau] \tag{1.11}$$

where $N_0(t_0)$ is the flux at time t_0, r is the measured crater radius, τ is the half life of the levelling off in the impact rate, and α is a constant to be fitted from the crater counting (together with the fit to τ). The total area of craters made per unit surface area per unit time, at time t, is then

$$A(t) = \int_0^{r_{big}} N(r,t)\pi r^2 dr \tag{1.12}$$

where r_{big} is the radius of the largest crater being produced. The probability $P(t)$ of finding rocks of a given age t can then be computed as

$$P(t) = N_0(t_0)\, exp\left(\frac{-(t-t_0)}{\tau}\right) - A(t_0)\,\tau\, exp(\frac{-(t-t_0)}{\tau}) \tag{1.13}$$

While in principle one should be able to estimate from Eq. 1.13 whether there was a late heavy bombardment, the age determination of different regions of the Moon that can be used to determine τ and α are too uncertain to allow for an answer. Some authors have estimated τ = 30 million years and $\alpha = -2.8$, while other authors find τ to be as large 150 million years. Extrapolating backward in time with a small value of τ will give a very large impact rate at the time prior to 3.9 billion years ago. The value τ=30 Gyr is small enough to produce so much impact before 3.9 Gyr ago, that no whole-rocks would have been left from that period, and consequently $P(t)$ is very small for t before 3.9 Gyr ago, and there will be a peak in $P(t)$ estimated

Identification	age [Gyr]	crater density	impactor mass [kg]	ejecta mass[kg]	D_f [km]	E_{impact} [Joule]
Oldest lunar dust	4.42					
South-Pole Aitken	$\sim$4.1		$1.4\,10^{19}$	$2.4\,10^{20}$	2200	$1.2\,10^{27}$
Oldest Apollo/Luna melt rock samples	3.92					
Mare Nectaris	$\sim$3.90	$\sim$16				
Mare Serenitatis	3.89					
Mare Crisium	$\sim$3.89					
Mare Humorum	$\sim$3.89					
Mare Imbrium	3.85 ± 0.02	$\sim$4	$1.7\,10^{18}$	$2.9\,10^{19}$	1160	$1.4\,10^{26}$
Mare Orientale	$3.80-3.85$		$8.1\,10^{17}$	$1.4\,10^{19}$	930	$6.8\,10^{25}$
Schrödinger	$3.80-3.85$					
Youngest Mare basalt	3.80	$\sim$1				

Table 1.2. Estimated age, relative crater density, impact mass, etc, of some lunar basins, from several sources.

from Eq. 1.13 at 3.9 Gyr ago, even though there were more impacts before that time. This would indicate that we have had a continuously declining impact flux, and hence the impacts were most likely related to the formation of the planets (and therefore ”dry rocks” according to our consideration in the chapter of the solar system formation). The highest suggested values of τ, on the other hand, only leads to a peak in $P(t)$ at 3.9 Gyr ago if there also was a peak in the impact flux at that age, and therefore predicts a (strong) late heavy bombardment (which may have been dry stones from the inner asteroid belt or water-rich comet-like objects from outer parts of the solar nebula, or any mixture of such objects).

While the relative crater chronology can be well estimated from relative crater counts, the absolute chronology that enters the formulas above, is dependent on determination of some absolute ages. These are usually taken from the Apollo radiogenic age estimates, but due to landing security considerations, the landings were limited to relatively restricted areas on the front side of the Moon, and the sharpest criticism of using these data, claims that all the melts brought back by the Apollo astronauts in principle could be from one and the same event, namely the impact that created the Mare Imbrium basin. Table 1.2 shows some age estimates and other data for the most important basin areas.

In order to compute the amount of material that has impacted the Earth and the Moon since their formation, two different approaches have successfully been followed. In one approach, one use empirical data, mainly from bomb explosions, to estimate the relation between the impacting mass (kinetic energy) and the resulting crater diameter. Such relations allow to transform the crater density estimates on the Moon described above to impact mass flux on the Moon. The impact mass flux on the Moon is then transformed to impact mass flux on the Earth, by considering formulas like those we used to estimate the Eddington accretion rate in the chapter about the solar system formation (leading to the Earth having a 24 times larger gravitational capture area than the Moon, and being able to capture objects at larger speed, and statistically a number of even larger bodies than those that created the mare-basins on the Moon). In an alternative approach, one tries to estimate the amount of chondritic material that would be needed in order to explain the abundance of highly sidrophile elements in the crust of the Moon and the Earth. The very sidrophile elements (such as iridium) would have followed iron into the core during the core-mantle separation. The amounts of these elements one finds in the Earth/Moon mantles, can therefore be attributed to collisions with chondritic-type asteroids, or chondritic-type dust-containing comets, at a later stage. In both of these two independent methods, one reach the conclusion that approximately 10^{20} kg of cosmic material must have hit the Moon after its solidification, and approximately 10^{22} kg must have hit the Earth. As described above, this impacting mass could have been leftover material from the formation of the Earth which had not yet been accreted by the time the core and the mantle separated, or it could be a late heavy bombardment. If it was a LHB, some theories predicts it to be related to the time of formation of Neptune and Uranus, and their perturbation of left over proto-ice blocks. If there originally were $600\mathrm{M}_\oplus$ of ice in the Uranus-Neptune region (one estimate), and if a fraction 10^{-6} of the perturbed objects hit the Earth (a common estimate from the literature), it would have resulted in 4×10^{21}kg (largely of water-ice), or close to the same mass estimate we found above from crater counting and from mantle abundances. This number is approximately 3 times the present mass of the ocean ($M_{ocean} = 1.4 \times 10^{21}$kg). A similar estimate is reached by assuming that the outer planets migrated such that Jupiter and Saturn passed over a resonance. Depentent on the exact resonance passed, the passage would perturb asteroids and/or comets.

It is interesting to notice in passing, that because of the larger gravitational field of the Earth, these formulas tells us that the impact energy per surface area of the Earth has been approximately 20 times higher than on the Moon at any given time. With an exponential decay in the impact flux, the impacting energy on Earth has therefore always been as it was on the Moon 3 half lives earlier ($e^3 \approx 20$). If the lunar crust was kept melted by impacts until 4.4 Gyr ago, the Earth's crust will therefore have been constantly re-melted until 4.4 Gyr - 3$\times\tau \approx$ 4 Gyr ago, or until approximately the age of the oldest piece of crust known on Earth today.

It is important to understand that a high-energy cosmic impact is an explosion (that is the reason for why craters are circular). If the kinetic energy of the impact is high enough, the kinetic energy will almost instantaneously transform the impacting body as well as some of the surrounding planetary/lunar material to vapour. In the highest energy impacts, the explosion and evapourization will be so violent that the mixture of vapourized impactor and target will form a plume of gas and solid particles that may raise with velocities higher than the escape velocity. When this happens part or all of the impactor material (plus some of the surroundings) will return into space and only part (or nothing) of the impacting material will remain in the surface material of the target body. The standard formulas for the energy required to form an escape-velocity plume, assumes that half of the impacting energy dissipate in the forward moving shockwave into the ground, and half goes to vapourize the impactor and an equal amount of surrounding target material. If the energy left after subtracting the energy to vapourize the material is larger than the kinetic energy required to accelerate the plume (of vapourized material) to above escape velocity of the target body, the material will escape back into space.

Whether a cosmic collision will send material back into space therefore depends on a combination of the velocity of the impactor and the esacpe velocity of the target body. High velocity impactors on small targets will return lots of material back into space, while low velocity impactors on large mass targets will add their impacting material onto the target body. It happens to be so that the velocity distribution of impacting asteroids and comets combine such with the mass of respectively the Earth and the Moon that a considerably amount of cometary material will escape back into space after a conmetary collision while lots of asteroid material will mix into the surfaces on asteroidal collisions. Comets come from further out in the solar system than asteroids, and therefore have higher impact velocity (on Earth and Moon). In fact the velocity of comets is so high that each comet collision on the Moon will reduce the total mass of the Moon rather than increasing it. The only remnant of a cometary impact on the Moon is the crater, nothing of the cometary material is left, and some of the surrounding lunar material will have escaped in the plume too. On Earth some of the cometary material will stay on the surface (due to the Earth's higher gravitational field). In contrast the lower velocity of impacting asteroids will leave some of the asteroid material mixed into the surrounding surface on the Moon (as well as on the Earth).

In order to create a vapour plume that expands with more than the escape velocity, obviously the impacting energy must exceed the energy required to evaporate the impactor (and other material to be included in the plume) plus accelerate this mass of material (plus the atmosphere above the plume in case of the Earth) to above the escape velocity. Since both the energy of vaporisation and the density of material is different for comets and asteroids, the minimum speed, v_{min}, they need to hit with in order to bring plume material above the escape velocity is also different for the two:

$$\begin{aligned} v_{min}^{moon} &= 11\mathrm{km/s} \text{ for asteroids, and } 7 \text{ km/s for comets} \\ v_{min}^{\oplus} &= 25\mathrm{km/s} \text{ for asteroids, and } 23 \text{ km/s for comets} \end{aligned} \quad (1.14)$$

Adopting the velocity distributions from today's Earth crossing asteroids and comets, one can calculate from Eq. 1.14 that on the Moon approximately 50% of asteroids and 100% of comets will create super-escape velocity plumes, while the corresponding numbers for the Earth are 10% and 50%.

These numbers can be used to first qualitatively resalising that a bombardment with asteroids will leave traces of the impactor's material on both the Moon and the Earth, while a cometary bombardment will leave material only on the Earth, not on the Moon. The most pronounced trace element of cosmic material is iridium. On Earth (and the Moon) all original iridium from the formation mixed with iron and sank into the planetary core. The present day upper crust of the Earth has an iridium abundance of 20 ppt (part per trilion; i.e. only 20 out of each 10^{12} atoms in the crust are iridium atoms), while the Allende meteorite has 560,000 ppt iridium. Mixing of only small amount of Alende-like material with the Earth's crust therefore easily reveals the impactor. It was in this way that scientists first realised that is was a cosmic impact that extincted the dinosaurs 65 million years ago. The lunar surface show no overall trace of iridium from cosmic impacts (< 10 ppt) while rocks on Earth from the time of the lunar crater formation (the LHB) show a factor 7 enhancement in iridium abundance compared to present day crustal values. Cometary impacts would leave such a difference in chemical trace between the terrestrial and lunar surfaces, while a bombardment with asteroids wouldn't.

Assuming that the LHB impactors were comets would allow to scale the measured iridium abundance in the Erath's oldest existing crust to how much cometary material must have hit the Earth during the LHB. The calculated value is in agreement with the value that one reach from summing up the mass that is needed to make the lunar craters and scale this value to how much material will have hit the Earth. The value is somehow mindblowing high. The LHB is the most violent event that has happen in the history of the solar system after the planetary formation itself. Each square meter of the Earth's surface was hit by 2000 tons of cosmic material during the late heavy bombardment period. In passing we notice that if this was cometary iceblocks, they will have delivered approximately the amount of water that exist in present day oceans on Earth. Does this mean that the oceans formed from cometary impacts during the LHB? There are very diverged opinions on this issue, mainly positioning most of the geological community with a clear "no" and most of the astronomical community with an equally clear "yes". One of the main arguments that traditionally has been put forward against the theory that our oceans come from comets is that the D/H ratio in the 3 comets that had been measured prior to 2011 were a factor 2 higher than the value in present day ocean water, as shown in Fig. 1.5. In late 2011, however, a fourth comet, Hartley 2, was measured, and it showed a D/H ratio identical to the D/H ratio in Earth's ocean water.

The mass of the cap of atmosphere above and tangentially to the side (which can be eject if the impact is plume forming, i.e. have a sufficiently high impact velocity) is

$$m_{cap} = 2\pi P_0 H R_\oplus / g \tag{1.15}$$

where P_0 is the terrestrial surface pressure, H is the scale hight (present value 8.4 km), g the gravity, and $R_\oplus$=6371km is the radius of the Earth, which leads to m_{cap}=3.5$\times 10^{15}$kg for the present day atmosphere. From the crater counting (Eq. 1.11) and its transformation to impactor masses, we can estimate how many impacts had masses larger than, say, m_{cap}. The result is that since 4.4 Gyr ago, 13000 impacts have had a mass large enough to potentially remove m_{cap} of the Earth's atmosphere. If these impacts were asteroids, only 10% (or 1300) of them would cause plumes (according to Eq. 1.14), and hence create atmospheric erosion, while if the impacts were comets, 50% would have been plume-forming, so 6500 cometary impacts would have eroded each m_{cap} of the atmosphere. Simple summation of these numbers, say 3000 impacts of 3.5$\times 10^{15}$kg, would give a total atmospheric erosion of 10^{19}kg or approximately twice the mass of the present atmosphere ($m_{atm} = 5.3 \times 10^{18}$kg). This order of magnitude estimate makes it likely that the original atmosphere will have been lost completely, and what we see today is the result of volatiles from later impacts. Assuming that comets are 50% chondritic material and 50% ice, makes it possible to scale the amount of chondritic (i.e., strongly sidrophile) material in the Earth's mantle to estimate how much volatiles have come together with the comets. This calculation shows us that not only could the comets have delivered the oceans, but they have also contained gases enough that the nitrogen content (i.e., all the non-biological part of our atmosphere), could have been a release from late cometary impacts.

Venus and Titan would have been bombarded with a similar amount of comets, delivering the same amount of N_2, which is what one sees, while Mars would have lost most of its cometary impact volatiles together with the rest of its atmosphere, due to its low gravity.

Remark that the detailed composition of comets is unknown. It is a general belief from popular and semi-popular literature that all comets are made almost completely of water-ice. However, the ices in comets

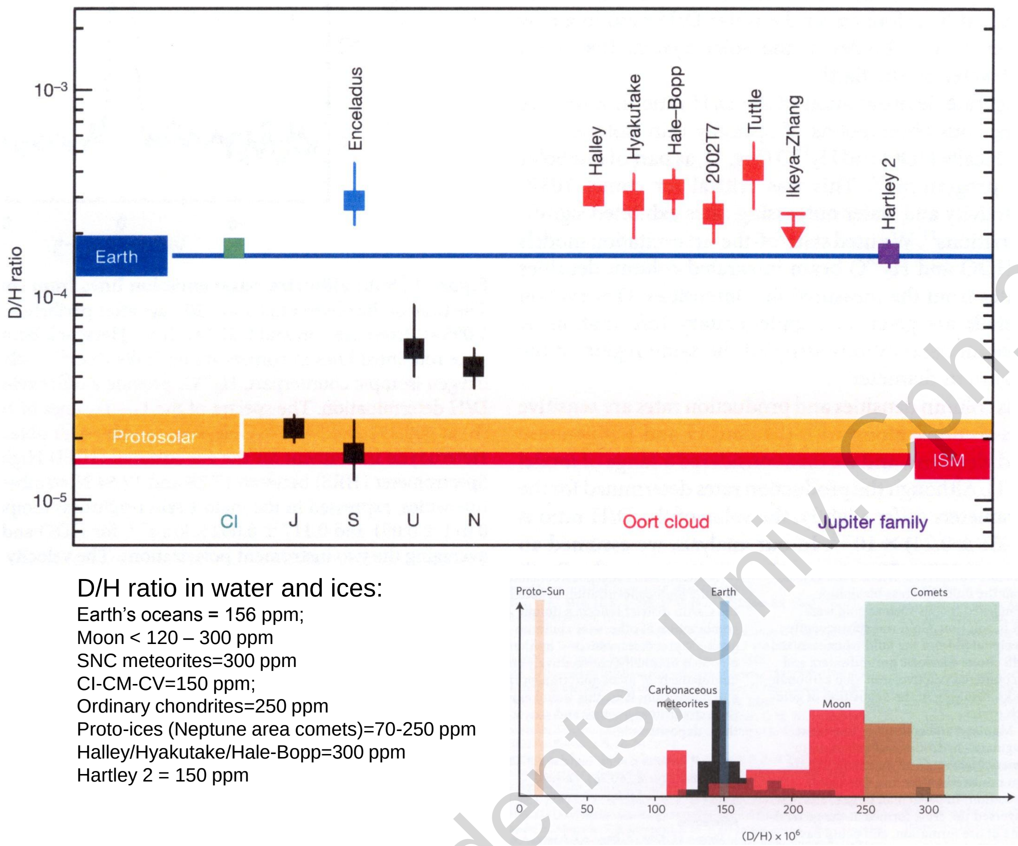


Figure 1.5. The deuterium to hydrogen ratio, D/H, in ocean water ("Earth") compared to various cosmic sources.

are a mixture of H_2O, CO, NH_3, and CH_4 ices (those relative abundances depend on the type of comet), and the ratio between solid material and ice probably vary as much as a factor 100 from comet to comet. Estimates of the ice-to-dust ratio in comets can be done (only) from determining the gas-to-dust ratio in evaporated material, and the full range of values from 1:10 to 10:1 has been found in different comets. While the size distribution of the evaporated dust-particles are well confined by measurements, the composition of the dust is only poorly known. It is therefore usually assumed that the dust is of carbonaceous chondritic composition. However, in situ measurements of the dust particles in the coma of comet Halley showed that only approximately half of the dust particles can have been of this composition, while the rest appeared to be some organic composition of H, C, N, and O. For the kind of magnitude estimates we discuss here, it will, however, usually be a good enough approximation to assume that comets are composed of 50% water-ice and 50% carbonaceous chondritic material.

If the water came from comets (or carbonaceous chondrites), it has very exciting consequences for the origin of life on the Earth. Comets formed in low-temperature regions of the solar nebula. Here large organic molecules have much better conditions for forming than in the hot region where the Earth formed. The primitive carbonaceous chondrite Murchison is by some people believed to be the remnant of a comet, while others believe that it is an ordinary carbonaceous chondrite with many similarities to cometary material. Inside Murchison we have been able to identify several amino acid molecules. These building blocks of the living cell is described in detail in the associated book scan and above, and we will just repeat here that the amino acid molecules are the constituent of the proteins, and proteins are the dominant constituent of the living cell, next after water. Proteins in any living organism on the Earth are build from the same 20 amino acids, independent of whether it is a flower, a tree, a mushroom, a human being, a blackbird, or what-so-ever living organism. This in itself points to all living organisms on Earth coming from the same uhr-cell. An exciting aspect in relation to life's possible origin outside the Earth, is that Murchison contain at least 11 of the 20 amino acids that is the backbone of all living organisms on Earth. Living organisms use only one cherality (i.e., symmetry form) of amino acids, but Murchison contain approximately 50% of each symmetry amino acid molecules. The Murchison amino acids are therefore not biologically, but they may have formed important building blocks for the formation of the first life on Earth. Even more surprising than the existence of the amino acids, is perhaps that also 3 of the 5 "letters in the gene alphabet" were raining over the Earth together with the cometary water 3.9 billion years ago – if this is what cometary water did. The genes are sequences on the DNA molecule, those information is transported into the cell by the RNA molecule to instruct how the proteins are to be assembled from the amino acids. The molecules that carry this information in the DNA and RNA are the nucleotide-bases as described in detail in the associated book scan and above. There are only 5 different in total in DNA and RNA. Three of them have been identified inside Murchison.

1.7 The geological periods, eras and eons.

We have discussed in a preceding chapter, the origin of the Earth and the solar system. We know with very good precision (in fact one of the best and least model dependent determined ages in astrophysics) that the parent bodies of the meteorites separated into a siderofile and a lithophile part (i.e., a core and a mantle) 4.567 billion years ago. There are all reasons and many good arguments indicating that this was the time all the major planetesimals in the solar system formed, including the planetesimals which were about to become the Earth. Within 100 million years after this event, more than 99% of the present Earth had assembled, the Earth had separated into a core and a mantle, and at approximately shortly after the Moon formed out of material from the Earth's crust and mantle. There are no traces left from this time on the Earth, but the oldest dust on the lunar surface is ≈ 4.42 Ga old. This leave us the possibility of one day finding a piece of Earth this old on the Moon, as a terrestrial meteorite, just like we find lunar meteorites on Earth. The oldest pieces of solid material on Earth, from the Earth itself, are zircon minerals 4.3 billion years old. It is debated whether these represent inclusions from the first solid crust on Earth or not.

