COMPLEX SYSTEMS, LIFE, & their ORIGIN

The true complexity of real solids and liquids is frightening to contemplate. They do NOT look like simple models of crystals and molecules. Instead there is an amazing hierarchy of patterns that develop in them, and in their dynamics.

Physicists and mathematicians have named some of these features. They talk, eg., of 'chaos', or 'turbulence', referring to hierarchical structures in fluids. Real solids & liquids move between a vast number of possible states, impossible to predict. Many inanimate structures, and all biological systems, are not in thermal equilibrium – they are driven by energy either from outside (typically but not always the sun), or from internal chemical reactions.

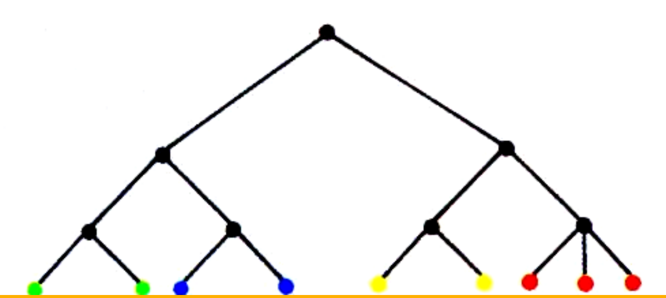
This allows them to evolve and, under certain circumstances, form ever more complex structures as time goes on. The existence of autocatalysis makes the formation of complex structures (including what we call life) inevitable in our universe. Life originated on earth by a series of accidents, which were contingent upon specific conditions on the planet – thus life elsewhere will likely look VERY different. Complex molecules form even in space, on, eg., interstellar grains.

Biological systems on earth, & some artificial structures like plastics, are at least partially made from 'soft matter', with large 'floppy' molecules, unstable to too much heat, but dependent on the sun's energy and/or radioactivity.

Even at the very lowest temperatures, quantum tunneling still drives some complex motion. Quantum mechanics is essential to understand the structures formed in biology.

COMPLEX MICROSTRUCTURE in SOLIDS

Even in simple inanimate solids, complex hierarchical structure forms naturally. Simple objects like window glass have an elaborate structure which is not apparent from the completely disordered spatial arrangement of the atoms. Crystals of course look highly ordered, but only microscopic crystals are common in Nature (a rock is a conglomerate of millions of microcrystals)



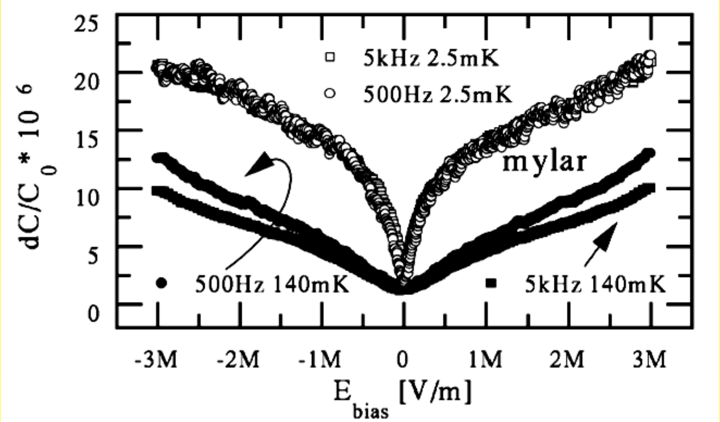
The hierarchical structure of 'glassy states' in a disordered solid

Even in interstellar space one finds 'interstellar grains' and polycrystalline dust particles, with an organized internal & surface structure – also found on rocks and sand on earth. One way complex molecules may have formed on early earth was on such surfaces, which both catalyzed and formed a template for their rapid synthesis. Interstellar grains, discussed later, are Typically C plus impurities, like the graphite in pencils, with a 'sheetlike' atomic structure acting as a template.

The surface of a lump of graphite, with its layered structure visible. Interstellar grains and dust look similar.

On earth, solid objects – rocks - formed initially by cooling of the hot liquid earth. Thermal energy drove chemical reactions – & it still does, along with energy from radioactive decay, & the sun.

