What is Life?

by:

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INTRODUCTION

We consider an egg as alive, but regard the Aurora Borealis as a non-living physical phenomenon. Textbooks of Biology and Physiology offer no explanation.

This is strange. No textbook on jet engines would neglect to define a jet engine, nor would a reference work on Mammals fail to remind us what distinguishes a mammal from other creatures.

ALL THAT REPLICATES IS NOT ALIVE

Stanley Miller who set the scientific world abuzz in 1953 with his synthesis of abundant amino acids during an in vitro simulation of the chemical dynamics of the primordial Earth, declared that the essential difference between life and nonlife is replication.

This is the definition that most of us, when challenged, would repeat. But not with much conviction. Rocks, rivers, galaxies and quarks do not replicate. But then, neither do mules or worker bees. On the other hand, fire replicates, so does rust, crystals, and in many respects clouds too. A nuclear chain reaction replicates (and furiously proliferates), as does free radical damage to cell membranes. None of these phenomena are "alive".

READING, 'RITING AND 'RITHMETIC

In fact life does something infinitely more fascinating and intriguing than merely reproduce and proliferate like fire. It reads and writes in symbols, using the DNA alphabet. This incidentally permits biological reproduction, because the writing process can produce almost limitless numbers of faithful copies of the DNA code, each one of which lists the instructions for the manufacture of a new living individual. At "reproduction" it is therefore not the individual (the living item) that is replicated, but the code. After the new copy of the instructions has been read an individual is produced who is then "replicated", in the case of humans for instance, more or less once every three months (such is the self-destruction rate of life - see below). During a standard human life, lasting three score years and ten, almost 300 brand new issues of that individual are produced sequentially.

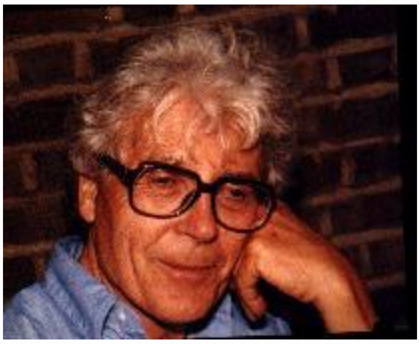
Although reading and writing are highly characteristic of life, certainly as manifest on Earth, I do not believe they are its defining characteristics. I believe that the printing press of life was invented for the same reason that humans reinvented paper and ink versions of it several billion years later. The items for which the encoded building instructions stand are precariously fragile and unstable. If there were no building instructions, encoded in durable and, particularly, reproducible form, the items described by the code would soon be lost for ever.

THE SEARCH FOR LIFE ON MARS

In 1976 two of NASA's Viking Landers touched down on different parts of Mars.

A major objective of those Viking Missions was the search for extraterrestrial life. Clearly NASA did not expect to find butterflies, chimps, dogs, bats, cockroaches, worms or dandelions (the stuff of Biology) on Mars. So what were they looking for?

One of the consultants invited by NASA to aid them in their search for life on Mars was James Lovelock, a prolific British inventor, who, amongst other things, unwittingly invented the microwave oven.