The oldest piece of preserved, full crust whose age determination is generally accepted in the community, is the Isua Greenstone belt north-east of Nuuk in Greenland. This 40×4 km mainly sedimentary geological region is 3.8 billion years old. It bears clear evidences that the Earth had an ocean (or at least a substantial region covered with water) at that time. Carbon (graphite inclusions) in sediments from Isua shows a photosynthetic isotopic $^{13}C/^{12}C$ ratio, in clear contrast to the isotopic composition of carbon in lunar rocks of the same age, which we believe have never been exposed to biological processes. The oldest direct evidences for life are the 3.5 billion years old stromatolites, which are believed to be bacterial sediments. An optimistic view on when life originated on Earth, would therefore say, ”right after the crust solidified and the worst cosmic bombardment was over". This is based on the argument that since we do not know rocks older than 3.8 billion years, and since there are traces of relatively advanced (i.e., photosynthetic) life in these, life must have been present almost from the very beginning. A more conservative view could claim that we do not have secure evidences of life older than 3.5 billion years, which is almost 1 billion years after the Earth assembled itself, and this might therefore be the time scale for the first living cells to have developed. Our present knowledge about the origin of life is therefore that once the physical conditions are in place it may happen within ”a split-second" (in geological timescales), or it may take much longer, or it may never happen.

The oldest "real" fossils are much younger than 3.5 billion years. They were first found in large amounts in mountains in Wales which are approximately 570 million years old. From the Latin name for Wales, Cambrium, the period in Earth's geological history where the Walisic mountains formed, is therefore known as the Cambrian period. Seen from a biological point of view, the Cambrian period represent a really astonishing development of life, as we will discuss in a little while. Due to the central importance of the Cambrian period, the whole history of the Earth is often divided into the pre-Cambrian period, the Cambrian period, and the post-Cambrian period. Because we find fossils from the Cambrian period and after, but never from the pre-Cambrian period, we of course know much less about the development of life during the pre-Cambrian period than what we know about the biology during the latest 570 million years. The multicellular lifeforms that developed in the Cambrian period are so much closer related to us than the pre-cambrian organisms, that all our intuitive, daily-life, layman feeling of the development of life on Earth, probably relates only to this limited period of 0.6 Ga only.

The geological times (Fig. 1.6) are divided into three main periods (eons):

- hadean eon, the period from 4.6 billion to 3.8 billion years ago
- archaean eon, the period from 3.8 billion to 2.5 billion years ago
- proterozoic eon, the period from 2.5 billion to 570 million years ago
- phanerozoic eon, the period from 570 million years ago to the present day.

The two absolutely most important changes in the history of Earth's biology, are almost identical to the two major divisions in the Earth's geological periods. The dividing line between archaean and proterozoic time marks the appearance of free oxygen in the atmosphere (and hence in biological terms the appearance of aerobic life forms), while the Cambrian period, which starts on the division line between the proterozoic and the phanerozoic geological epochs, in biological terms marks the invention of the skeleton and the solid shells, as opposed to the non-fossilizing organisms from the pre-Cambrian period.

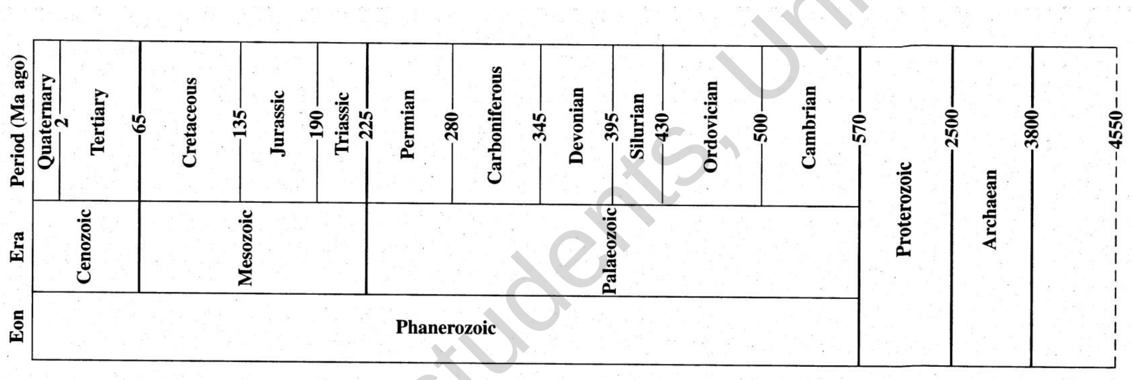


Figure 1.6. The geological periods, eras and eons in the history of the Earth.

1.8 Was "Snowball Earth" the reason for biology's most giantic leap forward?

During the Cambrian revolution animals appeared on Earth. Life took the gigantic leap from unicellular organisms to multicellular eukaryotic organisms like our selves. It is not clear what was the reason for this gigantic step forward in complexity, but one theory is the so-called Snowball-Earth. It was a gigantic global freeze down of the Earth, followed by an equally gigantic heat-up of the Earth, all-in-all lasting about 100 million years. The basic evidences for these dramatic climate changes are rapid and global changes in the chemical composition of Earth's geological sedimentary layers. Up to the beginning of the freeze down 700 million years ago, the $^{12}C/^{13}C$ ratio in sediments change from a biologically affected ratio to the pure geological ratio observed in volcanic gasses. Life seems to rapidly have died out over most of the globe, while a strong cooling sets in. During the global glaciation period, sediments starts showing pure iron minerals, indicating that the ocean became strongly depleted (or maybe even absent) in oxygen. During the end of the glaciation about 600 million years ago, sediments show minerals that will form under an atmosphere many-fold enriched in CO_2 compared to the present value. Studies of the orientation of magnetic minerals, shows that the magnetic field was horizontal on all continents.

A possible explanation that could make sense out of the unusual sediments from these peculiar 100 million years of Earth's history, is a scenario where all the continents lie close to equator (after the breakup of the large preceding single continent) at the same time as the Milanchowich cycle would normally indicate the beginning of a strong ice age. If the position of the land masses had been dominated by vicinity to the poles (as today) or more equal distributed over the globe, the low albedo of the oceans compared to the land, would have secured that the equatorial region stayed relatively warm, and ocean circulation would have prevented the full globe from being covered with ice. Water would still evaporate from the ocean, and rain would bring CO_2 out of the atmosphere onto land where it would erode land masses and bring carbon-rich sediments into the subduction plates, where it would melt and come back into the atmosphere as CO_2 again. When all the land-masses were close to equator, snow due to the decreasing temperature would increase the albedo, which would lower the temperature further, which would increase the percentage of land covered in snow and ice further, etc. The increased rainfall after the breakup of the single continent (and consequently more coastlines and snowfall) would increase rain-out of CO_2 from the atmosphere. More and more ice-covered land, would decrease land erosion, and therefore bring less CO_2 back into the geologic atmospheric cycle. As a result, the albedo would increase and the greenhouse effect would diminish, with the result that the surface would cool further. Eventually part of the oceans would start to freeze, hereby increasing the albedo even further and lowering the water evaporation to the atmosphere. The Earth would have went into an irreversible positive feed-back loop that would bring the whole Earth surface into a new deep frozen state. Model calculations indicate that the new equilibrium would establish itself at a surface temperature of around $-50°$C, with the ocean frozen from the surface down to more than a kilometer's depth. Below this, heat from the interior of the Earth would still keep the ocean liquid.

Basically all life would die out due to the low temperature and due to the lack of oxidation of the water. The only place that life would survive would be around hot spots at the ocean bottom and maybe around a few volcanoes. After long time, accumulated internal heat from the Earth would eventually have to escape through volcanic eruptions, and large amounts of CO_2 would again be pumped into the atmosphere. Due to the global ice cover, the atmosphere would have basically zero humidity, and the CO_2 would quickly build up to large concentrations (there would be no rain-out of CO_2 and no planets to convert the CO_2 to oxygen). A thousand fold increase in the CO_2 abundance would finally make the surface temperature increase enough to melting the ice-cover, which would bring the Earth into a new feed-back loop; this time decreasing the albedo while the ice disappears, thereby increasing the temperature, thereby increasing the atmospheric water-vapour content, which would increase the temperature further. Sedimentations indicate that this positive feed-back loop brought the global surface temperature up around 50°C, before rain-out of the CO_2 and renewed erosion and sedimentation from the exposed continents, renewed photosynthesis and volcanic CO_2 re-circulation, finally brought the Earth back on the balance we know it today.

Organisms that might have been resistant to the freeze down, would probably eventually have been driven to extinction during the successive heat-up, and when it all was over, most of the Earth's life would have gone extinct. In fact this situation might not have been fundamentally different from the extinction of life on Mars (if it is extinct, and if it ever arose). On Earth, however, active volcanoes and relatively stable conditions close to hot black smokers at the bottom of the ocean, might have saved life from going completely extinct. The tree of life will have been "pruned" (i.e., most species – "the branches of the tree" – will have died out), and this may be the explanation that the eukaryotic part of the tree looks like a long bared trunk, corresponding to its first 1.5 billion years, with a crown of branches at the top. It looks like a puzzle that the eukaryotic cell seemingly only developed into single-celled organisms (amoebae) during its first 1.5 billion years of existence, and then suddenly constructed all the basic multicellular lifeforms we know today within a timespan of only a few million years during the Cambrian explosion. The explanation may be that it didn't. That many forms of maybe more and more complex multicellular lifeforms developed during the first 1.5 Ga, but that they all died out during the snowball-Earth period (but if this is correct, it is still puzzling that none developed solid fossilable structures as they did during the Cambrian explosion). When the situation was finally over, most of life's niches were open to re-population, and all the basic structures of higher life forms we know today arose during the re-filling of the niches.

1.9 The increasing oxygen abundance in the atmosphere

During the earliest period of the Earth, the radioactive heat from the interior was 3 times larger than now. This will have triggered a higher level of volcanic activity. The reaction between basalt and iron in the oceans will have released hydrogen, which in the beginning will have escaped to space, but later will have been captured by biologically released oxygen, which will have reacted with the hydrogen to form water molecules. Free iron will have existed in the oceans together with traces of sulfur compounds and nitrogen, which will have absorbed any free oxygen that might have been in the oceans. The atmosphere itself might have been rich in CO_2, with some N_2, no oxygen, and traces of HS and H_2, but other possibilities are open too, like a more methane (CH_4) dominated early atmosphere.

The dominant life form during archaean time was the cyanobacteria (called so because of its blue-green cyano colour, and previously also called the blue-green algae although it is really a bacteria and not an alga). It is the precursor of the photosynthesis in modern plants, because of its ability to use the visual light from the Sun to break the bonds of oxygen with hydrogen and carbon, to form carbon compounds. It will have fixed carbon in its body, which slowly will have reduced the CO_2 content of the atmosphere, and released oxygen to other reactions than CO_2. Most of the carbon will have returned to the atmosphere from volcanoes or via biological processes in other organisms. Precipitation of calcium-carbonate excreted by billions and billions of cyanobacteria will, however, have formed large sponge-like structures, growing from the bottom of the waters where they lived, and now seen as stromatolites – the oldest known solid structures interpreted as being due to life forms.

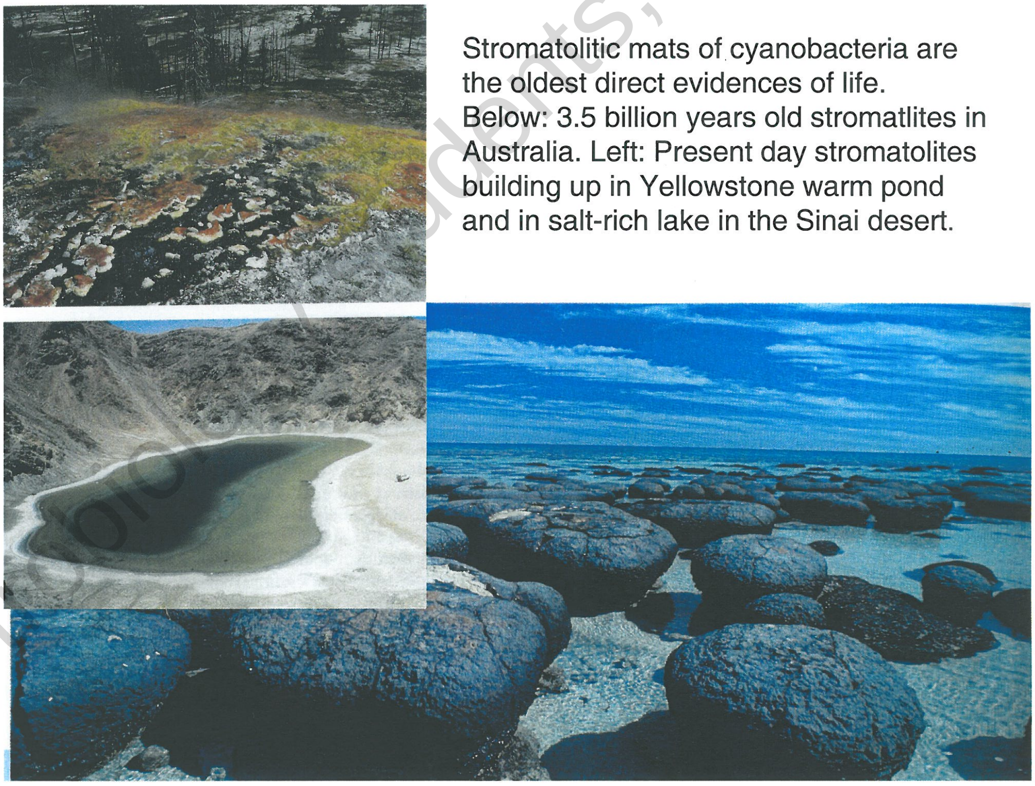


Figure 1.7. Photo of 3.5 billion years old stromatolites.

During most of archaean time, cyanobacteria had used sunlight to split atmospheric CO_2, using the carbon to build up organic material, and releasing the oxygen as molecular O_2. So far the released oxygen had been absorbed by free iron and other reactives in the ocean (and atmosphere), but sedimentation shows that by the end of archaean the environment was saturated with oxygen. From now on the oxygen released by the cyanobacteria could no longer be absorbed in the oceans. During a transition period of less than a million years, the abundance of free oxygen in the atmosphere increased from basically nothing to maybe as much as 1% of the atmosphere. This remarkable change in the chemistry of the Earth initiated a completely new period in Earth's history, which is called the proterozoic time.

For us, oxygen is a vital element, but for most of the organisms that lived on the borderline between archaean and proterozoic, oxygen was a highly reactive, dangerous, poison. A tremendous change in life forms and lifestyles must have taken place during this transition period – maybe the most dramatic transition ever for life on Earth. What used to be a brownish smog-like atmosphere with the smell of a septic-tank over a brownish-red ocean, slowly cleared up and became the blue planet we know today, with oxygen-rich, fresh (for us) air. For some organisms the changing environment has been the worst possible obstacle, for others a tremendous new opportunity. Darwinism has been at work in its most extreme during this time. Aerobic and anaerobic bacteria have most likely existed for quite some time when proterozoic began. Cyanobacteria and other anaerobic bacteria have been the dominating species on the globe. Aerobic bacteria have undoubtedly populated niches close to the oxygen releasing cyanobacteria colonies, where they have benefited from the released oxygen, while the cyanobacteria have benefited from the aerobic bacteria cleaning up their pollutants (oxygen), just like most bacteria function in the environment today. It is likely that the near surroundings of cyanobacteria colonies have been relatively abundant in oxygen, just as the organic mould (Danish: muldjord) today is 10 to 40 times more abundant in CO_2 than the present day atmosphere.

When oxygen became more abundant in the atmosphere, the already existing aerobic bacteria thrived better, and could spread freely into larger areas of the globe. The anaerobic bacteria, on the other hand, were forced to withdraw to regions where the oxygen couldn't reach. The aerobic bacteria became the dominant species, while the anaerobic bacteria from now on were forced to live in niches. For the anaerobic bacteria it was the largest *pollution catastrophe* in history. For the aerobic bacteria it was the biggest *pollution opportunity* in history.

The last few decades of research have made it clear that the anaerobic bacteria far from died out. In remote places far from the atmospheric oxygen, organisms independent of oxygen will dominate. These places could be in rocks kilometers below the surface, or at deep sea. We would regard such environments extreme compared to our daily surroundings, and term organisms living there extremophiles. But also much closer to us do we find anaerobic conditions. For example, our own body is crucially dependent on a symbiosis with anaerobic bacteria in our intestine system. Without these inhabitants in our body, our digestion system would refuse to function. Without us the bacterial colonies in our intestines would be exposed to oxygen and dissolve. We call such a mutually beneficial co-existence a symbiosis. An even more intricate symbiosis is the one between each of our cells and the mitochondria. The mitochondria is a true descendant of an ancient anaerobic bacteria, which at some point in life's long history was adopted into an eukaryotic cell, and became an independent part of the eukaryotic cell. The mitochondria is capable of storing energy (as explained in more detail in the previous chapter about the cell and basic biological concepts) for use by the rest of the cell, and it has its own independent life inside our cells, with its own DNA and its own independent reproduction. We do not know how the mitochondria entered the modern cell, but a likely explanation could be so-called phagocytosis, which is the closest one cell can come to "eating" another cell. A large cell forms a pocket in its cell wall, where it encompasses a smaller cell. By closing the pocket it becomes part of the interior of the large cell, and releases the smaller cell. Some small cells have specialised in entering and attacking larger cells by getting into them this way; e.g. tuberculosis and leprosy bacteria. A cyanobacteria family can have managed to, or even specialised in, entering larger oxygen-consuming bacteria via their phagocytosis digestion system, survived in the large cell, and developed a symbiosis with it. Without our cells the present mitochondria would die from the oxygen pollution, but without its refuge in our cells, our cells would be out of energy. It's the most intimate form of symbiosis we know of.

Life showed its enormous force by surviving over the archaean-proterozoic boundary line. But not only did it survive, it developed into new complexities never seen before on Earth. For some reason, cells adopted to oxygen surroundings can grow larger. Living cells from archaean times, were relatively simple structures with only one membrane around the whole cell. Such cells are called prokaryote. The cyanobacteria were

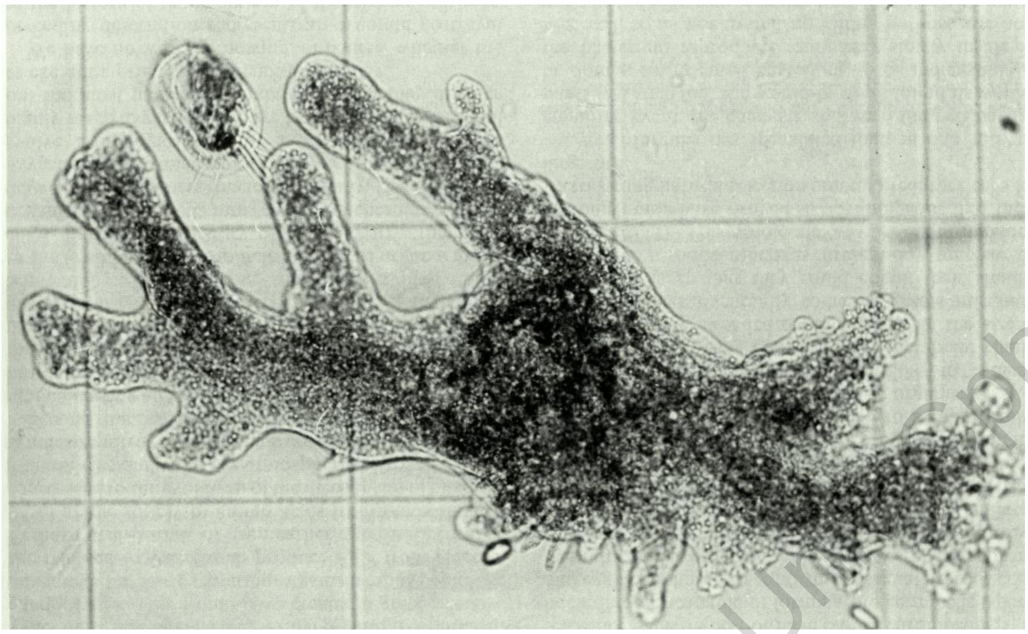


Figure 1.8. Phagocytosis – an amoeba is incorporating (or "eating") a bacteria by closing a pocket of its cell wall around the bacteria, and later resolving the cell wall.

prokaryotic organisms. Each cyanobacteria was a single little cell with no internal organisation. Its DNA and other functional molecules were floating around inside the same cell wall. The new cell-structure – the eukaryotic cell – that was able to develop in the oxygen-rich atmosphere during proterozoic time, was larger and therefore had room for more complexity. In the eukaryotic cell the genetic material of the cell is encapsulated in its own internal cell structure, the mitochondria has its own domain, and of uttermost importance is that eukaryotic cells are able to collaborate in large communities where each cell although keeping information about the whole structure, at the same time performs a specialised function in the community. Such a community with internal labour distribution includes what we now call an animal or a plant. It didn't exist during archaean time.