But even at extremely low temperatures, where conventional chemical reactions have stopped, quantum tunneling still allows things to change in time – the same thing can happen, very slowly, even in the depths of space, far from stars. So quantum mechanics drives change, & structure formation, everywhere in the universe.

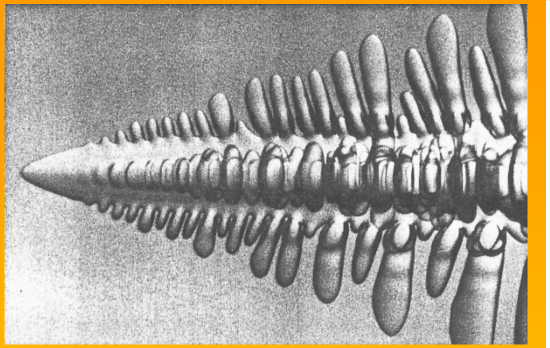


Experiments on mylar and on SiO_2 glass, showing how the capacitance is still changing even at only 2.5 mK above absolute zero! Most solids show this behaviour.

LARGE-SCALE PATTERN FORMATION in SOLIDS & LIQUIDS

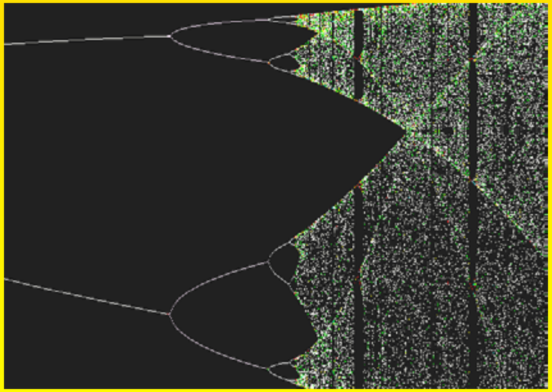
At our 'macroscopic' scale, one sees patterns forming – these may be affected by the microscopic structure, but they arise because of complicated 'collective' motions involving many sub-units together. The patterns include waves, vortices, and also much more complicated structures.

There is of course no purpose or design here – these structures arise from very simple interactions between the sub-units, with the addition of external energy. But in the real world they act as the templates or basic architectures used by most of the animate & inanimate objects that we see around us – ranging from simple fluid flows to the structures of plants and animals.



ABOVE: dendrite formation
BELOW: growing snowflakes

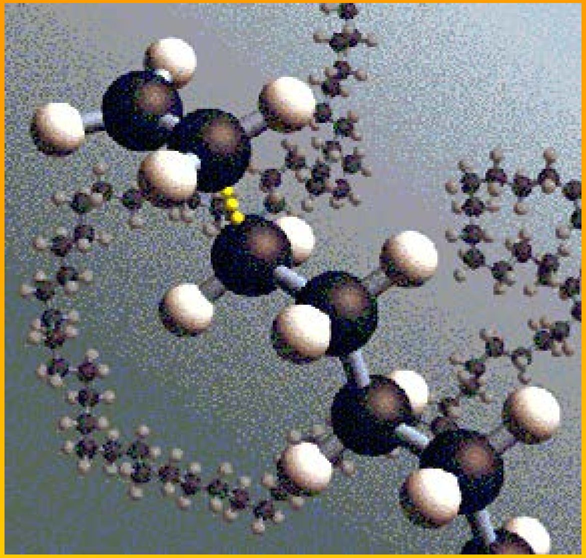
ABOVE & below: Vortex wakes



ABOVE: Period doubling to chaos – the oscillation modes of a system increase in number as an interaction is changed

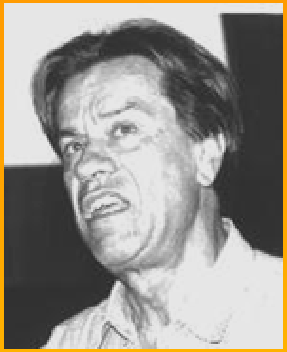
Beginning in the 1960's, both biologists & physicists began to speak of the 'emergent properties' of large systems – properties which did not exist at the small scale, which cannot easily be predicted & which often not depend on the form of the microscopic interactions.