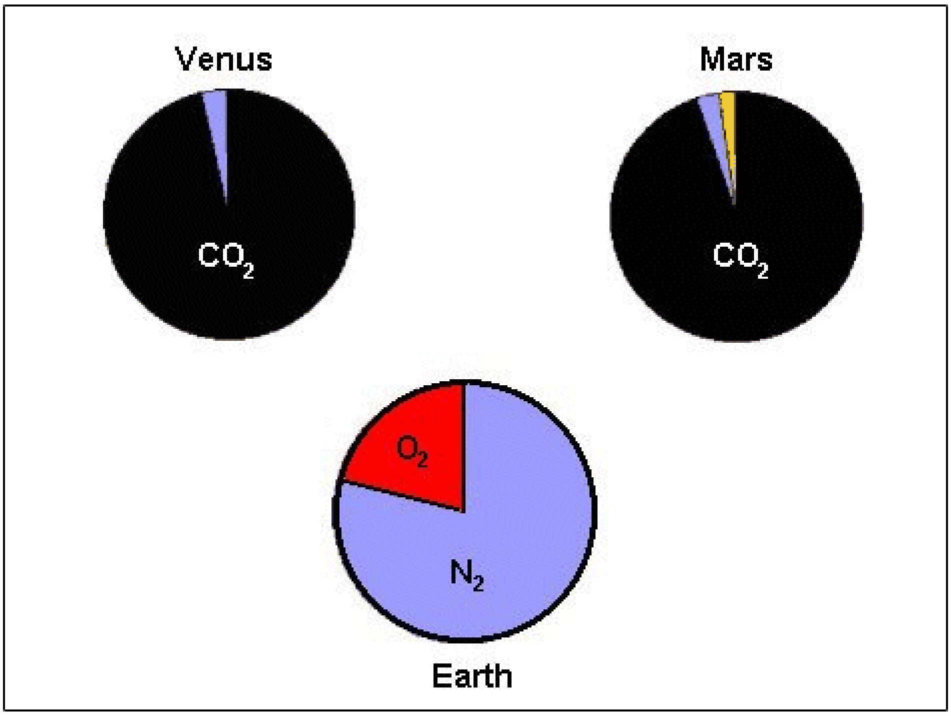


He idly used his contraption to cook potatoes while he was busy with other things. He thus neglected to patent it, and the credit for its discovery went to someone else. While at the Jet Propulsion Laboratory in Pasadena, James Lovelock came to the disconcerting conclusion that it would be totally unnecessary to go to Mars to establish whether there was life there or not. A chemical analysis of the atmosphere (which could be done from a distance) would provide far more pertinent information than a local search at the site of a Mars landing.

Of course the primary purpose of the Viking Missions was not really to search for life on Mars, but simply to demonstrate that NASA could land a sophisticated, fully functional minilaboratory on Mars. The Viking Missions therefore proceeded as planned, producing confusing data that were interpreted as indicating an absence of life on the red planet. Although never acknowledged as such, the alternative interpretation that there was evidence of life, was dismissed, probably largely because it conflicted with James Lovelock's findings that Mars' atmosphere indicated that the planet was stone dead.

THE EARTH BURNS,
THEREFORE THERE IS LIFE

An observer on a space craft, even from beyond the Solar System, could confidently conclude that of all the planets only Earth bears life. Confining our discussion to the three rocky Earth-sized planets, it would be immediately evident that the atmospheres, and rocky surfaces of Venus and Mars are in chemical equilibrium. All the chemical reactions that could have taken place have long ago taken place. No further chemistry is possibly on the surfaces of Venus and Mars. Their atmospheres consist of 95% carbon dioxide, a tiny bit of nitrogen and some trace gases. None of these will react with one another or with the rocky surface. There can therefore never be a fire (a violent chemical reaction) on either planet.



By contrast, the Earth's atmosphere is an extraordinary and unstable mixture of gases. Even if the extraterrestrial observer could not analyse its exact composition, a casual glance at the night side of the planet reveals continents dotted, like a Christmas tree, with chemical fires.

The largest can be seen from space. More, mainly in the form of veld fires, can be seen from an aeroplane. Vast numbers become visible on foot, particularly associated with human activity, but also elsewhere. Violent chemical reactions are the order of the day.

Earth is a very dangerous, flammable planet. It would quickly burn itself out, unless life constantly recreates the high energy chemical compounds that make fires the ever present hazard that they are.

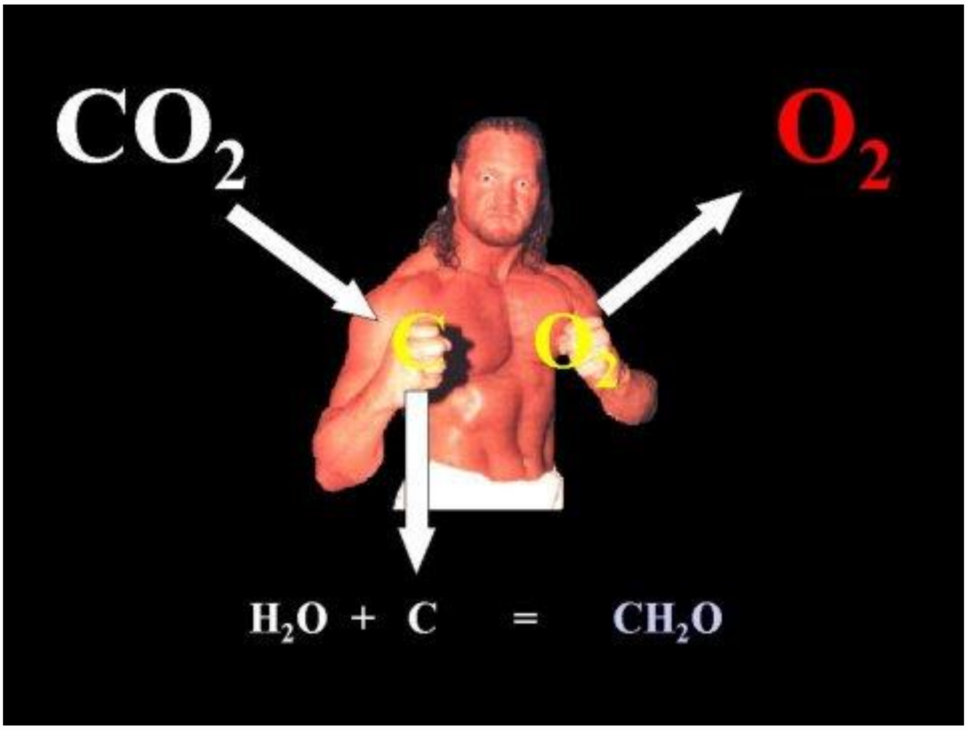
Regular *chemical* fires therefore constitute absolute, irrefutable proof that there is life on the third rocky planet from the Sun*. The Earth burns, therefore there is life!*

LIFE,
THE QUINTESSENTIAL POLLUTER

Life processes rely on fuel, chemical substances with high free energy contents. Such substances may have existed on the primordial Earth. But since such substances are by definition unstable, they would rapidly have disintegrated, releasing their free energy as heat, leaving a mixture very simple low energy materials, such as those on Mars and Venus.