It was long believed that life on land cannot have appeared before the cyanobacteria in the ocean had increased the atmospheric oxygen abundance to a level where oxygen molecules (O_2) in the stratosphere would dissociate (due to solar ultraviolet radiation) and form a sufficiently dense ozone (O_3) layer to prevent the UV radiation from the Sun to reach the surface of the Earth. However, many bacteria can sustain quite high levels of UV radiation (by forming a shield), and can have populated the continents already during archaean times. Second, some ozone might have formed from photo-dissociation of water. Finally, the methano-bacteria which lived from the waste products from the cyanobacteria colonies, probably released a substantial amount of methane, which can have been dissociated by UV radiation in the stratosphere and formed an absorbing layer of methano-aerosols with the same effect as the present day ozone-layer; forming a temperature inversion by heating the stratosphere, blocking the UV radiation for the lower atmosphere, and made the early Earth appear as a smoggy brownish-red planet like present day Titan.

A by-product of the increased oxygen abundance is that things can burn. The higher the atmospheric oxygen abundance is, the easier material starts burning (ignited for example during a lightening). The free oxygen abundance in the atmosphere will have been close to zero until the end of archaean where it started increasing. At oxygen abundances below 15% even the driest brush wood cannot catch fire. Charcoal is regularly identified in sediments as old as 200 million years, but not before that time, indicating that the oxygen abundance reached 15%, 200 million years ago. Today we measure it to 21%. At oxygen abundances above 25% even the wettest rain forests will be self-igniting. Hence, the atmospheric oxygen-abundance is today close to its maximum possible value.

1.10 The increasing salinity of sea-water.

Another increasing quantity during the early Earth, was the salinity of seawater – the content of dissolved salt in the oceans. The ocean water probably was almost fresh when the first oceans formed sometime between 4.5 and 3.8 billion years ago. With time rain has eroded the continental crust, and brought dissolved particles into the sea. Fresh water evaporates from the ocean, rains down over the continents, and brings water back along the rivers into the ocean, enriched in crustal minerals, and also volcanic eruptions add minerals and other compounds to the oceans. Some of these minerals are salts, i.e. crystals which typically are resolvable in water, where they exist as positive and negative ions (e.g. Na^+ and Cl^-). Of particular high poisonousness is the positive calcium ion from such dissolved salts. The concentration of calcium ions in present day sea water is approximately 10,000 times higher than the concentration that would be deadly poisonous if it was in our cells. Neutral calcium, on the other hand, is harmless to our body, and most large animals today avoid the calcium ions by storing away calcium in solid (neutral) form in the skeleton and the teeth. Smaller organisms have since the Cambrian period, likewise stored away calcium in the form of shells, which we can now find as fossils and sedimentary rocks. Even during archaean time, cyanobacteria deposited calcium in the form of calcium carbonates, forming a major deposit to the coastal sea floor.

However, the salinity of sea water is mainly ($\approx$75%) the abundance of NaCl, which is approximately 50 times more abundant than calcium salts (and 10 times more abundant than the second most abundant salt, MgCl). We do not know what the salinity of the archaean or proterozoic ocean was, but obviously the salinity must have increased over the geological time scales, when more and more material has been eroded from the continent and washed into the ocean, and the present value is surprisingly high for living organisms. We measure the salinity in molar concentrations. The most salty regions of the Earth's oceans (not counting such peculiar locations as the Dead Sea, but only regular ocean) are 0.68 molar. I.e., that 0.68 moles (= $0.68 \times 6 \times 10^{23}$ molecules) of salt is dissolved in each litre of the water. Since the most common salt, NaCl, has a molar weight of (23.0+35.5) atomic units per molecule, 0.68 moles weigh 40 gram, and therefore 0.68 molar salt-water is approximately the same as saying that 4% by weight of the ocean water at the most salty places, is salt. A fully saturated solution of NaCl in water contain 13% salt.

The water in our body, and in almost all other living organisms, including most fish, is only 0.16 molar (=9.3g salt per litre of water, or 1% salt in the water by weight). At around 0.8 molar concentration, the cell-structure of almost all living organisms would dissolve, because the electrical forces which keeps the individual lipids in the cell membrane aligned and fixed to one another, would be disturbed by the ionic electricity in the salt solution, and dissolve. The most salty regions of the ocean are therefore very close to the salinity which would prevent living organisms from existing.

It somehow is a surprise that the salinity of the water of almost all animals on land as well in the sea, is the same. Even such peculiar animals as the Artemia shrimp which lives in saturated salt water, has a salinity in its interior of 0.16 molar. Some biologists take the homogeneity of salinity among most animals, to indicate that we all originated from bacteria with this salinity, and that the value is the one the ocean water had when the first life originated. While such arguments seems valuable with respect to the identity of proteins in all living organisms, and the identity of nucleotides in DNA and RNA of all organisms on Earth, the validity of the argument is more questionable with respect to salinity. Probably the identical salinity of 0.16 molar in most organisms on Earth, rather reflects that living cells function optimal at salinities around this value. Further support to this interpretation is that there do exist rare species with other salinities; most extreme is the group of extremofile bacteria which is called halofiles (i.e., salt-tolerable bacteria), which can survive extreme salt concentrations. They have built a particular membrane structure which is not destroyed by extreme salt-concentrations, but the cost is that they are very fragile in any other environment, and their existence are completely dependent on the environment sustaining a delicate balance in their niche.

Whatever is the reason for the big discrepancy between the salinity of ocean water and body water, it requires an enormous amount of energy for animals living in the ocean to sustain this difference in interior water salinity from the surrounding seawater. Smaller organisms solves the problem by producing so-called sulfur- and nitrogen-betainer, which substitutes the ocean salt with electrically neutral salts, which are not poisonous for the cell. 15% of the dry-weight of algae near the coast are betainer. Obviously, an enormous fraction of the energy to all the living activities and processes that these organisms have, is used just to be able to survive the high salt content of the present day ocean water they live in. Larger animals have invented an osmotic pump to keep the salinity constant at 0.16 molar inside the body, independent of the ocean salinity; again of course at an enormous cost of energy – for example the pressure required for a whale to pump water against the osmotic pressure is about 1000 times the human blood pressure. If the salinity of sea water keeps increasing, there will be a time in the future where life as we know it, can no longer exist in the oceans. A highly relevant astrobiological question concerning the tidally heated water-rich moons of Jupiter and Saturn therefore concerns the salinity of their water. Is it of a value such that lipids can form cells ?

1.11 On the limits for life ?

During the period from the first early life forms arose until now, the solar luminosity has increased with 40%, but geological evidences seems to indicate that the surface temperature of the Earth has been constant. A possible mechanism that can have been responsible for this ”homeostase” is the continuous reduction of CO_2 (and possible CH_4) abundance in the atmosphere. Compared to the CO_2 abundances on Mars and Venus ($\approx$ 95%), the CO_2 abundance on Earth ($\approx$ 300 ppm = 0.03%) is almost zero. If this is a true ”homeostase” in the sense that the organisms on Earth have responded to the increasing solar luminosity by increasing consumption of the CO_2, then an obvious question is: ”so what now when the CO_2 is virtually gone ? – can the temperature still be constant in the geologically near future ?”.

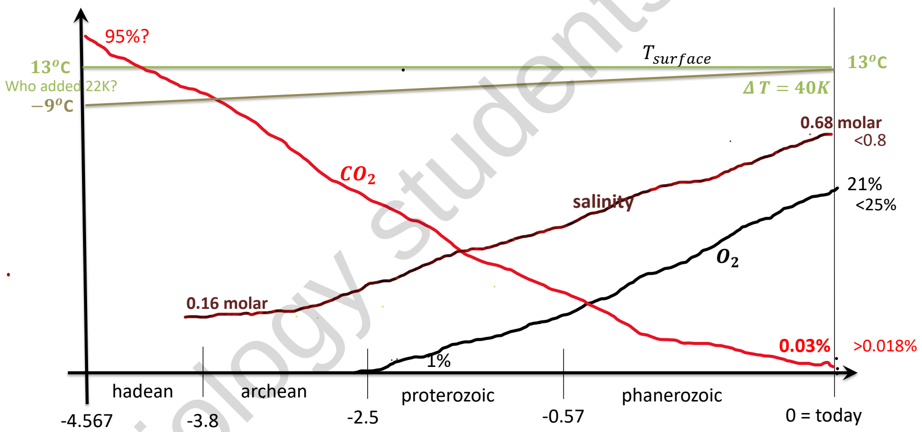


Figure 1.9. A scematic illustration of the development of temperature, O_2 and CO_2 abundances, and ocean salinity through Earth’s history. Is it natural for life to always live on the edge of the possible, or are we just about to approach ”the end”?

There are no known answer to this central question, but several possibilities. One should first notice that the ”greenhouse effect” – the ability for the CO_2, CH_4, and water vapour to absorb infrared radiation – is very non-linear. Due to saturation effects in the spectral line profiles, the energy balance of the Earth’s atmosphere is more sensitive to a decrease in the abundance of the greenhouse gases than to an increase in their abundances. If the content of CO_2 and CH_4 approaches further toward zero, even though their abundances are very small already, the cooling effect can be considerable. As discussed in connection with exoplanets, the tiny amount of greenhouse gasses in the Earth’s atmosphere has lifted the surface temperature 40°C above the value it would have had in an atmosphere completely transparent to infrared radiation (e.g. a pure N_2-O_2 atmosphere). Potentially life on Earth therefore has 40°C of cooling available yet to introduce (and additional possibilities related to the value of Earth’s albedo). Will life adjust the planet by continue to decrease the abundance of CO_2? Can life (plants and animals) survive in an atmosphere completely, or almmost, free of CO_2 and other greenhouse gasses ?

Approximately 10 million years ago, a new kind of plants arose in nature, which uses a different type of metabolism to perform the photosynthesis. The new type of plants are called C4-plants to distinguish them from the old type of plants which are called C3-plants. The C3-plants include trees and other plants with leaves. The C4-plants include some grasses but not all. While C3-plants can only survive in an atmosphere with a CO_2 abundance larger than approximately 180 ppm (the value reached during the last ice age), the C4-plants thrive well even below this value, but also at higher values of CO_2, like the present one. It would be a natural consequence of Darwinistic evolution that the C3- and C4-plants would live side by side during times with the present CO_2 abundance, but that the C4-plants would survive better and spread when the CO_2 abundance decreases, and eventually dominate the flora if the CO_2 abundance drops substantially below 180 ppm. Hence, there is no reason to believe that life as such would die out during a further drop in CO_2 abundance, but marked differences in the flora would appear. Hence, in theory there is nothing against that the Earth's "homeostase" could be kept by reducing CO_2 for still some time. Another biological possibility for keeping the average temperature constant is that ocean algae would increase in abundance if the global temperature increased, releasing more DMS (sulfur compounds) which would rise to the stratosphere where it will tend to form microscopic sulfur acid droplets which will increase the Earth's total albedo, and thereby lower the Earth's surface temperature, which would again decrease the abundance of ocean-algae.

Somewhat surprising, we see that both the oxygen abundance in the atmosphere, and the salinity in the oceans, are mysteriously close to the upper limit of what known life on Earth can survive, and the atmospheric CO_2 abundance is equally close to the lower limit of which trees and other plants can perform photosynthesis. It is astonishing that we have almost zero understanding about whether this means that the total system of living organisms on the Earth is close to a collapse, or whether it is a healthy indication that life has a tendency to always work on the limits of the possible.

1.12 The Gaia theory.

A very disputed theory for the life on our planet was introduced in the late 1960's and further developed into the late 1980's and onward by J.E.Lovelock; a British biologist and project-scientist on the Viking mission to Mars. According to Lovelock, all life on Earth interact in a more intricate and active way than is usually assumed in ecology. In Lovelock's Gaia (the mythological Greek word for Earth) theory, biology on Earth (i.e., Gaia) interacts on a large scale in a manner that somewhat resembles the interaction of cells in a living organism like ourselves. For example, he finds that Gaia is responsible for homeostase of the Earth's surface – the concept of keeping the temperature constant in spite of changing environments, which is usually reserved to describe processes within living organisms. During the Earth's history, the Sun has (according to standard stellar evolution theories, and observations of open clusters) increased its luminosity with around 40%. Nevertheless, geological evidences seems to indicate that the Earth's surface temperature has been approximately constant during this period. Lovelock speculates that it is not a coincidence that this constant temperature has all the time been at the level which is convenient for living organisms, and ascribes it to a feedback mechanism in the biological system which assures that the chemical composition of the atmosphere, or the physical conditions of the surface, are changing such in response to the changing solar luminosity, that the surface temperature stays close to the biologically most optimal temperature. Such a feedback mechanism could for example be that the oxygen from the cyanobacterial photosynthesis exchanged the surface-heating greenhouse gas CO_2 (and methane) with the infrared-transparent O_2 in the atmosphere, in such a pace that the increasing surface temperature we should have expected on the Earth due to the increased solar heating was always closely balanced by a decreasing greenhouse heating.

In the definition (5) above of life, the whole atmosphere is maybe a living organism. Any non-equilibrium system has a lower probability than its equilibrium counterpart, and therefore also a lower entropy, or a higher information content. The atmosphere is capable of locally lowering its entropy by consuming low-entropy, high-energetic solar radiation, and re-emitting high-entropy, low-energy infrared radiation. However it is questionable in what sense it is possible self-organising. It has seemingly no information encoding like a DNA molecule, but on the other hand it is able to self-regulate in order to e.g. keep a constant temperature suitable for life – for Gaia.

Lovelock himself has indicated at several occasions that he envision Gaia as an actual living organism, but he has (to my knowledge) never given a rigorous definition of what he means by life. He does occasionally refer to definitions like (5) above, but without the demand of self-organisation. In such a limited definition of life, Gaia could probably be regarded alive, but then on the other hand also such phenomena as tornadoes, whirlpools, sunspots, and other natural dissipative systems would be included in the consept of life.

Independent of the discussion of whether Gaia is to be included in the definition of life or not, the concept has interesting ideas about how to understand life's conditions on a planet, and how to search for life elsewhere outside the Earth. In fact, although the Gaia theory is often miscredited in the community, the method that was introduced to search for life in the design of the Darwin and TPS space missions, and to be adopted in the first giant telescope search for extraterrestrial life in the early 2020'ies, (i.e., searching for large-scale non-equilibrium atmospheric signatures which could most logically be explained as a consequence of large-scale biological influences on the atmosphere) is certainly along the recommendations laid out first time in the Gaia theory by Hitchcock & Lovelock already back in 1967.

Lovelock gives a simplified example to illustrate the nature of a mechanism that could regulate Gaia's temperature to a constant level, in spite of a changing luminosity of the star it orbits. Imagine a planet with a population of only two plants, existing side by side. A white and a black species. Imagine further that both plants grow best at 20°C, and that they die at temperatures below 5°C or above 40°C. If the planetary surface temperature increases above 20°C, then the white plants survive best, because they stay slightly cooler because of their higher albedo. Therefore the population of white plants will start dominating the flora, and the planet's albedo will increase. Hereby it will cool back toward a surface temperature of 20°C. If the planet cools below 20°C the black plants fits better, because their low albedo makes them stay a bit warmer than the white ones, and again the planet will be forced back toward a surface temperature of 20°C.

Compared to the traditional "survival of the fittest" concept, Gaia predicts that life takes a more active part in the environment, by postulating that the species (i.e., the bio-diversity) is capable of manipulating the physical-chemical-geological surroundings such that they best fit life. In this interpretation, life cannot exist as a small oases on a planet (e.g., under the polar ice cap on Mars), because it needs to be world-wide and wide-span (like on the Earth) in order to be capable of regulating the planet. Coming studies of possible life forms on Mars, Europa, Titan, and other locations in the solar system will challenge this prediction.

1.13 The Tree of Life.

The tree of life is discussed in detail elsewhere in these notes. Here we will just note that the modern view of the evolution of life counts three main groups of organisms, as shown above. The two early groups are both prokaryotic life forms, i.e. one-celled organisms without any internal membranes dividing the cell into internal substructures. One of these groups are bacteria, and the other is called archaea. For the layman archaea would be very similar to a bacteria (one-celled with no internal cell structure; multiplying by simple cell division), but in particular the outer cell-membrane of the archea has more similarities with the third main group, the eukarya, than with the bacteria, and biologists therefore find that it needs a separate group of its own. Remark that animals and plants are just two specific sub-groups of eukarya, among many other eukarya organisms. All eukarya are based on the eukaryotic cell. This is a much larger and more complex cell than the prokaryotic cell. Eukarya organisms can be single-celled (just like bacteria and archaea), but even a single-celled eukarya is much more complex than a prokaryotic organism, because the eukaryotic cell has internal structure. An amoeba is a single celled eukarya. Whereas the DNA in prokaryotic cells are floating freely around in the cell, the DNA in the eukaryotic cell is inside a separate cell nucleus with a separate cell membrane where RNA strings bring the DNA information content in and out, for production of proteins in the outer part of the cell outside the cell nucleus. The eukaryotic cell has the capability of forming organisms consisting of many cells that work together. Even though each cell in such an organism contain the information about the whole organism (the complete DNA), each cell performs a specified specific task. This is the case in human beings, that consist of approximately 10^{14} eukaryotic cells working together as one organism.

Each eukaryotic cell in an animal contain several prokaryotic sub-cells which are responsible for the energy budget in the cell – the so-called mitochondria. Plant cells also contain mitochondria sub-cells, but in

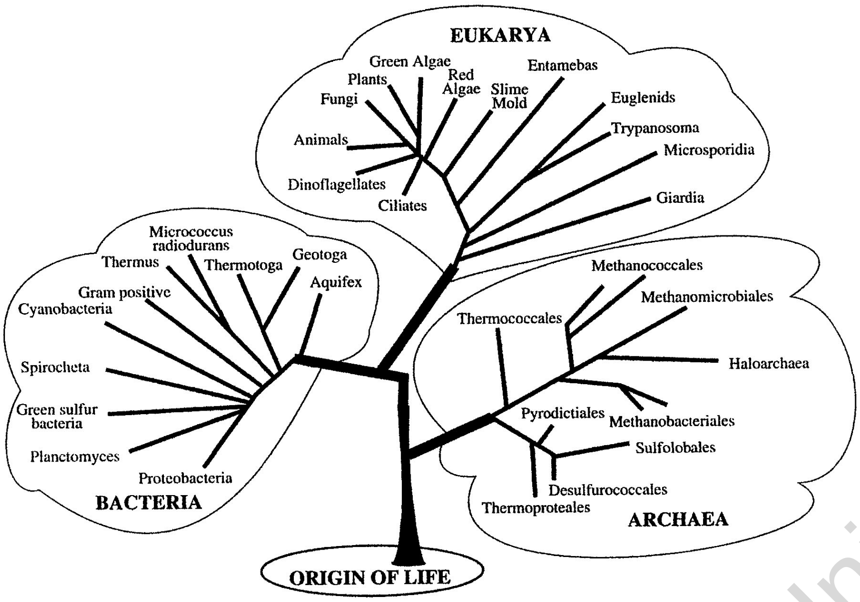


Figure 1.10. The origin and branching of life into the three main groups – the three domains – of living organism, the archaea, the bacteria, and the eukarya.

addition also chloroplasma which is a descendant of the prokaryotic cyanobacteria that is able to transform solar light and atmospheric CO_2 into sugar. In this sense the plant cell is more advanced than the animal cell.