SOFT MATTER



Chain of ethylene molecules (polythene)

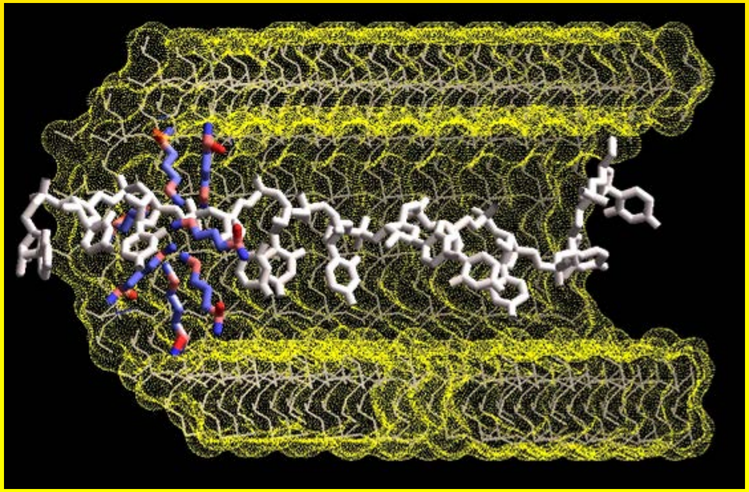
Solids are hard because of quantum mechanics, which creates strong bonds. However larger, more complex molecules are very 'floppy'. Only carbon-based large molecules can even hold together, because C-C bonds are very strong. Long chain structures with repeated C units form polymers which can assemble into a messy disordered network like rubber. Repetition of very long sequences of an 'alphabet' of a few different amino acids, in pairs of chains which can be linked or 'unzipped', gives DNA & the 'genetic code'. Proteins are malleable assemblies of complex folded chain structures.



PG de Gennes (1932-2007)

The general physical properties of 'soft matter': rubber, polymers, emulsions like yoghurt, etc., are now well understood (de Gennes & others). However in living things molecules are constantly changing, & the essence of this is not in the structure of the molecules or their constituents, but in the inter-connected *processes* they are involved in. One talks of 'dissipative structures' far from thermal equilibrium, exchanging material & info in a connected network of processes.

Living organisms are amongst such systems. Our knowledge of these is limited – but biologists & nanoscientists are starting to modify these structures to make new ones of their own. Such work raises profound ethical questions, & may be very dangerous, to us and other living things.



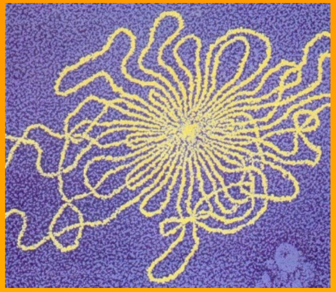
Artificial DNA/nanopore system

Structure of RAS-RID protein

MOLECULES ENCODING LIFE on EARTH

The DNA double helix molecule

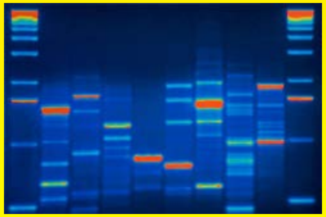
A key step in the evolution of life on earth was the evolution of RNA and DNA molecules. In our current understanding of 'life as we know it', life needs a copying mechanism to carry information about a living object to Its descendants. Note this isn't SUFFICIENT for life – even computer programs have it. But it's NECESSARY, otherwise no organizational structure can be maintained over time.



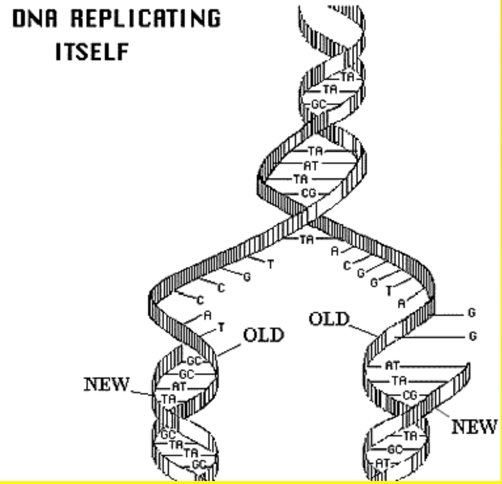
A virus dissociating: the very long RNA molecule is starting to unravel.