Now it would be possible to travel to Venus or Mars, and, with the aid of an external energy source such as sunlight or an electric battery brought from Earth, to create chemical fuels (high energy compounds) from the materials found on these dead planets. In exceptional cases it would, at least in theory, be possible to do so without producing any exhaust (i.e. confine the chemical disequilibrium to a self-contained fuel tank, without affecting the rest of the planet). For instance, if you could find them, three molecules of relatively low energy acetic acid ($CH_3.COOH$, or $C_2H_4O_2$) can be combined, and their atoms rearranged, to form high energy glucose ($CHO.CHOH.CHOH.CHOH.CHOH.CH_2OH$, or $C_6H_{12}O_6$), without producing any waste products. But this is highly unusual (and rather inefficient), and no human-made chemical factory is so environmentally friendly. Starting with the raw materials on Venus and Mars, it is in practice virtually impossible to synthesise fuel without producing effluents or exhaust. The most potent fuels are produced by stripping the oxygen from carbon dioxide or from water.

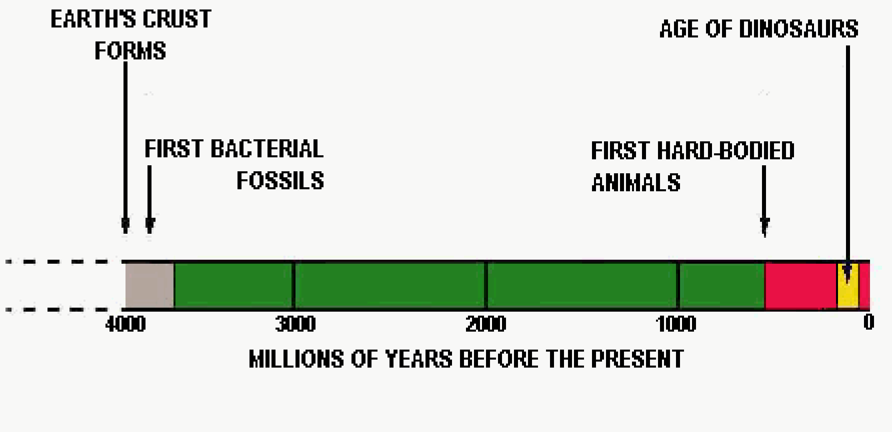
Thus, using sunlight to wrench the oxygen from CO_2 and combining the resulting carbon with H_2O to synthesise carbohydrates $(CH_2O)_n$, large volumes of oxygen gas are exhausted into the atmosphere.



Thus, life's chemical processes produce pollutants. Of the many pollutants that have been produced since life originated on Earth about 3900 million years ago, none is as aggressively reactive, corrosive, or as lethally toxic as molecular oxygen. Each molecule of oxygen gas has two unpaired electrons. It will therefore beg, borrow or mainly steal two electrons from almost any substance that leaves its electrons indecently exposed. A fire is, in fact, oxygen violently stealing electrons!

LIVING ON AN OXYGEN POLLUTED PLANET

Life started on earth almost as soon as it possibly could have started, shortly after a crust formed on its surface, about 4000 million years ago.