The building blocks of the DNA molecule (the nucleotides) are identical in all living organisms, as are the building blocks of the proteins – the main biomass. This is probably the strongest argument for a common origin of all living organisms on Earth. The genetic material – in humans the chromosome pairs – consist of strings of nucleotides. A sequence of nucleotides which is able to code for a specific protein, is called a gene. 40-50 of our genes are common with all known life-forms, including present bacteria. These must have been unchanged in the 4 billion years span of life on Earth. Present human generations are about 25 years, but generations for our early ancestors covered much shorter time spans. For some bacteria a generation is shorter than one hour. Resonable order of magnitude estimates of the duration of a generation through all our ancestor spieces back to the time of the first bacteria, leads to the estimate that DNA must have been copied 10^{11} times from generation to generation in the last 3.5 billion years, to have transfered genetic information from the first bacteria to a modern human being. At least 40 genes were transscribed unchanged and without errors all of these 10^{11} successive times.

1.14 Bacteria and the early life on Earth

When we talk about life on Earth (or when we make plans about identifying it elsewhere in the Universe) we have to be careful who we think about. It is probably well known that the biomass of the insects is considerably larger than all the other animals together, including the small perturbation of 6 billion humans. But yet, the amount of insects is nothing compared to the amount of bacteria. A typical spoon full of well nourished garden mould, contain approximately 10,000 different species of bacteria (the overwhelming part of which has of course never been identified nor classified with a name), and more individual bacteria than there are humans on the globe, or even more than there are stars in the Milky Way. A liter of ocean water contain 10^9 bacteria, and there are 10^{21} l of water in the oceans, so the total number of bacterias in the oceans alone is $\sim 10^{30}$. A typical bacteria is 1 μm in diameter and weights 10^{-12} g, so the total biomass of ocean-bacterias is 10^{18} g corresponding to 150 tons of bacteria mass per human being on the globe. Bacterias are the primary inhabitant of our globe, and it is the organism that have affected the biosphere, the physical crust, and the atmosphere of our planet most among all living beings.

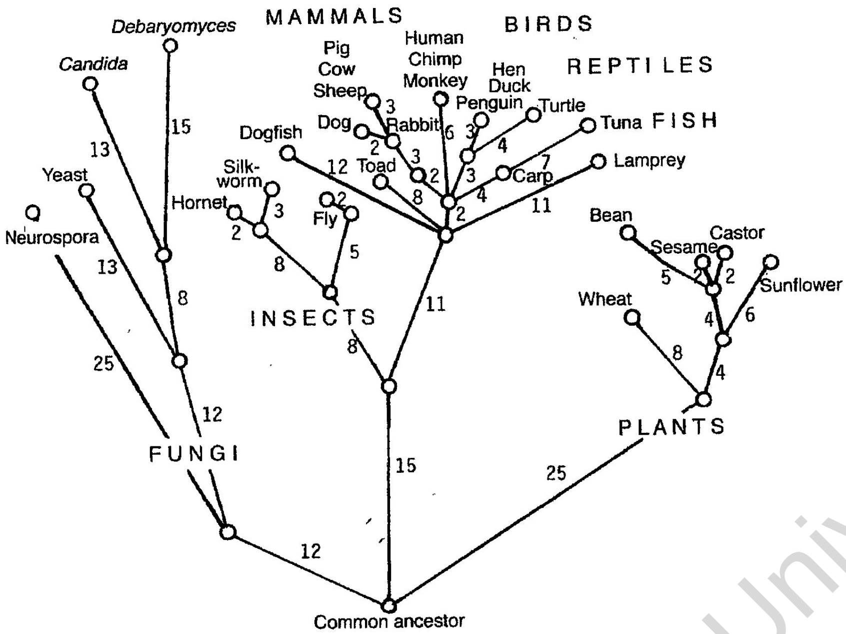


Figure 1.11. The branching of the uppermost left part of the eukarya in the tree in Fig. 1.10 into fungi, animals, and plants. Previously the word "kingdoms" was often used about animals, plants, fungi and other macroscopic morphological groups, but in particular the huge increas in knowledge about micro-organisms have called for introducing the new definition of domains illustrated in Fig. 1.10.

Nevertheless we have to be careful when we compare bacteria with "regular" animals or plants. A bacteria is a one-cell organism. Its DNA and everything else that makes up the bacteria, floats freely within the same single cell-wall (a prokaryote). An animal or a plant – "a higher organism" – is an ensemble of much more advanced cells (eukaryotic cells), where each cell in the organism has its own specialised function in the "community of cells". They form an organised structure, and the information about the organisation is transfered from generation to generation. A bacteria-cell divide with relatively regular intervals, and then it is (or they are) two bacteria. Some of the halfs divide again, and some of the halfs may perish, while some of them may merge with another bacteria cell and their common material may be enough material to divide into two new cells. Genetic material is crossed over between existing bacteria in this way, and it is not completely meaningful to talk about when the life begins and ends for a specific bacteria, just as we would have problems if we defined our birth and death based on the multiplication of our cells. In fact on average all the cells in a human body are exchanged with new ones every year, so if we were to accept to talk about the life and death of the bacteria whenever they divide into two, we would be forced to claim that we ourselves died and were re-born (continuously) every year (on average).

We are again reminded that it is not by itself meaningful (i.e., precise enough) when we claim we are looking for life outside the Earth. Life may well be a gradual change from simple chemical reactions to more complex reactions, and the emerging of more complex concepts when many entities of the simpler reactions together appear as a unity. We will discuss later the concept of emergence of complex features out of samples of simple features, or for short *emergens*. Intelligence may be an emerging concept of simple "bips" between nerve cells in the brain. Even though the brain consist only of nerve cells and their connections, we will not claim that a single nerve cell is intelligent, but many of them together, even though they are still just nerve cells, are claimed to be a new thing, an emerging concept, namely the magic intelligence. What we think of as death is not the death of all the bacteria our body is composed of, but somehow the ending of the ordered collaboration between them, and thus of the emergens that was the result of this structured communication. Maybe even life itself in our intuitive understanding of the word, is basically the emerging concept of many cells working together. If this is true, then our intuitive understanding of life – the way we use the word

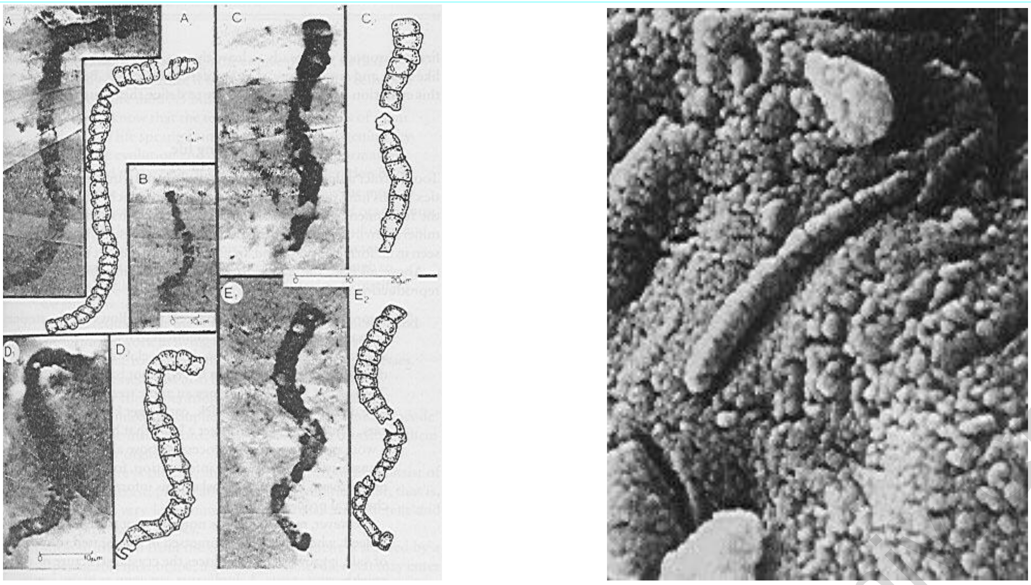


Figure 1.12. Imprints of 3 billion years old bacteria structures on Earth (left panel) and a possible imprint of an early bacteria on Mars, in the Martian meteorite ALH84001 (right panel).

when we talk – is different from the biological understanding of the concept life, and limited to what biology defines as eukarya or a subgroup thereof (Fig. 1.10).

The basis for the rise of multicellular organisms, and in its uttermost consequence intelligence, was pollution. As we saw above, the first bacteria on Earth – cyanobacteria or blue-green algae – lived from absorbing nourishment from the surrounding. A bacteria has no digestion channel, but contain enzymes which can dissolve nourishment from the surroundings. During the consumption of nourishment, bacteria produce oxygen, just like the plants today. However oxygen is very reactive, and once the oxygen content in the atmosphere had increased beyond about 1%, the cell walls of the original bacteria will have been destroyed by reactions with this oxygen. The bacteria couldn't survive the existence of their own waste – they had polluted the atmosphere beyond a tolerable limit. A more elastic cell wall developed in the oxygen-rich environment, and a radical new kind of organism appeared, the eukaryotic cell. This is the cell type all higher organisms are build from. The eukaryotic cell was the first predator. It was able to eat and digest a whole bacteria. This invention became the golden egg for further evolution; both the development of the eukaryotic cell and the survival of the old bacteria. Whichever way it may have happened, a prokaryotic bacteria with its well functioning energy producing machinery took home in an eukaryotic cell, and the oldest known symbiosis developed. All present cells consist of eukaryotic cells with prokaryotic internal cells, now called mitochondria. While the prokaryotic cell delivers the energy to the eukaryotic cell, the eukaryotic cell delivers the necessary protection against oxygen to the prokaryotic cell. This is the oldest, and very important, symbiosis between organism – a binding collaboration of vital importance for both parts.

But the eukaryotic cells have more abilities than this. Their space allow them to combine in organised structures, where each cell type specialises in different functions. Our own body contain 10^{14} eukaryotic cells, and 800 times more prokaryotic cells inside them. As many cells as there are stars in a million galaxies. In our own body some cells are blood cells, some are nerve cells, and other are skin cells, etc. Although each cell is a holistic picture of the whole body, in the sense of containing all the genetic material for the whole body, the cells are of different types that have specialised in specific functions of our body. It is the ensemble of this system of specialised cells with each their function, which together makes up the human body. When the organisation begins, the organism is born, and when the organisation breaks down, the organism dies, and in this sense the concept of birth and death doesn't really exist in a one-cellular prokaryotic bacteria. Although it may be fascinating, even mind-breaking, if spectra of planets around other stars will show a low-entropy (chemical non-equilibrium) atmosphere, we might be a bit humble with proclaiming that we found

”life”.

1.15 From Bacteria to Fish to Amphibians

In spite of all the questions above to what we mean when we say *life*, we will normally with full confidence say that the first kind of organisms were bacteria (or archea), and evolution with time transformed exactly these into wonderful organisations or complex multicellular cells we can intuitively recognise as life, and sometimes even talk to and/or communicate with. The first eukaryotic organisms were very small. Maybe they were in the beginning just single-celled (like present-day amoebae), but they may also, as far back as more than a billion years ago, have developed a kind of a miniature of all the animals which should later arise. Then, at the beginning of Cambrium something very drastic, never seen before in Earth’s history, suddenly happened. In a geologically very short period around 550 million years ago – maybe as short as just 10 million years, but no longer than 70 million years – all the major groups of animals we know today suddenly appeared on the stage. Often this period is called the Cambrian explosion. From this time on the Earth was populated with animals which, for the first time, left their trace as fossils. These are the first of such things our intuition would call life – ”macroscopic things that crawl around”. There are today 11 known animal body plans, and they all appeared during the short time of the Cambrian explosion, including the groups of annelids (”ledorme”), medusa (”gopler” i.e., jellyfish = ”vandmænd”), echinodermis (”pighuder”) (e.g. starfish=”søstjerner”), arthropods (”leddyr”) (e.g. crayfish=”krebsdyr” and insects), mollusc (”bløddyr”) (e.g. snails=”snegle” and bivalves=”muslinger”; the English word mussel refers to a particular bivalve which in Danish is called “blåmusling” and not to “muslinger” in general), and most interesting for us a type called chordate. The largest subgroup of chordate is the vertebrates (”hvirveldyr”). Vertebrates evolved to include mammals (”pattedyr”), and hence us. The oldest chordate fossil is 530 million years old (from China).

It is not really known what was the reason for the Cambrian explosion. Maybe it was a consequence of the high oxygen content the atmosphere had reached, and maybe it was the first introduction of sex, which (as opposed to the full gene-pool mixing of bacteria) speeded up the evolutionary principle, but maybe even more likely it was connected to the “snowball Earth” described above. In the latter case it would be in agreement with the general idea of Darwinistic evolution, that biological development mainly takes place under environmental stress. According to the snowball Earth theory, the freeze down of the Earth around 700 million years ago, and the succeeding heating, represent the strongest and most rapid climate change that has appeared ever in Earth’s history, and only a tiny fraction of life on Earth survived the environmental stress it created, but when it was over, the evolutionary tree had been “pruned” and the few surviving life forms had all niches open to expand into. From our point of wiev it became one of the most fruitful developments in all of Earth’s evolutionary history. Agin it was surprisingly “just right”, in the sense that it was strong enough to revolutionise life, but just not so strong that it destroyed life. Is this “normal” in the universe, or was it peculiar to Earth? We don’t have even the slightest clue to the answer to this central question, but it seems that on Mars the environmental swings were too large for life to survive, and if a Moon-sized moon in a Moon-like orbit combined with large (and small) enough distance to Jupiter was essential to get “just the right” climate change (only) once in Earth’s history for life to take its great leap, then at least it is not likely to have happened in many exoplanetary systems.

Already the first colonies of loosely connected cels may have developed some kind of ability to transmit information between the cells, but the first chordats had actual nerves, and a little clump of nerve-endings in one end of the body – the first tiny beginning of a brain. The Chinese chordate also had light sensitive cells which registered the difference between dark and light and transmitted the signal to its tiny brain. It was by no means an eye, and not constructed to form a picture, so nerve-cells and veins were on top of the light sensitive cells. Later on when the light sensitive cells slowly evolved into a regular eye, able to form a picture, this “unfortunate beginning” of the construction (with the light sensitive cells being beneath other cells) became a problem, and today our eye has to constantly move to register the shadows of the overlaying nerves and veins in order for the brain to subtract their shadows, and form the picture we think we see. The ancestors of the octopus happened to begin the evolution of light sensitivity the opposite way; the light sensitive cells were on top of the nerves and veins, and the octopus therefore has an eye that doesn’t need compensation by the brain in order to form a picture. Therefore the octopus has a much more efficient eye than we have, in the snese of needing much less brain processing in order to register the same image.

The first chordats were tiny fish, who ate microorganisms by straining them off water floating in through the mouth and out through the skin. Later this became gills ("gæller") that gave oxygen to the larger fish, and when they needed extra oxygen they swallowed a mouthful of air through the mouth, which was then taken up by the blood from an extension on the intestine which later developed to lungs.

Around 360 million years ago some fish had 4 legs with 5-8 toes on. They probably walked in low water among roots; their legs were not strong enough to walk on land. They might have humped up on land to put their eggs in security for other fish. The land was only inhabited by insects, plants, and snails – but don't misinterpret this: millipedes ("tusindben") could be two meter long, and dragon flies ("guld-smede") could easily be the size of seagulls ("måger"). About 320 million years ago the "four-legged fish" had developed into the first amphibians ("padder") – the first vertebrate on land.

1.16 From Amphibians to Reptiles and Mammals

About 320 million years ago the first fish invaded the land. These were four-legged fish which developed into amphibians ("padder"). From them, the first reptiles ("krybdyr") developed with a skin which could better keep the water inside the body, and who laid eggs in which the embryos ("fostre") had their own moist, isolated ecosystem to develop in, independent of the ocean.

About 300 million years ago a branch of the reptiles developed into synapsides, the proto-mammals (="proto-pattedyrene"). They had scale ("skæl") and were cold-blooded as many other reptiles, but during the next 40 million years the synapsides developed into the dominant among the vertebrates ("hvirveldyr") on Earth, counting from horse-big to mouse-small species, herbivores ("planteædende dyr") and predators ("rovdyr"; carnivore are specifically mammal predators; "pattedyr der er rovdyr").

At the transition between the two geological times Perm and Triassic (palaeozoic and mesozoic) 245 million years ago, however, a violent event drew 90% of all sea-animals and 80% of all land-animals, to extinction within less than 1 million years. The reason could have been an asteroid, but it could also be connected to climate changes due to the merging of the then two existing continents into only one.

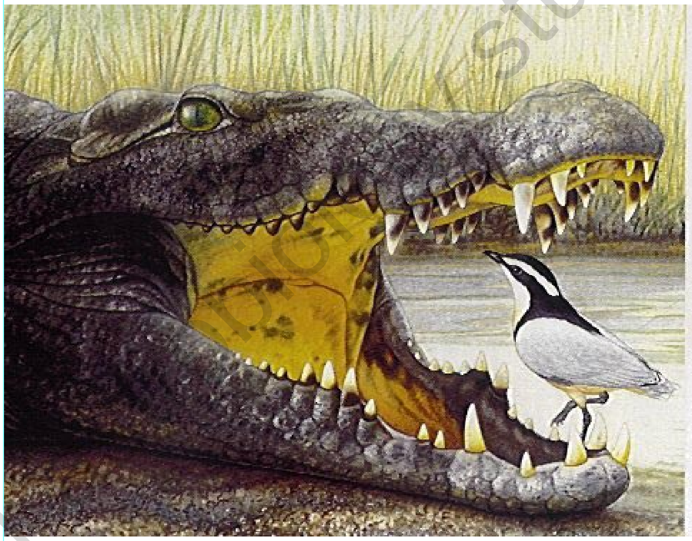


Figure 1.13. The teeth of a cold-blooded reptile are good for keeping the prey ("byttet"), and eventually for tearing it into big pieces, but it is useless in assisting the digestion. For warm-blooded animals, teeth that can chew are necessary in order to bring the speed of digestion up to a level that allows the body to stay warm.

Only few animals survived, and the Earth's fauna was very poor with only very few species for the first 10 to 20 million years after the extinction. Among the synapsides, the dog-sized cynodont (cyno=dog, dont=tooth) was among the few that managed well, and it can in some sense be regarded our first direct ancestor, because it slowly developed characteristics of the first mammals. Its skeleton shows it had whiskers (”knurhår”), which probably means that it had fur, which again probably means that it was warm-blooded (or better mono-temperature blooded), as opposed to the cold-blooded (or better alternating-temperature blooded) reptiles. Since also the branch of reptiles that soon should develop to become the giant dinosaurs, had managed well the catastrophe 245 million years ago, small synapsides that could better hide would survive better, and preferably those that could be out during the night when the big reptiles slept because of their cold-bloodednes. Therefore the next 150 million years didn't see synapsides larger than a rat, and only warm-blooded ones could have their night-life. However, 80% of the energy from digestion of our food goes into keeping our body at 36-38°. In other words, a reptile the same size as a mammal requires 5 times less food, and while a reptile can survive well without food for several days, a mammal will start freezing without at least daily food. Whether, and when, at least some of the dinosaurs developed warm-bloodednes is still a question of debate. Paleontologic evidences suggest that oviparous (”æglæggende”) dinosaurs hatched (”udrugede”) the eggs by lying on them in a nest, which would make only little sense for a cold-blooded reptile.