The RNA molecule can replicate, & also catalyzes itself – its formation in the early history of the earth was crucial, & many viruses still have a genetics based on RNA. However the error rate in passing down info is high, leading to a very high mutation rate, and loss of info – so this method does not work except for very simple systems, where these mutations are not so important (this is why viruses mutate so fast).

The DNA replication mechanism is common to all species of life on earth, & to some viruses – it first appeared roughly 4 Gya ago. The key is to have 2 chains of long molecules (each one basically an RNA), made from amino acids, which pair off and can be zipped/unzipped together. A copying error now shows up because the zip doesn't work properly - the error can be corrected. Now huge amounts of info can be transmitted to descendants. A small mutation rate is essential - new variations can then be tried – but it must be kept very small.



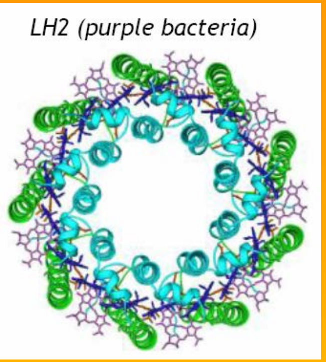
A DNA fingerprint, from a crime lab – it Uniquely identifies the organism from which it comes.

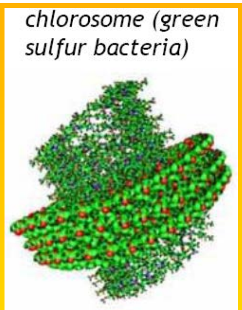


The DNA unzipping – the 'base pair' amino acids are labelled by letters A,C,T,G. An unzipped half will then attract base pairs that match up to form a new DNA double helix (replication)

The sequence of amino acids encodes info – it is then 'expressed' when the chain unzips to make proteins (ie., to make the organism). The DNA is the 'instructional plan' for living things.

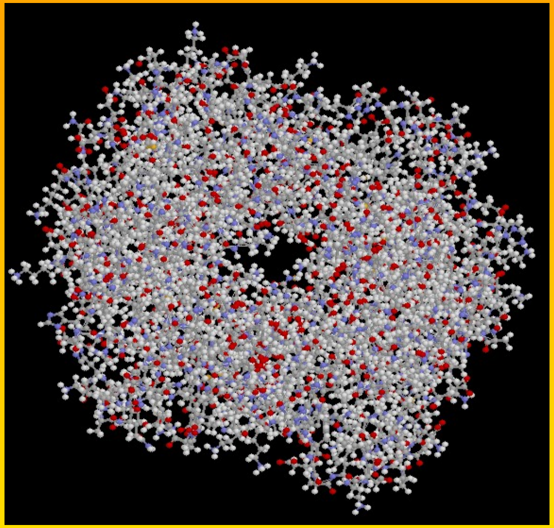
PROTEINS & MOLECULAR MACHINES





ABOVE: Two different LHMs

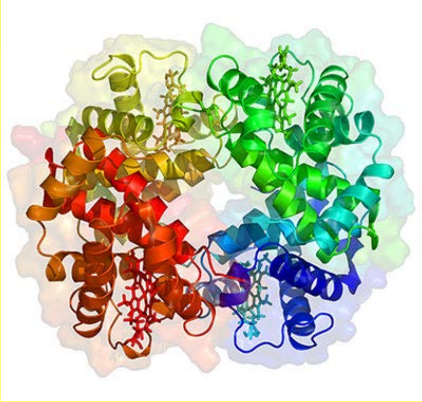
If DNA provides the architectural plans for living things, the bricks, Mortar, and furnishings are the protein molecules, made according to the instructions provided by the DNA sequences. These come in a very large variety. These range from small (eg. Haemoglobin, responsible for oxygen metabolism, has a molecular weight 38,000, ie., 38,000 H atom equivalent), to very large (some light harvesting molecules, or LHMs, responsible for photosynthesis, have MW ~ 10 million).