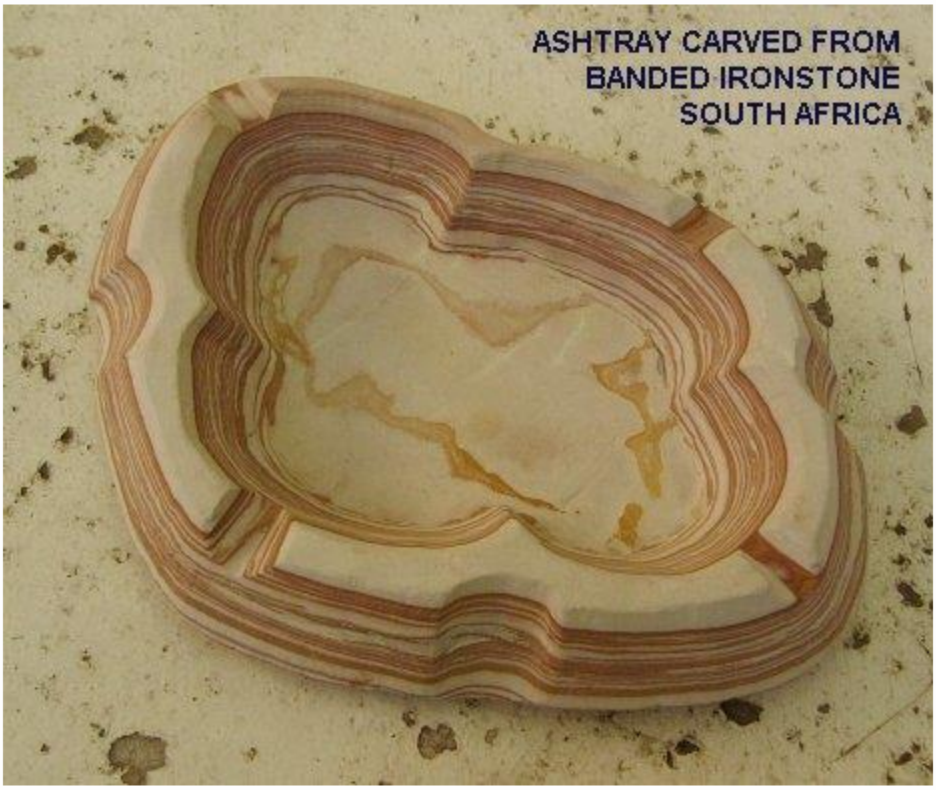


The very oldest sedimentary rocks dating back to this time, some of which occur in the Barbeton area of Southern Africa, contain unmistakable bacterial fossils. Each of these fossils was once a capsule filled with high energy substances (i.e. fuel), the raw materials for which were garnered from the surroundings. The process used is the one described above, which releases oxygen into the surroundings. But even if another process had been used, the production of fuel creates, by definition, chemical disequilibrium.

It is uncertain what external source of energy was used by the very first forms of life on earth, but by 3800 million years ago, cyanobacteria were using sunlight to strip oxygen from carbon dioxide which was then the dominant atmospheric gas, as it is on Mars and Venus today. Carbon, freed of its oxygen, was then combined with water to form carbohydrates in a process we now call photosynthesis.

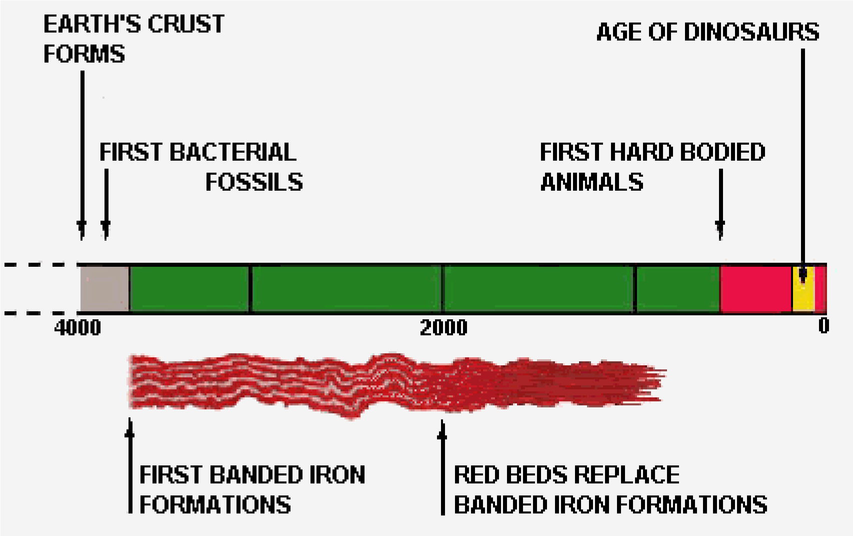
At first the oxygen exhaust just seemed to vanish into "thin air". It is certainly reactive enough that it would have found many substances on the early Earth's surface to oxidise, and thus to disappear (as oxygen gas). The energy captured by the early photosynthesizers in the form of carbohydrates was released by fermentation, exhausting, ultimately, methane and carbon dioxide into the surroundings.

By 3700 million years ago the first signs of seasonal oxygen accumulation in the atmosphere became evident. Iron salts brought down by rivers into ancient lakes rusted (due to the presence of oxygen) during the summer months to form banded iron geological formations (red-rusty layers alternating, like the the stripes of the USA flag, with lighter coloured rust-free layers of ancient mud).



Banded ironstone formations, all older than 2000 million years, are widespread throughout the world. In fact the Detroit motorcar industry is based on an banded iron ore, which originated in an ancient lake which occupied present day Ontario and Northern Michigan.