The ”night-life” of the cynodont challenged intelligence in a new way, favouring those individuals who were good at creating a strategy applicable in searching for food under difficult conditions, and memorising where to find it in darkness. Evolution solved the need for more brain, by adding the cerebral cortex (”hjernebarken”) on top of the reptile brain. When we response ”on the spinal cord” (”på rygmarven”) it is with our reptile brain part, while ”considerations” take place in the cortex. Also, dreams seems to have been introduced at this stage of evolution, in order to manage the new interaction between the two different parts of the brain. The brain size of even the early mammals were about 5-10 times larger than reptiles of similar size body. Also the smell and hearing developed markedly among the earliest mammals, while the seeing still was poor (although probably much better than the poor vision of a reptile) because of the night-life which didn't allow to rely primarily on vision. Probably the early mammals developed from colour vision to black and white vision when they turned into being night-animals – the colour vision only returned to our ancestors when they became dependent on ripe fruits much later as apes living in the trees. In order to digest the larger amount of food necessary to keep the body temperature constant, also the teeth developed, for the first time in history, into a quality that allowed chewing, maybe 200 million years ago.

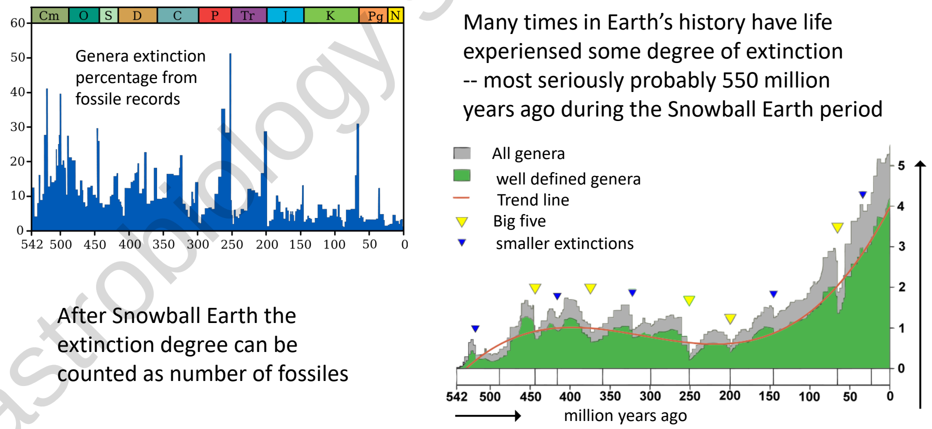


Figure 1.14. The extinction of species countable from number of fossils in sediments of know age.

When the next big catastrophe hit, 65 million years ago, the small mammals were well prepared to survive and take over the scene after the dinosaurs. They had developed a superior hearing, smelling, and brain capacity in order to survive 150 million years under constant danger of the dinosaurs. During the next 3 million years, mammals of rat-size developed into pony-size.

1.17 From Mammals to Primates

It was Carl von Linné (1707−1778) who invented a division of the fauna into Primates, Secundates, and Tertiates. The highest group of the animal kingdom was the primates, which consisted of humans, apes, and monkeys only ("mennesker, menneskeaber, og aber"). Linné was one of the greatest classifier of flora and fauna; by many considered the father of botanics. It is amazing that he so clearly saw, 100 years before Darwin, that humans, apes and monkeys had so much in common that separated them from all other animals, that they had to form one separate group alone, and yet it never crossed his mind – nor anybody else's mind at that time – that humans, apes, and monkeys had a common forefather, nor to speak about the postulate that humans had evolved from an animal.

Figure 1.15. The mammals during the domain of the dinosaurs were small. The primates lived in the trees to escape the rodents, and were only out during the night, when the cold-blooded giant reptiles had to sleep. Under these conditions they needed to develop warm-bloodednes and the superior smell, hearing, vision, and brain capacity, that should later be the major strength of the primates. Probably these early primates looked like something in-between a squirrel ("egern") and a mouse, but they were monkeys. The animal today which come closest to these early forms of primates, is probably the tree-shrew-mouse ("træ-spidsmus") seen on the photo above, which, in-spite of its name, is a monkey.

The Primates already existed along with the dinosaurs, but at that time they were small and looked like a cross-breed between a mouse and a squirrel. In order to escape the dinosaurs they probably were night-time animals, and they lived in the trees because of the fear for the rodents ("gnavere"), where they ate insects.

In the trees the mammals developed the hand-grip, and later (again) the colour vision (about 40 million years ago according to genetic analysis) which helped them spot ripe fruits when they slowly shifted from insect eating to fruit eating. The life in the trees benefited from stereo vision (in order to estimate the right distance in a jump), so the face developed flat. It requires many sensors to see in colour, and the cost of colour vision is therefore to be less light sensitive (as opposed to e.g. a cat which sees dimmer light, but cannot see colours). Therefore the Primates shifted from night-time animals to day-time (and started sleeping during the night). Insects and leaves are everywhere, while fruits are at particular places. Therefore monkeys with good memory will be better at remembering where the fruits grow at different times of the year, and we see even today that monkeys that live from leaves and insects have smaller brain than those who live from fruits. The fruit eating might therefore have been the beginning of a growing brain, and it might also have triggered the baby care-taking, because it was necessary to bring the small ones around, and (therefore) also to have fewer of them.

The first ape ("menneskeabe") seems to have developed 25-30 million years ago. The oldest known species is called proconsul and lived 20 million years ago from fruits (judged from the teeth), had no tail, and a larger brain than the monkeys. It might be the forefather of the apes. The apes were larger than the monkeys, and therefore moved in the trees by swing along ("armgang") instead of running on the branches as monkeys do (and therefore apes also didn't need a tail), and therefore developed exceptional movement in the shoulder (and for humans later in the wrist ("håndleddet") too). Hundreds of ape species developed, but about 10 million years ago they were ousted ("udkonkurreret") by monkeys who developed an enzyme which allowed them to eat non-ripe fruits. It is one example among many, indicating that maybe the brain is not such an overwhelmingly important and evolutionary significant development as we often would like to believe. Obviously the invention of a single enzyme was, seen from an evolutionary point of view, much more important than the development of intelligence, and Homo sapiens became so close to extinction in-spite of its superior brain, that probably only coincidences saved our species from being an unnoticed parenthesis in the evolution of life on Earth. Today there are only 6 species of apes left – gibbons and orangutan in Asia and gorilla, chimpanzee, and bonobo in Africa, and humans all over – but a couple of hundred of species of monkeys.

Genetic studies show that the branch that lead to the bonoboes and the chimpanzees and the branch that led to hominids, divided some time between 7 and 5 million years ago. There are no known skeletons of the chimpanzee ancestors, which is probably because they stayed in the rain-forest where skeletons quickly dissolve, but genetic studies indicate that the common ancestor of the chimpanzee and the bonobo lived in Africa as recent as a million years ago. Morphologically they are so similar that they can be almost impossible to distinguish by their sceletons alone. The bonobo is on average somewhat smaller than the chimpanzee, and was for long called the "dwarf chimpanzee". Sociologically, however, they are widely different from one another, with the bonobo groups living an much more advanced social life than the chimpanzees.

1.18 What triggered human development?

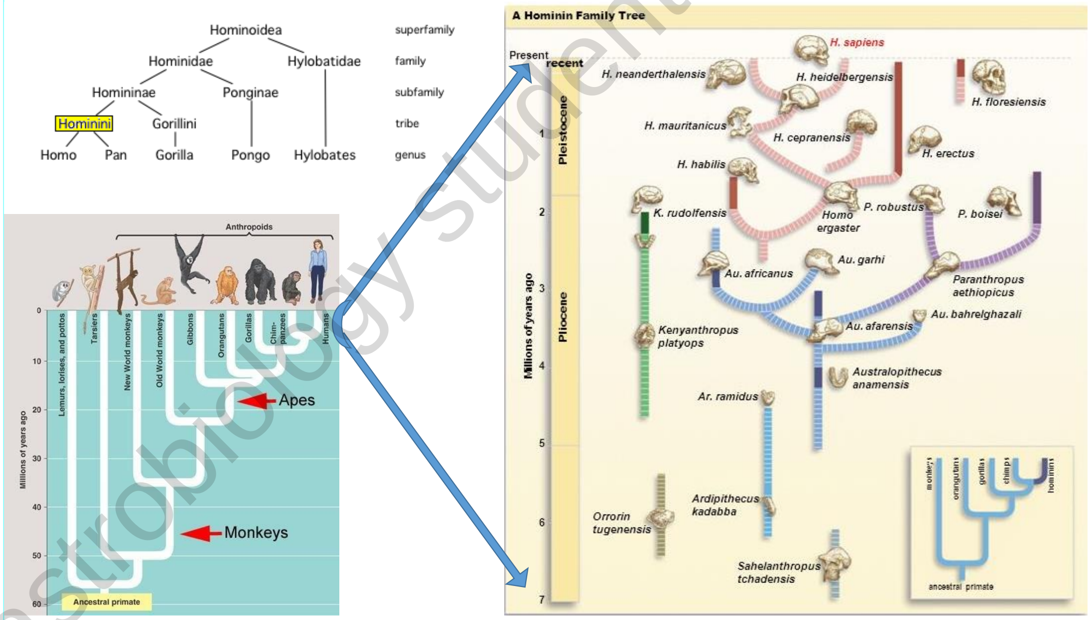


Figure 1.16. The hominin family tree in perspective of hominids, apes, monkeys and primates.

Three factors, already pointed out by Darwin, seems to distinguish Homo sapiens (and other late hominids) from the rest of the primates:

- Upright walking
- Better tool making
- A larger brain

A central question is whether these three factors developed parallel or one triggered the other. Did the larger brain result in better tool making, or did the increased dependence on tools put evolutionary pressure to the advantage of species and individuals with a larger brain? Did more intensive use of tools promote upright walking, or did the upright walking promote better tool making? Modern research points at the surprising conclusion that the upright walking lead to better tool making, and the increased tool making provoked accelerated development of the brain. Not visa versa. Does this mean that there is no central evolutionary advantage of a larger brain? Does it imply that intelligence is not an obvious and natural consequence of evolution? Shall we expect that even old and evolutionary advanced societies outside the Earth are unlikely to be populated by intelligent beings?

1.18.1 The upright walking

Upright walking began 5−7 million years ago. By definition we distinguish hominids from apes by the upright walking. The oldest known hominids are Sahelanthropus or Orrorin (the human from the Sahel-area, or the original human in local dialect). Their thigh bones ("lårben") were big enough for upright walking – whether, or how often, they actually walked upright is of course not possible to judge from the thigh bone alone, and they may likely have looked more like an ape than a human, but they were the first hominids.

It is hard to guess why the first hominids started walking upright, but we do know now that it was not because they were more intelligent, and not because they had started using the hands for something else. The major development of the brain, and the major increase in abilities to use the hands came much later. The first of the three developments that should distinguish Homo sapiens from the rest of the Primates, was the upright walking, and it didn't develop hand in hand with the two other human characteristics.

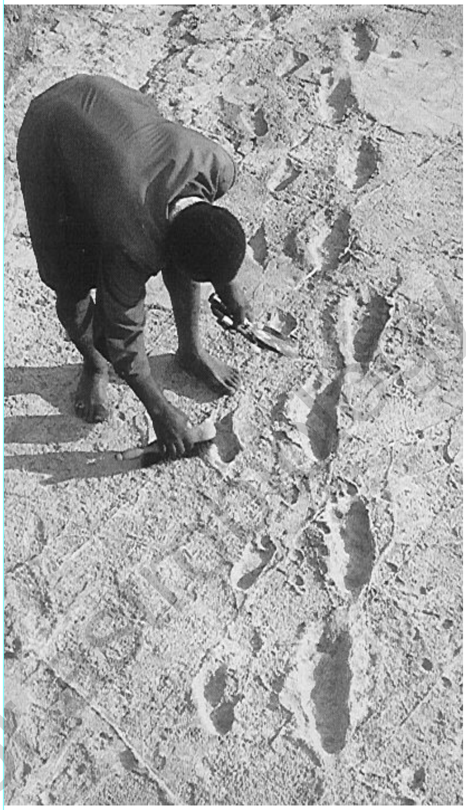


Figure 1.17. Footprints from two or three Australopithecus afarensis ("Lucys") walking through new-fallen volcanic ashes 3.7 million years ago in Tanzania.

The first really clear evidence of upright walking is from "the Lucy family", or more scientific the Australopithecus afarensis. Two or three Lucys (it is debated whether there is a second one walking behind the first large person in its footprints) and a small one, walked over new-fallen volcanic ashes in Tanzania 3.7 million years ago. Shortly after it rained so the warm ash formed a solidifying mud ("cement"), and an additional layer of ash felt over the solid clay and preserved it. There are 18,000 footprints from many different animals, and marks of raindrops. The two (or three) Lucys stopped midway on the 27 m long path that can be followed, and looked back. The walking indicate such balanced walking, that it is obvious that these species had been on two legs for a long time already. Australopithecus afarensis are 110 – 150 cm high and have relatively short legs (compared to us). Their hands and feet are somewhat bent, indicating that they still spent quite a bit of time in the trees (maybe the nights in security). Older skeletons indicate upright walking already 5−7 million years ago (among the first Australopithecus). It can be inferred from the position of the balance point ("nakkehullet") where the spinal nerves enter the head, and from the size of the thigh bone.

1.18.2 Tool making

The tool making came much later than the upright walking. The oldest findings of tools are sharp pieces of stones which were probably used to scrape meat from bones. Findings of animal bones show that tools of stones have been used to scrape off the meat from horses, antelopes, etc, in Kenya 2.5 million years ago. Marks in the jaw bones ("kæbeben") of an animal shows that the tongue was cut out (as a delicates for a human?). The oldest stone tools found are 2.6 million years old. Making these tools required the skillful hand that had developed because it was no longer used to walk on. Apes don't have it. When chimpanzees work with their hands, the movements are primarily located to the shoulders and elbows, which developed flexibility only to ease swing-along movements in the trees. Wrists are locked on apes in order to make the hands useful to walk on, while the wrists ("håndled") are moved a lot when humans work with their hands.

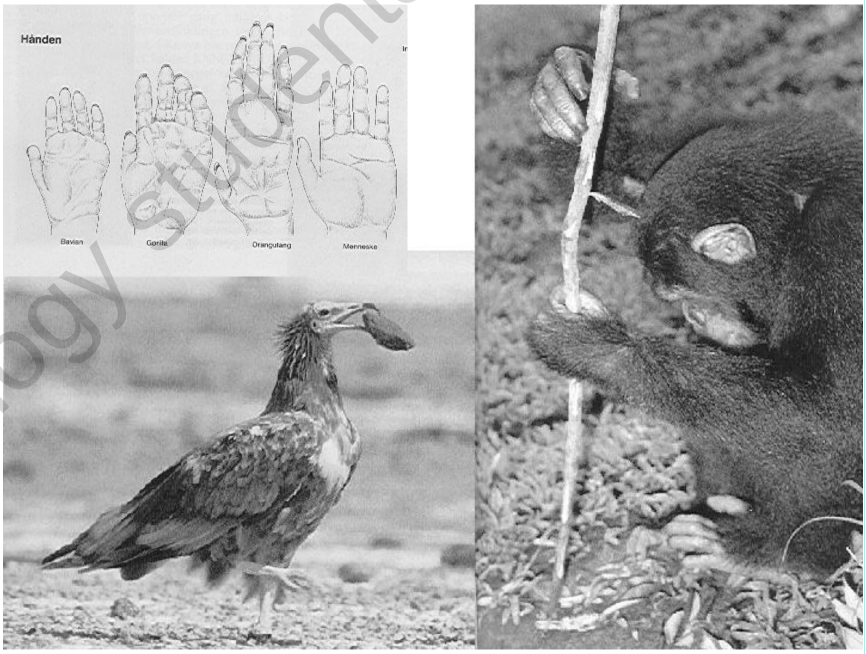


Figure 1.18. Several animals use tools, and some even make tools. It is only the level of sophistication that makes human tool making unique in the animal kingdom. The upright walking freed the hands of humans to develop into a more fine-tuned instrument for making tools. Upper left: The hand of Baboon ("bavian"), Gorilla, Orangutan, and Human ("menneske").

Chimpanzees in nature always make simple tools; no group of chimpanzees are known that do not use tools of some kind. For example they can peal off leaves and small branches to make a good stick to fish for termites (i.e., put the stick into the termite hole, let the angry termites attack the stick, pull it carefully up and lick off the termites; Fig. 1.18). The first pre-hominids may have done the same 5 million years ago; we of course do not find remnants of wooden tools. Chimpanzees can also carry good stones from a few hundred meters away in order to make a platform to break nuts on ("hammer og armbolt"). This means they plan the process of breaking nuts ahead in time. It takes young chimpanzees several years to learn the technique to break the nuts between two stones.

Even sea otters ("havoddere") at the North American west coast brings with them well formed stones they have found when they dive for mussels, in order to have tools to open them with, and many other animals use tools too (Fig. 1.18).

Already 2.6 million years ago it seems that Hominids made stone tools to make wood tools with. The wood tools are of course gone, but marks on the identified stone tools indicate that they have been used to cut in wood. It was probably Homo habilis ("fortidsmennesket"), with his 600 cm^3 brain volume, who made the first simple stone tools 2.6 million years ago, although also Paranthropus robustus ("et abemenneske"), with his 400 cm^3 small brain, lived in the same area and may have produced the tools that were found. They look like random pieces from smashing stones, but archaeological evidences show they were made intentionally (many are found together at specific places, and some times the stones have been transported from as far away as 10 km before they were prepared to tools, etc).

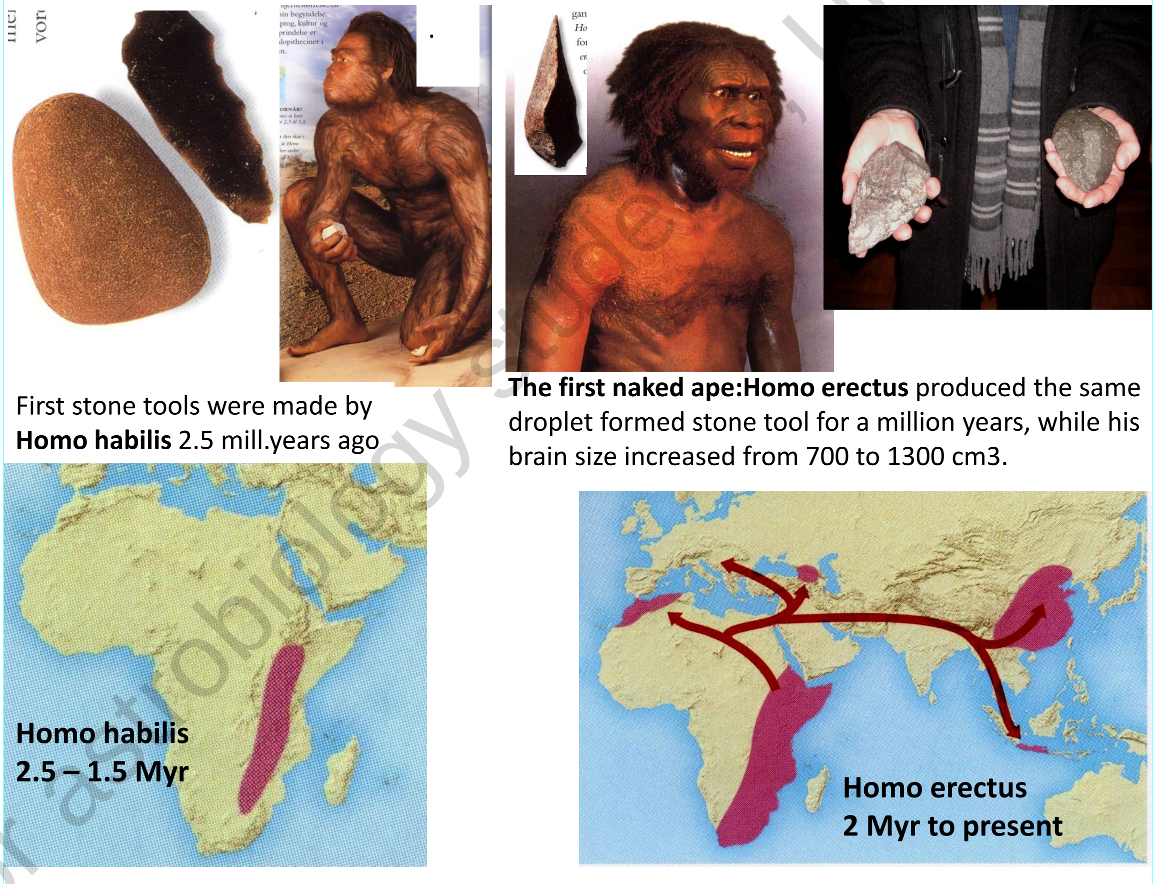


Figure 1.19. The tools of Homo habilis (upper left) were on the level of what a modern chimpanzee or bonobo can be taught to make, while 1.5 million years old tools of Homo erectus never were superseded in sophistication by anybody other than later hominides. Homo erectus became the first global hominid, but for more than a million years he only did the tool you see to the right in the figure (uppermost right inset is a modern Homo Sapiens holding two Erectus tools produced 1 million years apart in time, upper middle is a Homo Erectus worrying about where the Sapiens got them from) – maybe the most successful technological invention in human history?