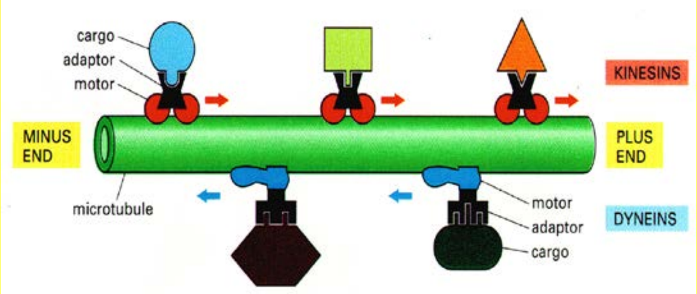
A simple protein – haemoglobin (Molecular weight = 38,000)

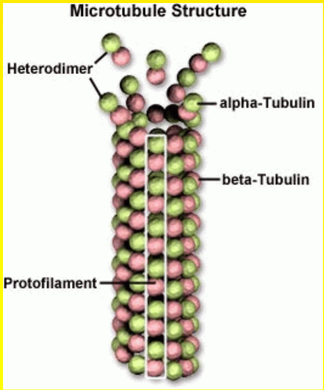
All proteins have the basic same structure, of long C chains, having lots of bells & whistles attached in the form of small sidechains of molecules. These then curl into long helical structures, which then fold up into unique shapes. These shapes are easily disrupted, either chemically or by heat.

Materials like proteins diffuse around the body via the bloodstream or sapstream. But inside a cell they can be moved in a more organized by 'molecular machines', which use energy to change shape, and which can then grab & transport proteins along 'conveyer belts' called microtubules.



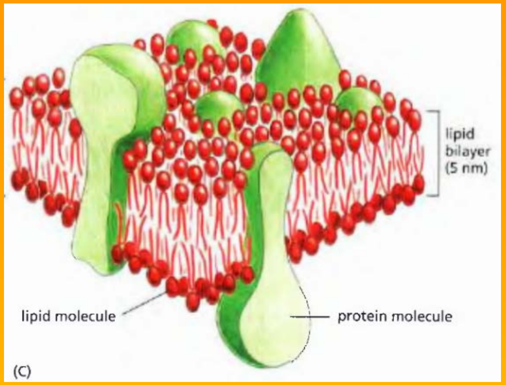
Haemoglobin structure – carbon skeletons with various attachments curl into helices, which fold up into unique shapes.





Cells have an internal scaffolding of microtubules; molecular machines transport molecules along these, to be assembled or dismantled.