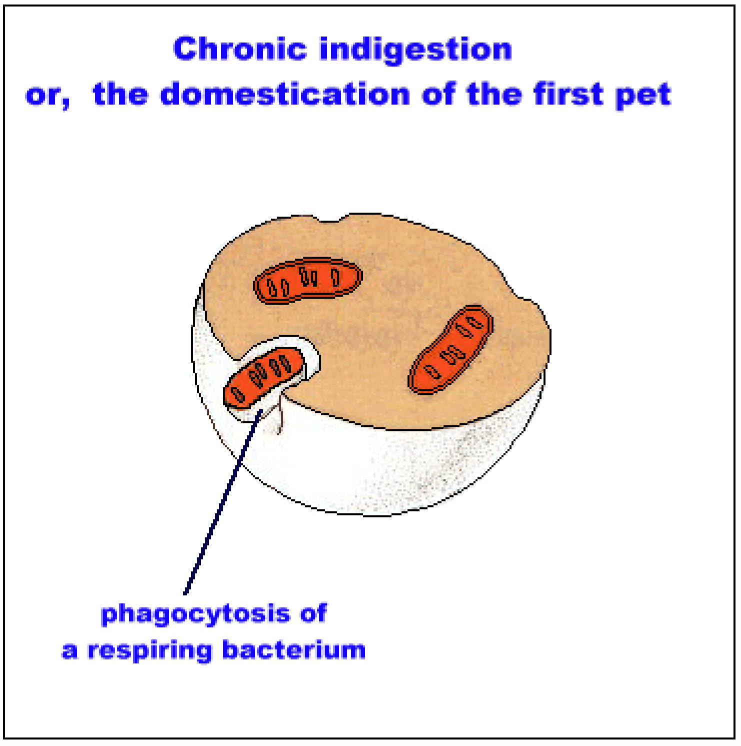
From 2000 million years ago no more banded iron formations were formed. Instead iron deposits now formed red beds indicating that oxygen was no longer disappearing from the atmosphere and lakes during winter. It was present in molecular form all the year round. Atmospheric pollution by oxygen had therefore begun to take on serious proportions.



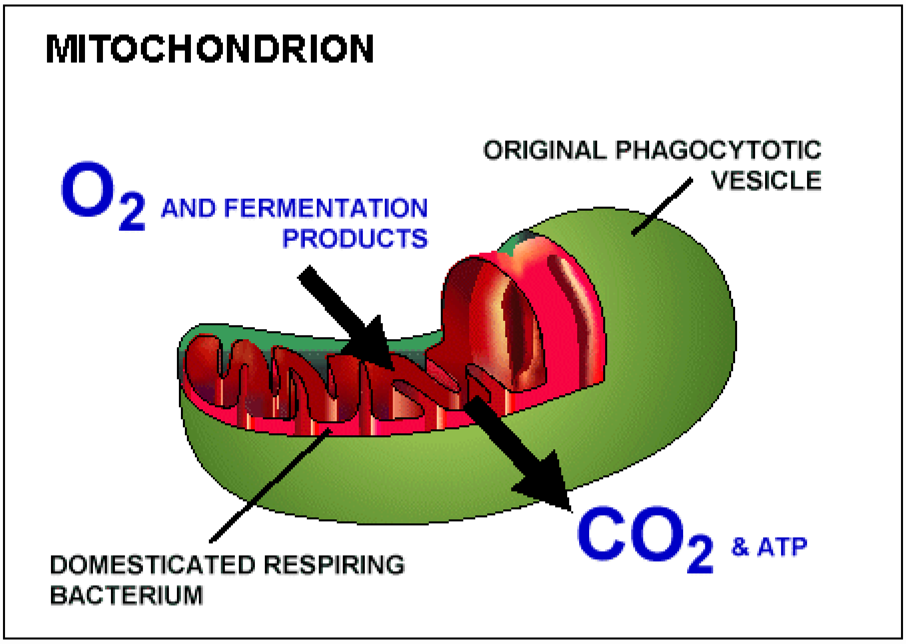
PRIMITIVE INDIGESTION
AND THE DOMESTICATION OF THE FIRST PETS.

A few bacteria evolved the ability to use this oxygen to squeeze more energy out of the breakdown of carbohydrates than the fermenters were able to do. In addition they could, for the first time, utilize the vast quantities of oils and fats that had accumulated in the seas and lakes during the previous 1500 million years (from discarded cell membranes). Fats cannot be fermented. In fact, without oxygen they are virtually indestructable - the "plastic pollution" of the Archean Eon. But in the presence of oxygen fats burn fiercely, yielding 50 ATP molecules per 6-carbon unit compared to only 38 (per 6-carbon unit) when carbohydrates are metabolically burnt, and 2 when carbohydrates are fermented. Burning fats (and carbohydrates) was a highly risky process, which few organisms dared undertake. There must have been many casualties before all the safety mechanisms (dismutases and other fire extinguishers) were in place. Apart from the photosynthesizers (who could not hide from the atmosphere if they were continue photosynthesizing) probably only one lineage achieved success in harnessing molecular oxygen for this purpose.

The remaining bacteria hid in damp soil (oxygen is not very soluble in water), preferably under a reducing blanket of organic detritus, to become today's anaerobes. The others survived, probably by mistake, after a non-fatal case of indigestion.