It took another 1 million years before any noteworthy step forward was taken compared to the randomly looking primitive tools. 1.5 million years ago the droplet formed, hand sized stone tool you see in Fig. 1.19 was invented by Homo erectus. It demanded the advanced, abstract thinking to form them, and the large brain, that Homo erectus had. It took additionally more than one million years (to the beginning of Homo sapiens) before a new revolution in tool making took place, about 200,000 years ago, with many new kinds of stone tools with each their specific purpose. Homo erectus may have made the first fires 1.5 million years ago (i.e., probably kept fire alive from blitz fires etc), but it is debated whether findings of burned ground ("sammenbrændt jord") is to be interpreted as fire places or just accidental natural fires. Only 100,000 years ago fire places were common. They were from Homo sapiens.

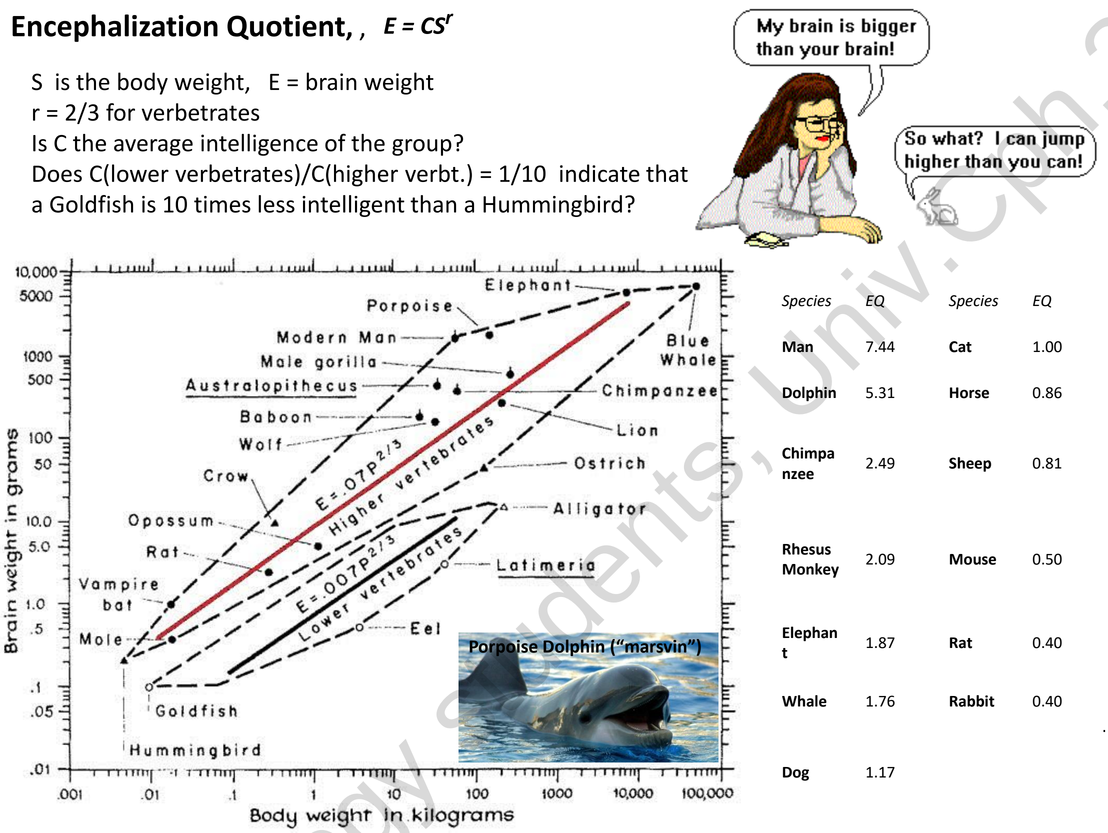
Bonoboes ("dwarf chimpanzees") use tools to much less degree than chimpanzees, but seems to have the same intelligence as chimpanzees. A particular smart and famous Bonobo named Kanzi, however, was challenged to make tools. For example a box of food was closed with a rope which could only be cut with a knife, and Kanzi was given a stone instead of a knife, simulating maybe situations like those our forefathers could have been in more than a million years ago when they were inspired to make the first human stone tools. Kanzi was able to figure out to throw the stone such that it broke into pieces that could be used as knifes, and to select the sharpest piece and cut the rope with it in order to get the food. However, Kanzi was very domesticated, and he had his own weekly TV program on BBC together with Desmond Moris. In the end he obviously thought he was a human being and died under tragic circumstances. He was able to select the best "knifes" he more or less randomly produced by throwing stones (just like Homo habilis seemingly did more than 2 million years ago in east-Africa), but his intellectual capacity never stretched to thinking about manipulating the stone pieces to make a more specialised or perfect tool, such as Homo erectus, the first "naked ape", did one million years ago when he became the first globalised hominid. It is probably of relevance to mention that the brain size of a present day Bonobo is only slightly smaller than that of Homo habilis, but about half the size of that of Homo erectus.

1.18.3 The brain

Linné defined the class Homo for those primates whose brain volume was larger than 800 cm^3. Later primates with 650 cm^3 were found who seemingly had many similarities to us, and the border to Homo was reduced to 600 cm^3 ($\sim$ Homo habilis). Today we define Hominids as primates that walk on two legs. The first hominids ("på dansk ofte kaldet abemennesker, ikke at forveksle med termen menneskeaber som svarer til det engelske apes") 5-7 million years ago had a brain volume of 400-450 cm^3, only slightly more than a modern chimpanzee. The fact that chimpanzees still have approximately this brain size, indicate that the branch of primates that developed into the chimpanzees during the next 5-7 million years, didn't encounter the same large challenges in the environment as the branch that developed into the hominids. Maybe because the chimpanzees stayed in the rain-forest eating mainly fruits. Only in the environment where the hominids lived, did it become an evolutionary advantage to have more brain capacity. On the other hand, this also means that studying the intellectual capacity of chimpanzees, probably gives us a good picture of how our (common) ancestors were 5 to 7 million years ago.

The development of the brain of the Hominids has been tremendous. On average 150,000 additional brain cells have been added per generation (per 25 years) since we branched away from the chimpanzees, but it went particularly fast between 2-1.5 million years ago, and between 500,000 to 200,000 years ago. 1.8 million years ago (Homo erectus) the hominid brain had reached 800 cm^3 (and the same body size as modern man). 500,000 years ago it passed 1 kg, and 200,000 years ago the modern size of 1300 cm^3 was reached. Of course size alone is not everything. Lots of other factors are important for the survival, even for species whose main evolutionary advantage is "brain". It is difficult to physiologically characterise what possibly makes our brain more biologically fit than for example the brain of a dolphin, but of course it must be crucial both how and what evolution forced our brain to be occupied with. The largest brain size among the hominids was obtained by Homo neanderthalensis (often called just the Neanderthals; 1500 cm^3), but they never spread outside Europe, while both Homo erectus and our own species, Homo sapiens, developed world wide.

Future will show whether the development of the human brain was an advantage or a disadvantage for the human survival over biological and geological time scales – whether hominids became more or less fit in a biological sense because of the huge development of the brain capacity. In other words, will we survive shorter or longer time as a species on Earth because of the increased intelligence and all that follows with it? The answer to this question is of course central to our expectation of finding intelligent life elsewhere in the universe. Are humans right now a dominating species on the globe because of our intelligence, or in spite of our intelligence?



Species	EQ	Species	EQ
Man	7.44	Cat	1.00
Dolphin	5.31	Horse	0.86
Chimpanzee	2.49	Sheep	0.81
Rhesus Monkey	2.09	Mouse	0.50
Elephant	1.87	Rat	0.40
Whale	1.76	Rabbit	0.40
Dog	1.17		

Figure 1.20. brain size versus body weight (and EQ number) of various species of animals.

Whatever the answer to this question will turn out to be, it is worth at this place to at least kill a very common misunderstanding about the human development. Humans did not survive better than the other primates because of a larger intelligence. Humans developed a larger intelligence as a consequence of having already survived better than the other primates. For some yet unknown reason hominids started upright walking, maybe 5 million years ago. As a consequence of the upright walking, the wrist had the possibility of developing to a more sophisticated anatomy (chimpanzees never developed a fully movable wrist, which would be un-practical as long as the hands are to a large extent used for the walking). As a consequence of the finer mobility of the hands, a hitherto unknown sophistication in tool making developed. Evolution had now crossed a barrier where tool making became a central advantage for the survival. The best tool makers had a better chance for getting food than the poorer tool makers (this is in strong contrast to for example the primitive tool making of chimpanzees, where a more sophisticated tool making would allow capturing more delicate termites, but it would add nothing important to the total food intake). Now intelligence also for the first time became a substantial advantage worth the biological sacrifices a larger brain demanded. More intelligent individuals could, because of the anatomy of the hands, use their larger intelligence as a help in constructing more advanced tools, and hence survive better. Only at this point did intelligence become central for survival, but it was long after hominids were already into a fruitful development – maybe 3 million years after the beginning of upright walking, and maybe 1 million years after the first relatively advanced tool making.

The brain has (at least) two basic functions, namely (mainly) to control the body motorics and (to a less extend) to help thinking. The needed capacity to control the motorics differs between different groups of animals (for example between reptiles and mamals) due to the different body structure complexity (e.g. warm blooded structure versus cold blooded design). It is threrefore not immediately meaningful to compare brain size or brain size divided by body size of animals belonging to different kind of animals, but within a certain group (e.g. mammals) it may have some meaning to compare brain mass divided by body mass to obtain some feeling of the relative intelligence of the species. For example, it has been tried to fit the brain mass E versus body mass S of different species by an exponential law

$$E = C \times S^r \tag{1.16}$$

In Fig. 1.20 this relation is shown for r = 2/3 and two different values of the constant C. One value, C_{lv}, could be claimed to be representative for lower verbetrates and another, C_{hv} for higher verbetrates. The ratio C_{lv}/C_{hv} could then be claimed to be an expression for the ratio of intelligence of lower verbetrates relative to that of higher verbetrates, and for many groups of animals this ratio is along the lines of our intuition of their relative intelligence. Once the C value is established for a group of animals, one can compare the EQ (Encephalization Quotient) ratio of individual species with that of the group to obtain a relative ranking within the group. This is done in the table in Fig. 1.20 for various animals compared to the C-value for an average of mammals. The graph and the small table show for example that humans rank a factor 7.44 above the mammal average while a rabit rank a factor 2.5 below the average mammal. Maybe the system has just the desired advantage that we have constructed a measure of relative intelligence among animals that rank our selves highest, but it may also say something about the excess brain capacity that is available above the capacity required for motoric necessities. Other attempts to rank the relative intelligence of animals include measuring the area of the unfolded cerebral cortex, which is assumed to be proportional to the cognitive abilities ("the finer thoughts").

The cerebral cortex (lower right) is the deeply convoluted surface region of the brain that is most strongly linked to "intelligence" (logic thinking, reasoning, etc). The human cerebral cortex, if flattened, would cover four pages of typing paper, a chimpanzee's would cover only one, a monkey's would cover a postcard, and a rat's would cover a postage stamp.

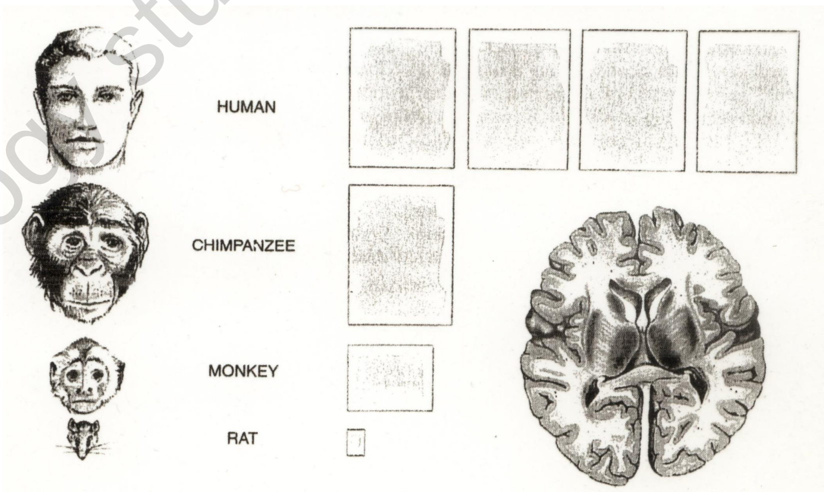


Figure 1.21. The area of the unfolded cortex for various animal species.

Some of the expenses of a large brain – and maybe the major reason that it is in most cases not biologically beneficial to have a large brain – is its energy requirement. The brain requires an enormous amount of energy per kg tissue in order to function, which could otherwise had been used for something else, for example muscles in the legs which increased the possibility to run away from the enemies, or to catch the prey, which in most cases would have increased the chances for survival more than the extra brain capacity would, and hence increase the survival of those individuals who were born with larger leg-muscles rather than those with the larger brain. It is this discussion which is simplified in the cartoon in Fig.1.20 between a rabit and a human.

A human embryo ("foster") uses 60% of its energy to develop the brain, and only 40% on all the rest of the body. In a grown-up person the weight of the brain is approximately 2% of the weight of the body, but the brain uses 10% of the oxygenized blood. It has been speculated that it was biologically only possibly to find the extra energy to the brain because of a transition from plant eating to meat eating. The morphology of the hominid skeleton indicate that the first period of rapid development of the size of the hominid brain, coincides with a substantial decrease in the length of the intestines. Digestion of meat requires lower energy and a smaller intestine system than efficient digestion of vegetables, and it is therefore likely that it was a transition to mainly meat eating that was the cause of a seemingly decreased intestine mass of approximately 800 g (it is probably just a funny coincidence that the increase in the brain mass over the same period was also 800 g). The lowering in required energy for the digestion is likely to have been the boost that made it possible to find the increased amount of energy that was necessary for having a larger brain.

Another expense of the larger brain, is the more complicated birth. This is what the Bible describes as women having to give birth with pain because of the increased intelligence (size of the head of the babies). It is a typical example of how evolution works. With the small brain (i.e. head) of a chimpanzee baby, the pelvis ("bækken") of the mother give good space for a painless birth. For the larger head of a modern human baby, the pelvis is becoming too small for a risk- and trouble-free birth (Fig. **??**). An engineer would have argued for the need of a new construction, for example a birth channel through the soft stomach tissue instead of through the pelvis, and this is exactly the doctors emergency solution during a Caesarian. However, evolution will always try to evolve the existing solution to the best possible compromise. Therefore evolution's solution for the humans was to increase the size of the pelvis a bit and decrease the length of the pregnancy, such that the mothers would usually still survive the birth in spite of the too big baby head for the existing pelvis, and the babies would be evolved enough that they would usually also survive the first months after births where they optimally rather should still had stayed as embryos. As a result of this compromise, the brain of a newborn human baby is only 25% "ready". Compared for example to a rhesus monkey, the brain of their babies are 2/3 developed at birth, and fully developed after only a few weeks. It would require additional 12 months of pregnancy for humans to give birth to a baby with a fully developed brain; so in reality the "natural" length of pregnancy for humans is 21 months, but after 21 months the head of the baby would be too big for the birth. This is evolutions compromise, as opposed to the doctor's Caesarian or the engineer's inclusion of a new "abdomen-channel-exit".

Human's unnatural short pregnancy, however, had another consequence which might have been equally important for the human development as the construction of more efficient tools. Because the human babies are literally born as embryos, *care* became crucial for the survival of our species. Humans with "humane" characteristics now had a better chance for surviving in the gene-pool. Individuals that took better care of their offspring, had a better chance of bringing their genes through to future generations, just simply because human babies were crucially dependent on this care for their survival. Social responsibility and interest may have developed in this way, and it might well be this characteristica that secure human civilisation a long survival time on our planet. In spite of the worries we can, with all right, have about all the violence and fighting among humans on Earth, it is hard to envision chimpanzees or any other mammal living as peaceful as humans with the abundance of technical and military capabilities humans have developed. After all we may be so humane that our species will not destroy itself over biological time-scales, such that we will live long enough to communicate with other similar beings in the Galaxy, and it is fascinating to speculate that it may be because of the evolutionary compromise between the size of the pelvis and the brain. Could it be that the gravity of an extra-solar habitable planet is important for how large the skeleton of an animal can be, and would this affect the evolution, as in the example described above for Homo sapiens? In which way would it shape its psychology, and hence its odds for long-time survival as a technical civilisation if the planetary gravity had not been "Earth-like"?

1.19 Out of Africa.

Traditionally, paleontologists (palaeontology = the science about animals and plants that have died out) study the morphology of the bone and skeletons and fossils of species and individuals, in order to trace the evolution and affinity of groups and species. This method has the advantage that it can be used at least back till the beginning of the Cambrian period (the oldest fossils). One can often draw surprisingly strong conclusions about even non-preserved details of the anatomic structure of the plant, animal or person in question from such studies. We have already discussed that the skeleton of early hominids showed that Homo ergaster had a 800 g smaller intestine, than his forefathers had, and we concluded that he probably was the first regular meat eating hominid (”the first hunter”). Studies of his teeth supports this interpretation, as they indicate that he mainly was chewing meat, not plants. Even more indirect and further back in time we conclude from small holes in the head that the first forefathers of the mammals, the cynodonts, had whiskers 250 million years ago, and concluded from this that they probably had fur, which probably meant that they needed to keep warmer than the surroundings, which indicated that they were the first warm-blooded animals. We even dared to speculate that they probably lived during the night to hide from the cold-blooded reptiles, and that this was a first advantage of being warm-blooded. Another example of the force of the paleontological studies we have discussed, was the ability to date when the first primates started upright walking (i.e., per definition became hominids) even if we have only (parts of) the skull left (because of the position of the balance point).

We would also to some extent be able to discuss social behaviours of animals from paleontological arguments. For example, we would be able to conclude that gorilla males surround themselves with harem (fight regularly with other males, and have ease in physically controlling a group of females) while chimpanzees don’t, just from the fact that the ratio of the weight of the male to the weight of the female (estimated from the corresponding rates of the size of the male and female skeletons) is much larger for gorillas than for chimpanzees. In line with these arguments we conclude that the first hominids socially were closer to present day gorillas than to present day chimpanzees. The males of the first hominids were 1.5 m and weighed 35-40 kg, while the females were about 1 m and weighed about 25 kg. Two million years ago, the weight difference between the hominid male and female had reduced to 20% and today it is $\approx$ 15%. This morphological (paleontological) observation is probably in line with our conclusions above about the increased importance of taking care of the offspring and its implication for the evolution in the social relations among humans.

The morphological studies also give us the first clues to when and why hominids migrated out of Africa. Until approximately 1.8 million years ago, skeletons of hominids are known from the African continent only. Up to that period Homo ergaster had probably developed into a feared hunter on the African savanna. His successor at the important transition period 1.8 million years ago was Homo erectus (i.e., ”the upright hominid”, even though hominids had already been walking upright for more than 3 million years at that time, and there was nothing particularly more upright about Erectus than other hominids). His brain capacity was an impressive 800 cm^3, and his teeth show that he was even more focused on meat eating than Ergaster. While Ergaster might in principle not have been hunting himself but rather been eating the leftover meals from the big predators (of which the dominant one at that time was a big lion, ”sabelkatten”), Erectus was for sure hunting the prey himself. He is also the first hominid whose skeleton we find outside the African continent, approximately 1.8 million years ago, and we might speculate that he was so embarked in hunting that changing hunting conditions made him follow the prey out of Africa and populate the Asian continent all through to Eastern Asia.