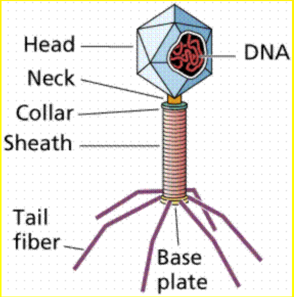
CELLULAR & VIRAL STRUCTURES



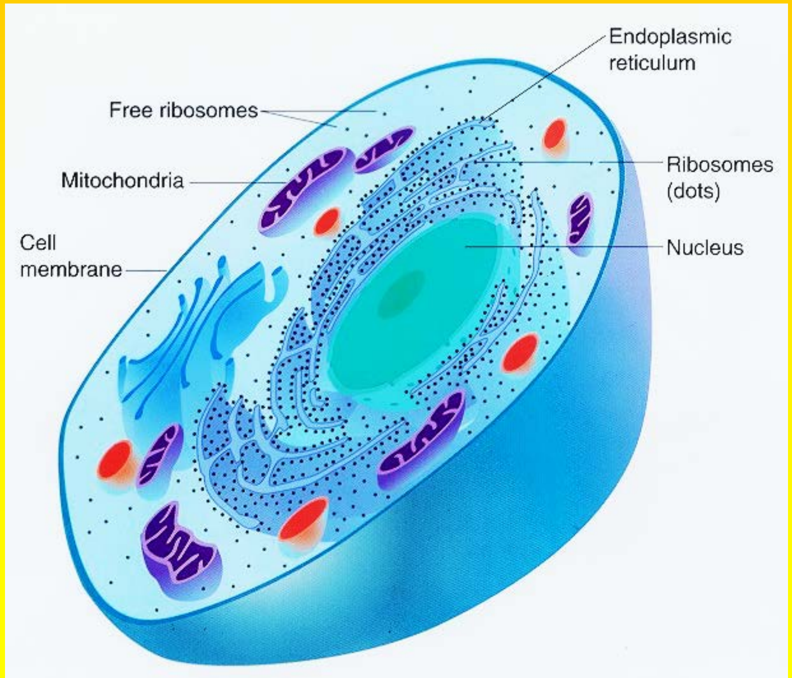
Cells first appeared on earth some 3.7 billion yrs ago. They are best characterized as extremely sophisticated factories – a large variety of molecules are synthesized from raw materials which float around inside the cell, & which enter through the cell membrane.

The cell membrane looks a junkyard at first glance – large numbers of macromolecules straddle the membrane, which itself is impermeable. Some of these macromolecules act as gates, allowing through certain molecules – others react to molecules outside the cell, & then undergo changes which initiate chemical reactions in the cell. In effect, instructions are passed into the cell. As discussed on the last slide, most of these instructions concern the manufacture and assembly of proteins. However the totality of processes going on inside a cell at any time – a connected network of 'factory operations' – is enormous, & still being unravelled (as are the even more complex relationships between cells in a multicellular organism).

At a smaller scale one has viruses, which are parasitic upon cells, and often invade them to plunder their DNA. However, the cell nucleus in eukaryotic cells also evolved from an ancient bacterial invasion. The nucleus is a former virus.



A virus piercing the cell wall – structure shown above



A eukaryotic cell. The info is contained in the nucleus. Factory operations are done outside the nucleus.

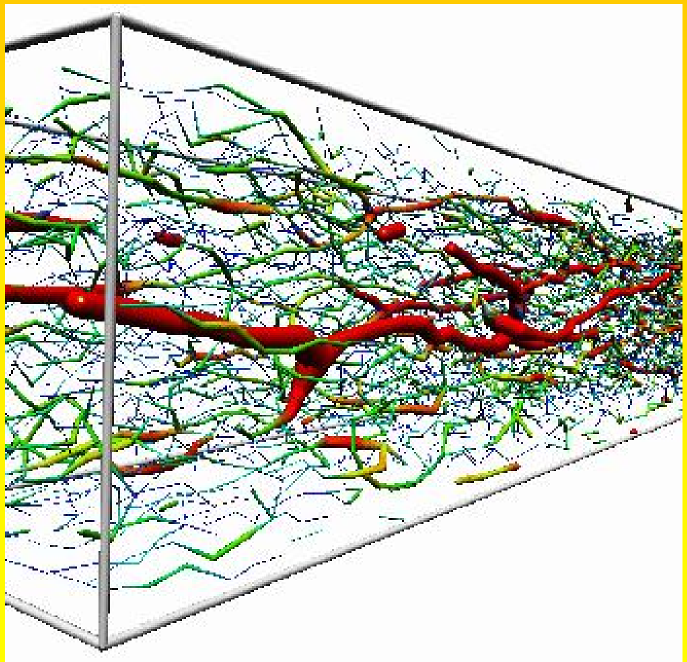
SOFT STRUCTURES in LIVING ORGANISMS

A key feature in terrestrial evolution was the formation of multicellular organisms (different from, eg., microbial mats, where many microbes lives in a colony together). In such organisms, the functions of each cell are subordinated to the entire organism, which controls & organizes the whole. Much of our ideology about the ‘Self’, and ‘Consciousness’ (which are very culture-specific) originates in this central control mechanism. I should note here that all sophisticated life forms are continually conscious of their surroundings (often in ways we are not), and of many features of their own state. To argue that only humans have emotions or ‘feelings’, or are ‘self-aware’, makes no sense whatsoever, given how close we are to many animals both genetically and structurally. Whether computers might become self-aware is still an open question.