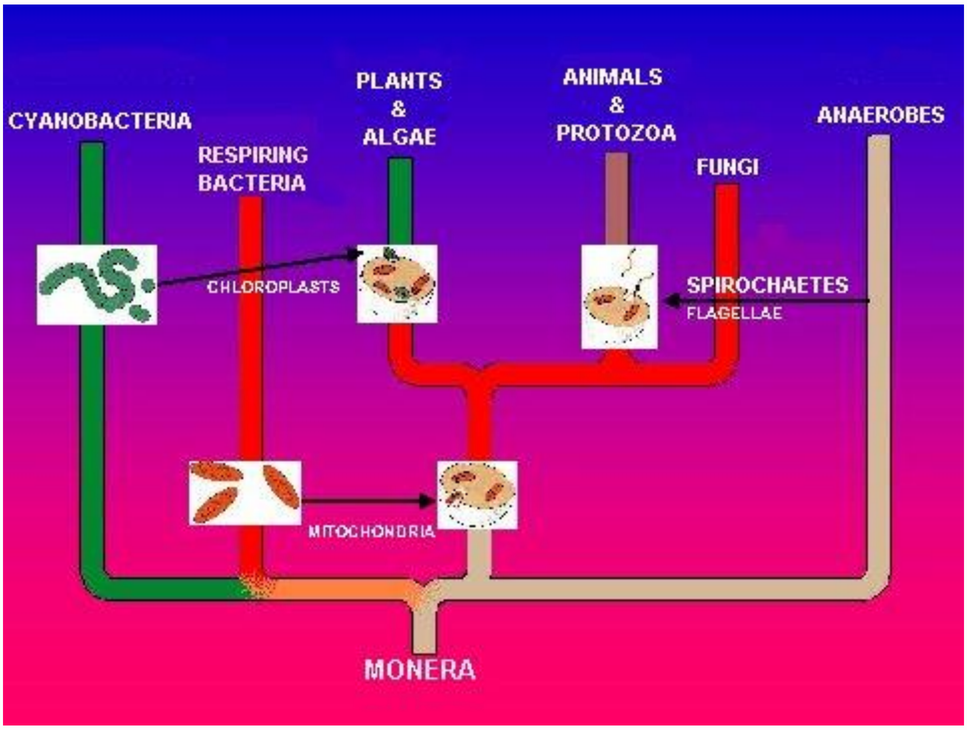


Just as macrophages today phagocytose oxygen-loving Mycobacteria, but are then unable to digest them, a group of free living "macrophages" probably had the same happen to them 2000 million years ago. A stalemate and subsequent truce eventually developed between predator and prey. The predator realised, to its delight, that it could now expand its range into the toxic, oxygen-polluted environment, knowing that its undigested oxygen-eating hitchhiker kept its cytoplasm virtually free of this corrosive, poisonous gas. The hitchhiker was a veritable oxygen vacuum cleaner.



The tamed prey, confined to a phagocytotic pen, became life's first domesticated animal. The arrangement was clearly mutually beneficial, as it has persisted to the present day. That ancient "macrophage" with its domesticated pet became the ancestor of all the eukaryotes: every present-day protozoan, alga, plant, fungus and animal.

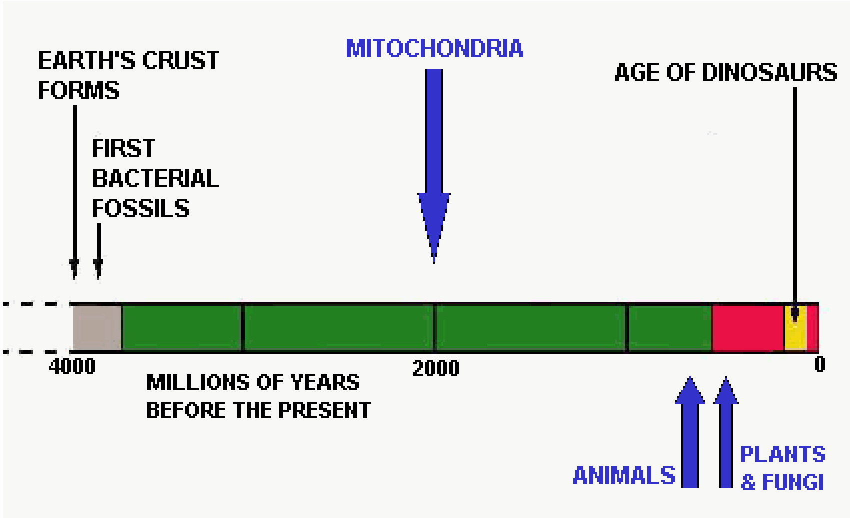
The hitchhiker settled into the role of the mitochondrion, which retains its own circular DNA, its own cell membrane, and considerable metabolic autonomy, and a predeliction for fats. (It detests carbohydrates, which it will not take up, except in fermented form!) It also reproduces independently of the host cell, and prudishly eschews sex. Its main role is still to act as the host's oxygen vacuum cleaner, keeping the cytoplasm clean, safe, anoxic, *and* comfortably hypercapnic (soothingly high carbon dioxide concentrations) into the bargain. A further spin-off from this primitive animal husbandry was that the host could feed the pet its fermentation products (although it much prefers fats), and then milk that pet for ATP.