Studies of fossil carnivores (i.e. mamale preditors) in eastern Africa over the last 7.5 million years, indicate a fairly stable population untill 3.5 myr ago, followed by a slow decline from 3.5 to 2 myr ago. But from 2 myr ago (and even more pronounced from 1.5 myr ago) the number of large carnivor species nosedived, and not even individual speices, but whole groups of speices, such as the sabercats went extinct. For large carnivores (ı.e. with body weight above 21.5 kg) in particular their diversity decrease drastically. The diversity is a measure of the number of different ecological niches filed out by the different species, for example in the form of the diversity of food sources they live on. Carnivores can be classified from their tooth and jaws as hyper-carnivores (earting basically only meet, such as cats), omni-carnivores (eating a variety of food, such as e.g. dogs and humans), or hypo-carnivores (such as e.g. racoons that eat mainly

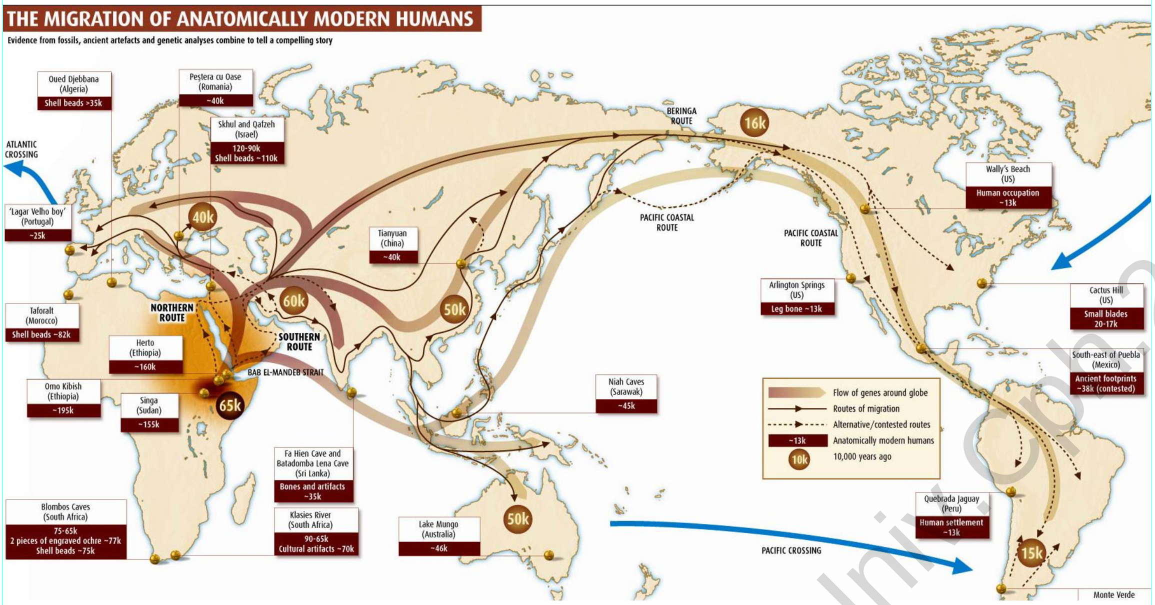


Figure 1.22. The route of humans out of Africa can be traced by investigations of mutations in the DNA of human mitochondria. In this way it was realized that all humans originate from a rather small, almost extinct, group of hominids which left Eastern Africa less than 100,000 years ago. North-Europeans came from Africa via Asia, while South-Europeans came on a more direct route out of Africa. The native Australian population was likewise a mix of a quite direct migration and a migration via South-East Asia. Controversially, the North-American native population now seems to be a mix of a small early European migration and a later but larger population that migrated via North-Eastern Asia, as the original South-American population seems to have been a mix of polynesian and North-American migration.

fruit, vegetables, and berries, but also a small amount of meet). Untill 2 myr ago a wide range of carnivore spieces existed, filling a large diversity of ecological niches, but during the next few hundred thousand years, the diversity declined with 99%. It is likely that before $\sim$2 myr ago, homonids were mainly food for the large carnivors, but after the appearance of Home erectus, homonids bacame rather a compatitor of the food (the large mamalian herbivores) than a meal, and Homo erectus with his stone tools and social hunting collaboration abilities will have been a strong compatitor to the other large carnivors, and maybe even the cause of their high extinction rate during the time when humans shift diet from mainly fruit and vegetable eating to a high concentration of meet. Small carnivores, on the other hand, do not change in diversity or number of speices, but rather has increased a bit, indicating that competition for the large herbivores was the cause of the decline of the large carnivore diversity.

However successful the paleontological arguments have been, they have of course also their limitations. For example it would not be possible to distinguish a chimpanzee from a bonobo from their skeleton alone. In fact they look so similar that it was not before the 1920's that it was first realized they were two different species, and the older designation "dwarf chimpanzee" is occasionally still used about the bonobo, even though it is not a chimpanzee. Their social behaviour are widely different, and they are certainly two completely different kinds of species. Recently it has been possible to add genetic studies to supplement the morphological studies, and this is well on its way to revolutionise our understanding of the development of hominids and of our understanding of the development of life in general. DNA can be isolated from bones and other organic material up to $\approx$ 100,000 years old (and at special places all up to more than one million years), and contain detailed information about the relationship between species. Proteins are somewhat more stable than DNA sequences, and can be traced to even older ages, but their information content is not as precise as the DNA sequences. Particularly valuable are DNA analysis on mitochondria and the Y-chromosome, because they are not sexually mixed, and therefore easier to interpret.

Mutations on the DNA sequence takes place regularly. If two species have widely different DNA sequences, it is therefore an indication that it is long time ago that their common ancestor lived. Only 40 of our genes, or 0.1%, are identical to those in bacteria and all other known life-forms on Earth. We can therefore conclude that it is biologically very long time ago the common ancestor of us and the modern bacteria populated the Earth. On the other end of the scale, 99% of our genetic sequences are identical to those of the chimpanzee, and we can therefore conclude that it is not so terribly long time ago that our common ancestor was alive and our tribes divided into the branch that should later become the chimpanzees and the branch that should later become humans.

In most cases the genetic changes due to mutations are small and neutral for the survival of the individual, and negative mutations have a tendency to die out in the sexual reproduction, because of the pairing of chromosomes from two different individuals. However there is an exception even in our own cell, because actually far from all our reproduction is sexual. Each of our cells contain between a few and a few thousand mitochondria cells ($\sim$800 on average). These cells are direct descendants of prokaryotic bacterial cells, which reproduce by simple cell division. The reproduction of our mitochondria cells are therefore not a sexual reproduction, and their mutation history therefore also do not have the complex history that follows from continuous splitting and pairing with other chromosomes through generations of sexual reproduction. In fact our mitochondria DNA is inherited only from our mothers. By tracing the mutations in the mitochondria DNA, we therefore have a relatively simple and straight-line description of the evolution of our species. In a similar way, though for different reasons, the Y-chromosome is only enherited from father to son, so that it defines another straight line independent of sexual mixing.

The first and very important conclusion we can draw from the mitochondria DNA studies is that the sequences are amazingly similar in all humans on the globe. In fact the variation is so small that it is possible to conclude that we are all descendants of a quite small group of people (that lived in eastern Africa approximately 200,000 years ago). A too quick early announcement of the results even indicated that we might all be descendants of the same individual woman. Even though this conclusion was quickly realized to be erroneously, it is such a result that has the tendency to stay in the memory for a long time, and we will probably hear it referred to as a possible true result many decades ahead. It would truly be fantastic if scientific results had proven that the Biblical Eva literally existed, and that she had lived somewhere in the region of present day Ethiopia about 200,000 years ago – the uhr-mother of all human beings on the globe. However, the real result was also extremely fascinating, and a bit spooky indeed, because it shows that the small group of humans we all are descendants of counted maybe as little as 1000 individuals, and for sure no more than 10,000 persons. This is what we today would call an extinction endangered species!

Whether Homo sapiens had been a larger group before that time and actually was on its way to extinction, we will never know, but we do of course know that it survived extinction 200,000 years ago, and later spread to all corners of the globe. The population of chimpanzees have a considerable larger variation in their gene pool than humans, and chimpanzees have therefore not been as close to extintion as Homo sapiens.

Mutations that took place in the mitochondria of the original population in Africa before it started diverging over the globe can of course now be found in humans all over the globe. However, certain mutations can only be found among people from certain regions of the globe, and we can therefore conclude that these mutations took place after humans divided into different populations after they left Africa. For example the DNA in the mitochondria in the cells of native north and central Europeans have mutations found in the south and central Asian native population, while south Europeans have none of these mutations in their mitochondrial DNA. We therefore conclude that one route out of Africa went through south and central Asia to the north and central Europe, while another went directly from Africa to the southern part of Europe. Similarly we see that none of the mutations we find in Asia and Europe are present in the native Australian population, and we therefore conclude that the native Australian population came (somewhat surprising and a bit mysteriously) almost directly from Africa to Australia. The major emigration routes humans took to settle the world as we believe it today can be found in Fig. 1.22.

In fact, the mutation rate in the mitochondrial DNA is quite regular in time, so it is also possible to give approximate times for when the immigration had spread to different regions of the world. In this way we know relatively certain that the humans arose in Africa as late as 200,000 years ago, the first humans left Africa about 100,000 years ago, and they had spread to all areas of the globe 15,000 years ago. Among the most surprising results are probably that they populated Asia 40,000 years ago – while Homo erectus still lived there, and they also lived side by side with Homo neanderthalensis in Europe until 30,000 years ago. In reality, our own period (since the last Neanderthals died out in Europe 30,000 years ago) is the first and only period of the 7 million years long history of hominids on Earth that there exist only one species of hominids. Very recent findings indicate that a small group of the last descendants of Homo erectus may still have lived on the island of Flores in Indonesia only 18,000 years ago, and local tellings at the island report somewhat controversially about the existence of ”small people” living at the interior of the island as late as the time when the Portuguese colonised this part of the world. Could it be that Homo sapiens really lived side by side with another hominid on Earth as late as in historical times during the middle ages ? Can it be that Homo sapiens in the future will develop into several different hominid species, such as it happened for previous hominids and such that the Earth again will be populated by more than one single species of hominids, as it has been the case almost all of the the few million years there have been hominids on the Earth, except during the last few hundreds or thousands of years?

1.20 How unique are Humans ?

99% of our DNA material is common between Humans and chimpanzees. The genetic difference between Humans and chimpanzees is smaller than between the African and the Indian elephants. On the other hand the big human genome project described the human DNA as 30,000 genes (only), which makes it quite obvious that there cannot be a gene for everything. Even a fruit fly has 14,000 genes, and a mouse 30,000, just as a human. A gene code for a protein, and not more. Something additional must be involved in how the final human individual will look like, not to speak about behaving, so it is not obvious what we shall conclude from the percentages of genetic similarities and differences, beyond that it is a good relative measure for how long time ago our common ancestor lived.

Chimpanzees have many similarities to us, beside the genetic sequence, including several of those we usually attribute to be non-genetic (“cultural”). Cultural abilities manifest themselves as a different behaviour among different groups of identical genetic identity. I.e., they are not inherited, but spread to the group because one individual in the group started to do it. For example, to use stones to break nuts is a cultural ability of some groups of chimpanzees. It is not very easy for the individual chimpanzees to do it, and it usually takes the young chimpanzees a couple of years to learn it by looking at how the elder individual chimpanzees do it. Other examples of cultural abilities distinct to specific groups of chimpanzees are to wash potatoes before to eat them (i.e., to clean them for sand), or to hold hand (rather than just touch wrists as other groups of chimpanzees do) while pealing one another’s fur. Chimpanzees in nature also use medicine. They are e.g. known to search particular, rare, plants and eat their leaves when they have stomach ache (and it helps by pulling out parasites from their intestines), by eating the pith (”marv”) underneath the bark of some particular branches against diarrhoea, etc. In total, Chimpanzees are known to use 30 different plants as ”natural medicine”, but there are cultural differences between the groups about which plants to collect and how to use them.

Chimpanzees also apply a common cultural moral codex in their behaviour and expectations toward one another, which many people would otherwise tend to call a specific human character. E.g. chimpanzees obviously remember other chimpanzees that use to share their food generously with the group when they have. These chimpanzees always get food from other members of the group if they are in need, while “stingy ones” don’t get from others when in need. If one chimpanzee helps another one in trouble, it expects to be helped by that one if it gets into trouble itself, and if the help fails to appear, it gets angry and can start beating the one that didn’t live up to its moral expectations of help.

As opposed to most other animals, chimpanzees have the capacity to feel its identity and to abstract this concept into understanding that also other chimpanzees must have a feeling of identity. When a chimpanzee sees itself in a mirror, it starts to make faces to itself, and if it has learned to recognise itself in the mirror, it recognises when something is wrong with itself (e.g. if a dot of paint has been put in its forehead it tries to remove it). It also understands the identity of other chimpanzees and are able to project its own feelings onto the other individuals (e.g. it can pretend that food is hidden somewhere to make other chimpanzees go there so that it can go to the right place while the others are busy at the wrong place – i.e., it knows the concept of cheating other individuals by guessing what they think). However, it does not understand e.g. that a person with a bandage for the eyes cannot help it in telling where something is to be found (which a child of 2-3 years would not be able to either, but a child of 3-4 years would). Psychologists estimate that a chimpanzee has an intelligence as a 3 years old child, that Homo habilis had an intelligence as a 5-6 years old child, and Homo erectus as a 6-8 years child – but all of them with no (real) language.

Everyone that have had a pet at home knows that it is possible to communicate with animals. Certain gesticulates or sounds can be transformation of information between humans and animals, and it can have some (limited) meaning. However, nobody has ever had a conversation with an animal. It is widely debated whether the reason that we cannot have a conversation with a chimpanzee (or for that case a dolphin or several other animals) is an intellectual barrier or an anatomical barrier. Two anatomic differences between humans and apes makes it possible for humans to talk, and impossible for apes. The first is the low place on the neck of the larynx ("strubehovedet"), and the other is the free movement of the tongue. Both have some imprints in the skull (the details of the construction of the bottom of the skull, and the size of a hole in the skull where the nerve regulating the movement of the tongue runs through the skull). We know that the larynx began moving lower down on the throat already during Home erectus' time 1.6 million years ago (allowing more sounds, on the cost of producing difficulties of breathing while drinking) and reached a level that would allow varied sounds about 400,000 years ago during the times of late erectus and early neanderthal. At that time also the size of the hole for the nerve that regulate the movement of the tongue reached the size it has in modern humans. Seemingly hominids were able to talk 400,000 years ago. The oldest traces of the written language dates to 5-6,000 years ago, but it is of course much more difficult to trace the first spoken language. Today 6,000 different languages exist. Cultural changes that must have required talking (burial of the deads, trading, art, and strongly improved tools) didn't appear before as late as only 100,000 years ago. It therefore seems as if hominids were able to talk about 400,000 years ago, but didn't "say anything" before 100,000 years ago.

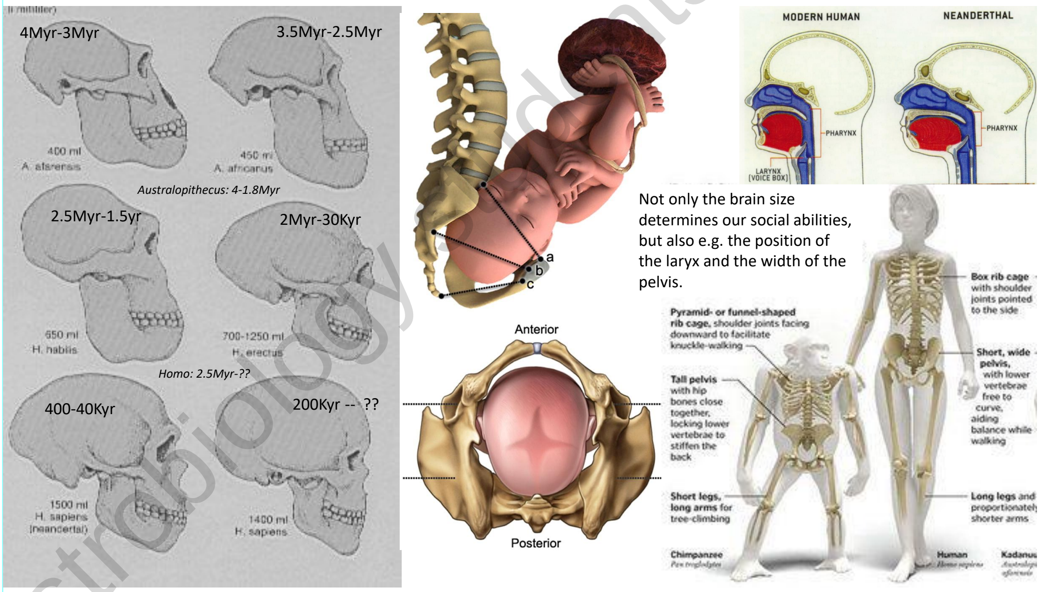


Figure 1.23. The skull of various hominids (left), the birth of a Homo Sapiens, the relative position of the laryx in Homo Sapiens and Homo Neanderthal (upper right), and a comparison of the body structure of a Chimpanzee and a modern Human. The compromise between the size and structure of the human (female) pelvis and human babies's head size at birth, compared to the corresponding structure of a chimpanzee, caused a decissive different evolutionary path of humaninids and chimpanzees that may have been the most important evolutionary step toward us becoming collaborative and peaceful ("human"), as discussed in the text.

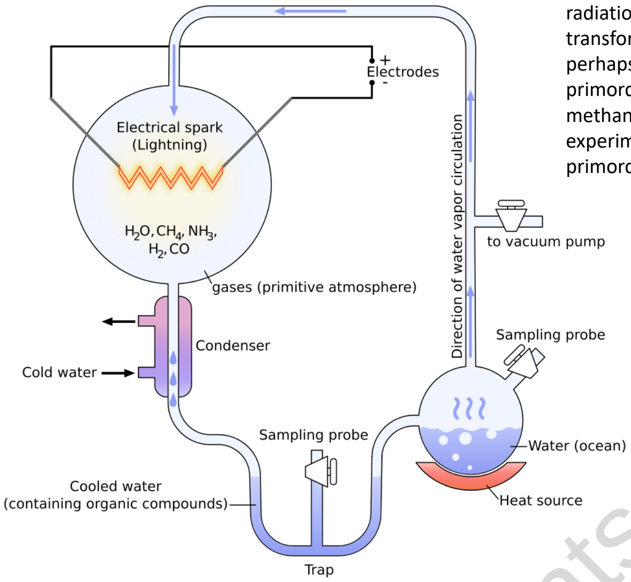
When we speak, one of the two areas in the brain where activity seems to increase is the one called Brocas. This part of the brain also leaves an imprint on the skull, so one can see when in evolution it developed, which seems to be as early as 1.8 million years ago – long before sociological and other paleontological evidences indicate that humans were able to talk. However, Brocas is also active when we use the hands, and it seems therefore likely that our forefathers developed gesticulations 1.8 million years ago, before the language. It seems therefore likely that Homo erectus were gesticulating to one another when they were hunting, and they may have used sounds, but they were not making plans by talking to one another about the hunt. Gesticulation and talking, however, always stayed closely connected in the same area of the brain, and it is still so intimately connected that even blind people gesticulate when they talk to one another. Chimpanzees of course have the ability to gesticulate, and they are known to communicate feelings in face expressions. There is, however, big disagreement about whether chimpanzees have the intellectual capacity to talk (although they are missing the anatomic capacity). When a chimpanzee in the laboratory puts a brick for water and a brick for bird together when it first sees a swan landing on the water, does it mean that it created the word water-bird for swan, or does it mean that it communicates that it saw water and it saw a bird?