A third, but poorly understood, spin-off from the host-mitochondrial relationship has been the tendency of these organisms to aggregate in dense societies that eventually formed the basis of multicellularity. Indeed all multicellular organisms on Earth are eukaryotes with their herds of domesticated mitochondria. Did these creatures originally huddle together to create localised pockets of comfortable hypoxia (and soothing hypercapnia) in an increasingly chemically hostile environment?

HIDING FROM OXYGEN
BEHIND A LAAGER OF SKIN OR BARK

Whatever the origin of multicellularity, it permits large families of cells to retreat into a laager. Safely ensconced behind a tough, oxygen- and water-proof integument, they could regulate their immediate environment independently of the polluted exterior. Behind the integument it was back to the good old days, when oxygen was scarce, and carbon dioxide pleasingly plentiful. Organisms could now live in a comfortable, portable environment - in a relic of an ancient sea, exposed to a portable atmosphere that has not existed for 1000 million years ago.



But it requires a lot of energy to live in such air- and water-conditioned circumstances.

Nevertheless, from now on it mattered very little how polluted the atmosphere became. Plants which had domesticated not only the mitochondrion, but also teams of cyanobacteria which had become their chloroplasts, took photosynthesis to its limits, discharging vast quantities of oxygen into the atmosphere, and depleting the atmosphere of virtually every vestige of carbon dioxide. Within only a few hundred million years the oxygen concentration in the atmosphere rose from 5% to its present 21%. This is dangerously close to the 25% at which fires break out spontaneously. Even at 21%, on hot, dry days, veld fires break out at the twinkling of a spark, as we know only too well, here in the Cape (of Southern Africa).

CARBON DIOXIDE DEPLETION

Serious carbon dioxide depletion did not begin with green plants. Living cells maintain an intracellular environment that, almost from the beginning, has been markedly different from that of the surroundings. Sodium chloride, abundant outside the cell, is poisonous inside the cell. But nothing is as poisonous as calcium. Molecule for molecule calcium is many times more poisonous than cyanide. Both sodium and calcium are therefore vigorously pumped out of the cell. To keep particularly the calcium at bay, many cells render it insoluble by combining it with carbon dioxide to form extracellular calcium carbonate. This can be discarded or used as armour, or various forms of structural support (i.e. a skeleton).

Life is opportunistic, if nothing else.

The effect has however been to trap billions of gigatonnes of atmospheric CO_2 in the form of calcium carbonate, most of which sank to the ocean floor to form immense geological structures (lime stone, coral, dolomite and marble).

The evolution of green plants was accompanied by the invention of lignin, the chief ingredient of wood. This in itself would not have depleted the atmosphere of carbon dioxide as effectively as it did, were it not for the fact that no organism could digest it at the time. Vast quantities of undecayed wood therefore heaped up during 50 million years, to become buried as coal some

300 million years ago. That coal was once atmospheric carbon dioxide. Coal deposition effectively ended with the evolution of fungi and their ability to digest lignin.

"THE APPEARANCE OF HAVING BEEN DESIGNED FOR A PURPOSE"

Richard Dawkins

Consider an extraterrestrial scientist who by sheer bad luck landed in the middle of the Namib Desert. The very high oxygen concentration in the atmosphere would puzzle him (we assume that anyone who goes to an oxygen saturated planet just "because it is there" must be male). Try as he may, however, nothing at the landing site will burn. Reluctantly he concludes that the oxygen is of volcanic origin, and Earth is devoid of life.

He then happens upon a watch. Its structure is quite unlike that of the rocks and sand, and when he eventually discovers that it can be wound up, he discovers that the little hand turns through exactly 720° (two complete turns) for each revolution of the Earth on its axis. It does so even in the dark, and in outer space. He concludes it is a time piece, although what use such a contraption could be to anyone on Earth, where the day-night rhythm, and the passage of the sun and stars across the sky, is already strikingly evident, remains puzzling. Yet that it was "designed for a purpose" is inescapable. A machine like that does not happen by chance.

Richard Dawkins points out that life gives us the same overwhelming conviction that it was designed for a purpose. It is this ("the appearance of having been designed for a purpose"), he says, that distinguishes life from non-life. In Socratic philosophic jargon life is endowed with "teleology".

Teleology is a very dangerous concept, and the source of probably more hubris than all of mythology put together. It is more an emotion than a scientific principle. People see design in objects and phenomena that others, in a less romantic mood, would deny have teleological explanations. Thus, people see purpose in the tilt of the Earth's axis, stating that the resulting seasons are designed to give plants well deserved periods of rest. Similarly, ice forms on the surface of water out of consideration for the fish and other creatures in the pond. But how does one distinguish this nonsense from the very real and unavoidable sense of design evoked by the cardiovascular system, or by the migration of birds?

The Second Law of Thermodynamics states that "entropy" in the universe increases relentlessly. "Entropy" is a measue of the structureless diffuseness of heat and matter. Thus, the universe is irreversibly *en route* to a soup of uniform warmth and evenly spread atoms, totally lacking in gradients of any kind (e.g. heat gradients, concentration gradients, electrical potential gradients, pressure gradients etc.). Physicists, in fact, claim that time is just a measure of the increase in entropy (or loss of gradients) in the universe. Since there can never be a net decrease in entropy, the arrow of time always points in the same direction.