It is somehow surprising how large difficulties we have in communicating with other animals on the globe, considering that we have the same evolutionary background and live in the same nature. It is even more surprising that we cannot have an inspiring conversation with another primate whose anatomy is almost identical to ours, with whom we have common grand-grand-grand...-parents only 5 million years back in time, and whose genetic sequence is 99% identical to ours. And even most surprising is maybe that opinion polls show that our prime expectations to the results of the search for extraterrestrial beings, is that they will reveal for us the meaning of life.

In the next chapter we will go into details about physical and biological limitations in communication with extra-terrestrial beings and possible civilisations. Do they exist? Can we talk to them about something meaningful? Can they visit us, or can we even go there?

Summary of some basic biological consepts (from power points)

The Uri-Miller experiment



We calculated elsewhere in the notes that solar UV radiation the first millions of years could have transformed a fresh water ocean to a diluted soup of perhaps 0.1% organic material in the water, “the primordial soup”, provided the atmosphere contained methane, ammonia and water as in the Uri-Miller experiment. A CO2 atmosphere would not lead to a primordial soup.

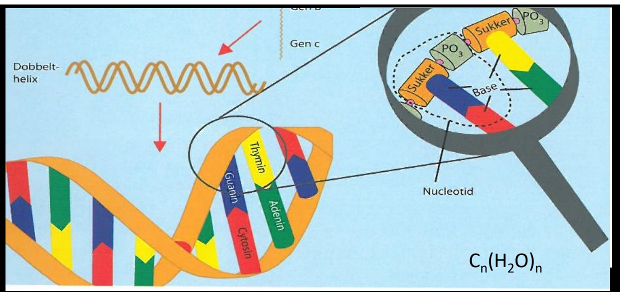
$$f_{\rm organic} = \frac{n_{br}}{d} \cdot m_\nu \cdot t \;\approx\; 10^{-3}\ {\rm g/cm^3}$$

Large organic molecules such as sugar and amino-acids can form in space over long timescales and at low temperatures.

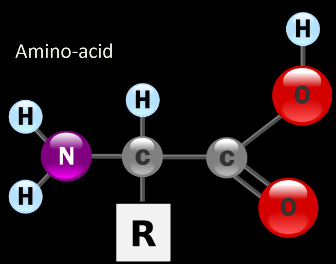
They could also have form in Earth’s oceans, under lightning and UV radiations in a methane/ammonia-rich early atmosphere (but not in a CO2 atmosphere).

If comets delivered the water for Earth’s oceans, they will also have delivered building blocks for life.

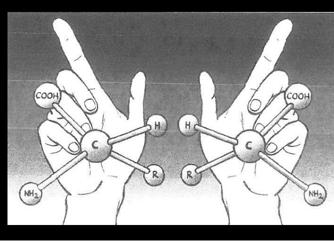
11 of the 20 aminoacids making up the proteins in all living organisms on Earth has been found inside the (cometary?) Murchison meteorite

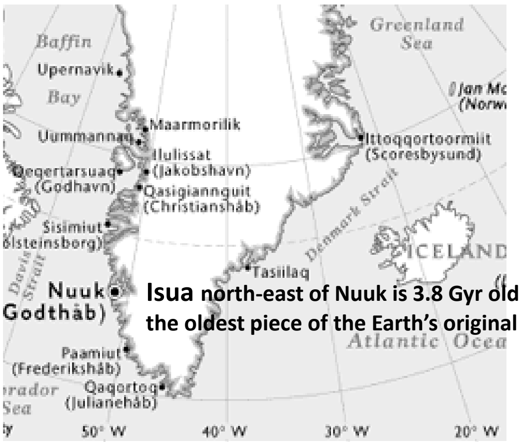


3 of the 5 nucleotide bases of the gene alfabeth has been identified inside Murchison



The amino-acids found in comets (and in the Uri-Miller experiment) are 50% “left-handed and 50% “right-handed”, while in all organisms on Earth they are racemic (100% left-handed).





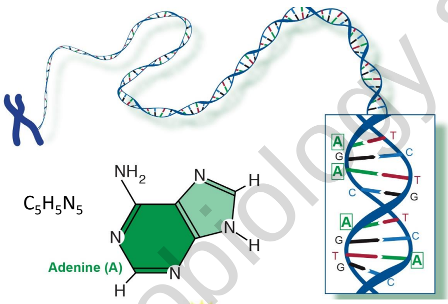
Isua north-east of Nuuk is 3.8 Gyr old -- the oldest piece of the Earth's original crust

If life came from comets, then the same rain of building blocks for life came over Earth, Venus and Mars.

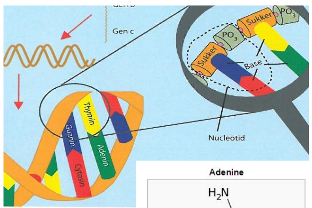
If the building blocks for life originated in-situ then the same material was available for it on Venus, Earth and Mars.

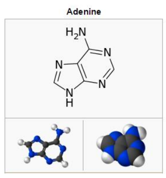
Isua is of the same age as the lunar craters. Was a bombardment with comets responsible both for the lunar craters and the lack of crust on Earth older than Isua?

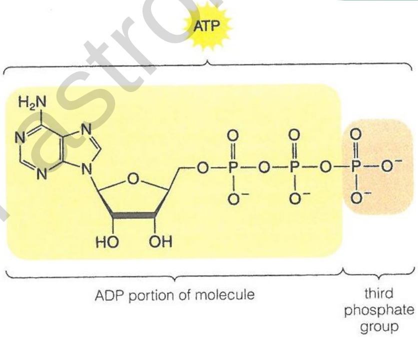
Graphite inclusions in some Isua rocks are measured to have photosynthetic 12C/13C ratio, indicating that life originated (well) before 3.8 Gyr ago.

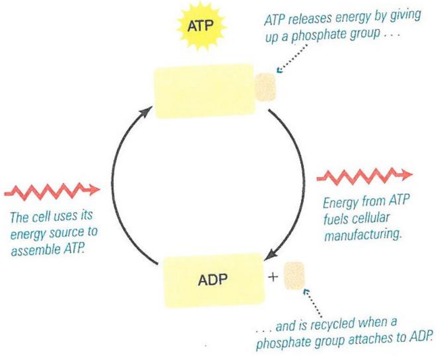


Sugar, phosphate, and amino-acids, may have been freely available in the primordial soup. Also nucleotide bases may have formed spontaneous or have come from comets. The nucleotide adenine could add phosphates to form ADP and ATP. All living organisms use ATP as their cellular energy source.



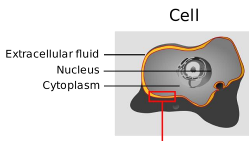






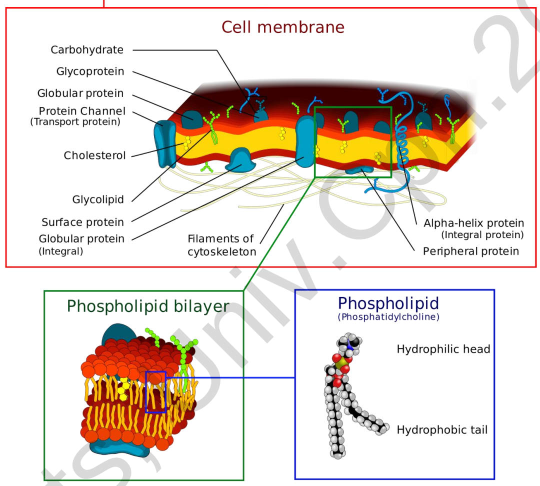
Sugar = (sukker =) $C_n(H_2O)_n$ glucose/ fructose= $C_6H_{12}O_6$ carbohydrate

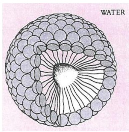
With reproducibly information stored in the DNA molecule and ATP molecules available as the energy carrier, in principle we "just" need also a membrane that could isolate the molecules and processes from the surroundings in order to define a living entity.



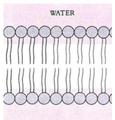
A complex modern biological cell has the DNA inside a cell nucleus, surrounded by the cytoplasm, which consists of 80% water; all of it enclosed by a bilayer membrane.

The primordial soup could well have been able to spontaneously cook up lipid molecules ("fat"). Lipid molecules have a hydrophilic "head" and a hydrophobic tail (i.e. liking and disliking contact with water) and will therefore spontaneously form closed entities with the heads toward water and the tails away from water. We know this phenomenon from oil forming small droplets when poured into water.



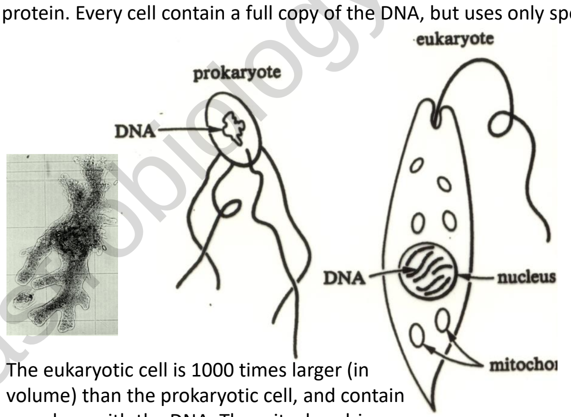


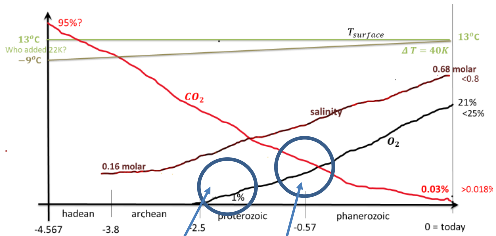
An oil droplet forms spontaneously in water by sticking the hydrophobic tails of the oil molecules together to avoid contact with the surrounding water



A piece of a double membrane where the tails are sticking together to avoid water while the heads stick toward surrounding water on both sides of the membrane.

The human body contain 3 x 10^{13} eukaryotic cells, which each are home to on average 800 mitochondria cells.
The hereditary information is stored as DNA. The DNA in humans consist of 3 billion base-pairs, called the genome, ordered into 23 chromosomes (DNA-strings) containing a total of more than 20,000 genes that each code for a specific protein. Every cell contain a full copy of the DNA, but uses only specific instructions to define its specific function.

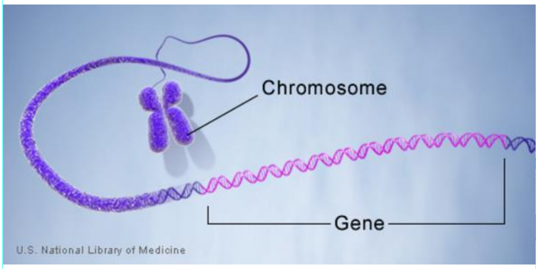


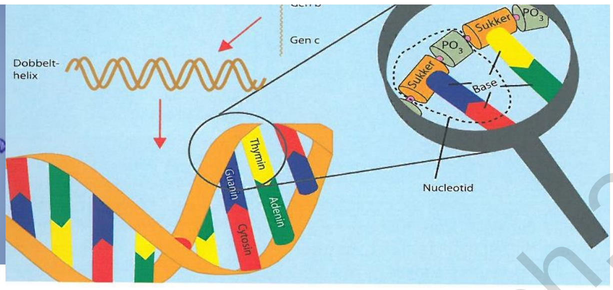


The eukaryotic cell is 1000 times larger (in volume) than the prokaryotic cell, and contain a nucleus with the DNA. The mitochondria are descendants of ancient prokaryotic cells engulfed into the eukaryotic cell. In each of our cells there are 800 mitochondria cells. They produce the ATP energy to our cells.

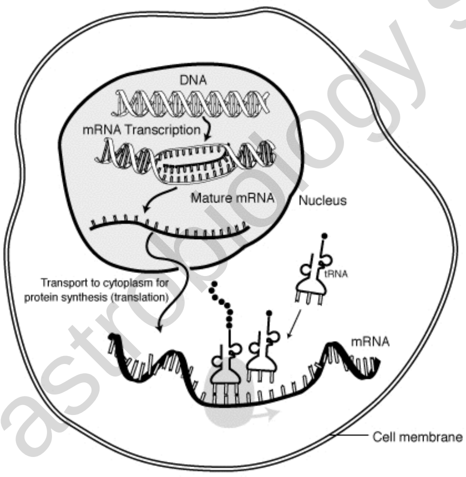
The first eukaryotic cell appeared when the oxygen content in the atmosphere was larger than 1% about 2 Gyr ago.

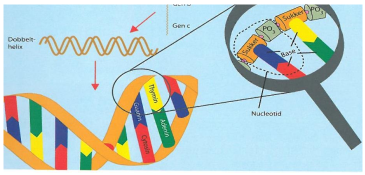
The complexity of the eukaryotic cell allows multicellular organisms – the first simple ones arose maybe 1.5 Gyr ago, but exploded at the Cambrian revolution after snowball Earth.

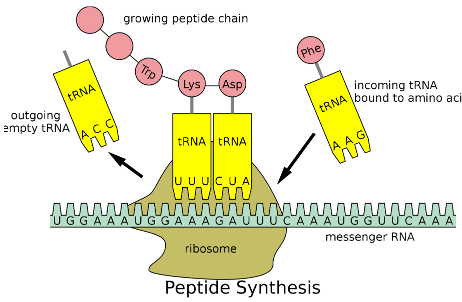




Chromosomes are long strings of DNA that can contain up to a couple of million base-pairs. Humans have 23 chromosomes. Enzymes (=short proteins) can open up the double-helix DNA and let the DNA sequences be copied to RNA molecules. The RNA can then line up the sequence of amino-acids corresponding to the DNA information. Each set of 3 base pairs will in principle code for a specific of the 20 amino-acids life uses. Strings of amino-acids put together in the right way becomes a protein. Strings of the chromosome that code for a full protein is called a gene. Humans have approximately 25,000 different genes. However this can barely be all the information needed to construct an individual human, so something unknown else must also play a role. One hypothesis is that abundant pieces of non-protein-coding sequences do something else of additional importance. The human genome is particular rich in non-protein-coding sequences. The function of the proteins in our body depends not only on the order of the amino-acid molecules, but also on how the protein is folded. The non-protein coding parts of the chromosomes may contain information about how to fold the proteins. Enzymes, peptides and proteins are all chains of amino-acids, but have different lengths and functions.



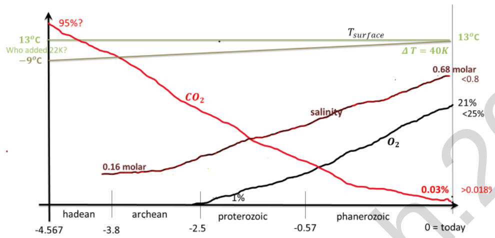




Peptide Synthesis

Messenger RNA (mRNA) transcribe strings of the DNA and brings it out of the cell nucleus to the cytoplasm where transport RNA (tRNA) brings and align the amino-acids according to the mRNA information to form proteins (or "small proteins", called peptides).

Stromatolites are sediments from cyano bacteria colonies; The oldest direct evidence of life on Earth is 3.5 Gyr old stromatolites

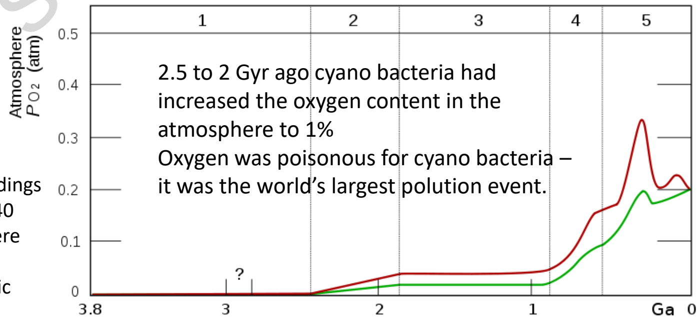


The cyano bacteria, and later on plants, produced oxygen + sugar from CO2 + water via photosynthesis: $6\,CO_2 + 6\,H_2O + \text{visual light} \rightarrow C_6H_{12}O_6 + 6\,O_2$

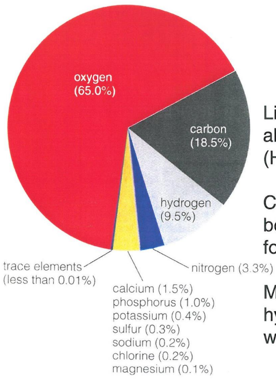
On short timescales the animals' production of CO2 by using the oxygen is in balance: $C_6H_{12}O_6 + 6\,O_2 \rightarrow 6\,CO_2 + 6\,H_2O + \text{energy}$ with the plants, but on long timescales the CO2 production is too small to form a stable balance.

The archean atmosphere ”cleared up” from brownish-coloured septic-tank smelling atmosphere to our present clear blue fresh air atmosphere, but it was poisonous to the anaerobic cyano bacteria so they dyed out in their own polution.

The oxygen content in stromatolite surroundings has been high, just as CO2 content is 10 to 40 times higher in mould than in the atmosphere today.
When oxygen abundance passed 1%, aerobic organisms had an advantage.
...and the archean atmosphere ”cleared up” from brownish-coloured septic-tank-smelling atmosphere to our present clear blue fresh air atmosphere



O_2 build-up in the Earth's atmosphere. Red and green lines represent the range of the estimates while time is measured in billions of years ago (Ga).
Stage 1 (3.85–2.45 Ga): Produced oxygen absorbed by free ion in the oceans; practically no O_2 reach the atmosphere.
Stage 2 (2.45–1.85 Ga): Fe+O_2 being saturation as “rust” in oceans causes small amounts of oxygen to get into the atmosphere.
Stage 3 (1.85–0.85 Ga): O_2 now gas out of the oceans, but is absorbed by land surfaces and formation of ozone layer.
Stages 4 & 5 (0.85 Ga–present): O_2 sinks filled, the gas accumulates



Life is build on the 4 most abundant elements (H,C,N,O) except helium.

Carbon plays a central role because of its ability to form complexmolecules.

Most of the oxygen and hydrogen is in the form of water which is the solvent.

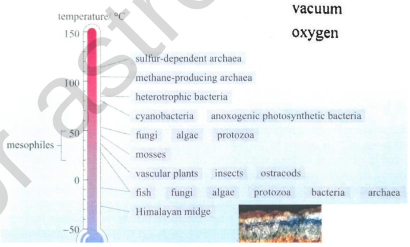
	Percent of total weight	Number of types of molecule
water	70	1
inorganic ions, e.g. Na^+, K^+ and Ca^{2+}	1	20
small organic molecules (< 1000 atomic units), e.g. fatty acids, sugars, amino acids, nucleotides	7	750
large organic molecules (> 100 000 atomic units), e.g. collections of lipids, carbohydrates, proteins, nucleic acids	22	5000

We are mainly made of the most common atoms in the universe, H, C, N, O, and the most abundant (after H2) molecule in the universe, H2O, is also the most abundant molecule in living organisms. The search for extraterrestrial life goes after traces of these, too.

It is, however, remarkable that the Earth is very under-abundant in water and in carbon, because water, CO and CH4 cannot condense at the high temperatures in the proto-planetary cloud where the Earth formed.

What are the physical limits for the existence of life as we know it?

Environment	Limiting conditions	Type	Example
temperature	<15°C	psychrophiles	
	15–50°C	mesophiles	*Homo sapiens*
	50–80°C	thermophiles	*Thermoplasma* can reproduce at >45 °C
	80–115°C	hyperthermophiles	*Pyrolobus fumarii* (113 °C)
radiation			*Deinococcus radiodurans*
salinity	15–37.5% NaCl	halophiles	
pH	0.7–4	acidophiles	
	8–12.5	alkalophiles	
dessication	anhydrobiotic	xerophiles	nematodes, microbes, fungi, lichens
pressure	pressure-loving – up to 130 MPa	piezophiles	
	weight-loving	barophiles	
vacuum	tolerates vacuum		microbes, insects, seeds
oxygen	cannot tolerate O_2	anaerobes	
	tolerates some O_2	microaerophiles	
	requires O_2	aerobes	*Homo sapiens*



On Earth life has adapted to exist in all niches of the globe, but there seems to be places on Antarctica where the temperature and humidity is just simply too low for life as we know it -- is this the limit for life or could something else exist here?

How about Venus and Mars, could something exist and thrive there?