Thus, if one were to burn a log of wood in a room, the heat, carbon dioxide, water vapour, and, eventually, even the ash would spread out evenly throughout that room. Structure has disintegrated into the diffuseness, or structureless uniformity. The even spread of heat, carbon dioxide, water vapour and ash would never, in all eternity, spontaneously return to the corner where the log had originally been, let alone recombine chemically to form a log again. A video showing such an event would clearly be being played backwards. Yet life does just that! A plant growing in the corner of the room would quite literally vacuum up the carbon dioxide, water vapour and ash to recreate a log. (It does so using energy from the sun, and not the heat that was originally given off by the burning log. So it does not really flout the Second Law of Thermodynamics; it only looks that way.)

Very low entropy systems, in themselves, tend to evoke the emotion of teleology.

However, consider our Extraterrestrial in the Namib. Instead of finding a watch, he finds a beautiful, perfectly formed, quartz crystal. Assuming that where he comes from there are no crystals (he comes from a gaseous planet), I am sure that that alien would be able to go on a highly successful lecture tour with his find, and encounter no more trouble convincing his audiences that there is life on Earth than if he had returned with a watch. The perfect geometric shapes, absolutely flat surfaces and sharp, straight edges represent a level of organisation and order that just should not occur in the inanimate universe. It has all the hallmarks of "having been designed for a purpose".

We, of course, know that a watch constitutes proof of life on Earth, but a quartz crystal does not.

The difference is, I believe, that living structures not only give the impression that they have flouted the Second Law of Thermodynamics, but they also seem to reverse cause and effect. It is a fundamental, common sense, but nevertheless absolute principle that "causes" always precede their "effects". Thus, following the arrow of time, events will always be arranged in a cause-followed-by-effect order. But, consider a flower. The reason it is brightly coloured, has a sweet smell, and is baited with nectar is because of the need to attract bees who will then spread that flower's pollen to other flowers, thereby setting the reproductive process in motion. It, therefore, seems as if "cause" (the need to attract bees) and "effect" (the appearance and smell of the flower) have been time-reversed, with the "cause" occurring *after* the "effect". It is particularly this apparent time-reversal of cause and effect that convinces us of "purpose", or teleology. Stated differently, teleology is the description of events in a time-reversed manner (e.g. a meeting with your boss at 8:00 am "causes" you to drive your car out of the driveway at your home at 7:00 am).

So Life appears to reverse time in two ways: it seems to reverse time with the creation and maintenance of steep gradients (i.e. thermodynamically unlikely structures), and by its apparent time reversal of cause and effect (i.e. "having the appearance of having been designed for a purpose").

A major component of this "time-reversing" activity is homeostasis, otherwise known as negative feed-back control. This rectifies Second Law of Thermodynamics damage on a moment to moment basis. The warm body of a mammal loses its heat with time, a process that would normally inexorably result in the loss of the heat gradient across the skin of the animal. But homeostats constantly "turn the clock back", reinstituting the steep heat gradient between the animal's interior and its environment of a few minutes ago. It is this ongoing repair of Second Law of Thermodynamics damage that defines *being alive*. Much of the "purpose" we associate with life is, in fact, this constant returning to past states, whether it is the relatively "simple" maintenance of the heat gradient across the skin of a mammal or bird, or the recreation of a log of wood out of carbon dioxide and water when a flower is pollinated, a seed develops, which then germinates to grow, eventually, into a tree.

CONCLUSION

Energy consuming negative feed-back systems (i.e. homeostats) are unique to life, and, in my opinion, its defining characteristic. The discovery therefore of an air-conditioned cave on Mars would be compelling proof of the existence of life on that planet, as would any construction that constantly recreated chemical, pressure or electrical gradients in apparent defiance of the Second law of of Thermodynamics.

We recognise LIFE, and the living processes all around us because we see containers of relic environments from billions of years ago that are actively maintained in this unlikely state by batteries of energy consuming negative feedback controllers (pulmonary air composition homeostats, blood glucose homeostats, plasma sodium chloride homeostats, plasma osmotic homeostats, body temperature homeostats, blood pH homeostats, blood pressure homeostats, stomach acid homeostats, etc.). The moment the homeostats stop working we declare the container of these unlikely physical and chemical gradients to be "dead" or a "corps".

Indeed, without operational homeostats, corpses very quickly disintegrate, rot, or burn to become one with the surroundings. The rate at which this happens, especially when set alight, gives an indication of how far life is out of equilibrium with its surroundings, and how fierce the ongoing battle is between the homeostats and the Arrow of Time.

Thus, if there is a "vital force", our present understanding suggests that it is primarily a creature's armamentarium of energy consuming homeostats.

And homeostats are the stuff of Physiology.

Illustrations by Ann Koeslag Mail me)

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