All mobile organisms have a structure of soft organs, supported by a hard exoskeleton or internal skeleton. Even plants can change shape slowly by changing the pressure distribution between the fluid in the cells.

In an organism, there is huge ‘cell differentiation’ as the organism grows – different parts of the genetic code are expressed as instructions for different cells in the organism – thus leading to many different specialized cells in the organism. All this is organized collectively, in ways of which we are unconscious, & have mostly not yet discovered.

Biological structures have to be ‘soft’ to be able to grow and be flexible. An internal skeleton allows growth more easily - exoskeletons have to be shed to allow growth, but also provide armor (trees, insects, turtles, etc.). Biological molecules combine great strength at the atomic scale (because of C-C bonds) but great flexibility at longer length scales (because they are really long).



The structure of the vein & capillary system in an animal. Cells differentiate so as to form these remarkable structures (& repair them).

COMPLEX MOLECULES in SPACE

The atmospheres of most stars become unstable at certain times; the cooler red stars blow off lots of molecular gas and dust. Massive stars of course end as supernovae.

This dust floats in giant clouds in interstellar space, and then recondenses to form new stars when the clouds collapse under their own gravity, initiated often by shock waves from nearby supernovae. Successive generations of stars and their planetary systems thus become ever richer in heavier elements.

However the interstellar dust is itself also evolving. Light from distant stars can drive chemical reactions, and catalysis on the surface of the grains (often only a few microns or less in size) then facilitates the creation of complex organic molecules.

Gomez's 'Hamburger nebula'; a planetary system forming.

Catalysis is enormously important in the universe. For a chemical reaction to take place,

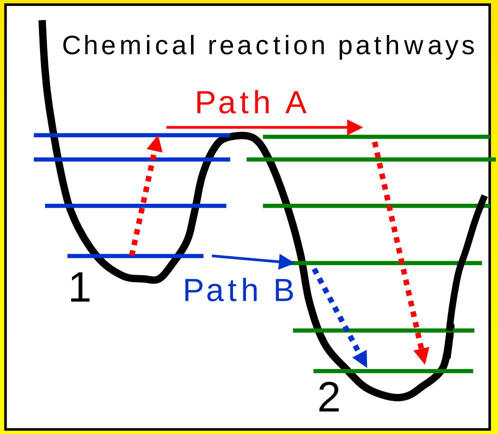
(i) An energy barrier must be overcome (path A below) for the constituents to combine together; or

(ii) the constituents can tunnel through the barrier, (path B) a much slower process.

ABOVE: MZ3 nebula, blown off by star
LEFT: Star & dust clouds near Milky Way centre

Path A involves external energy (eg., a photon from a star), to kick the system up to the top of the barrier; path B just goes through the barrier.

CATALYSIS occurs when some other system, in contact with the reactants trying to combine in the chemical reaction, LOWERS the energy barrier – this makes the reaction (fusion of the reactants) go much faster. These reaction pathways win out.

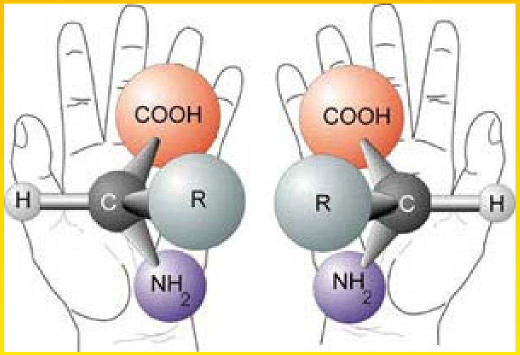


Two paths to get from state 1 to state 2, with barrier between.

AUTOCATALYSIS & the INEVITABLE EVOLUTION of COMPLEX STRUCTURES in the UNIVERSE

A major problem in understanding the origin of complex structure in the universe is the 2nd law of thermodynamics – disorder always increases with time. So how do local pockets of order appear - and what keeps them intact and evolving towards ever more complex order (of which life is an example)? There are 2 key parts to the answer:

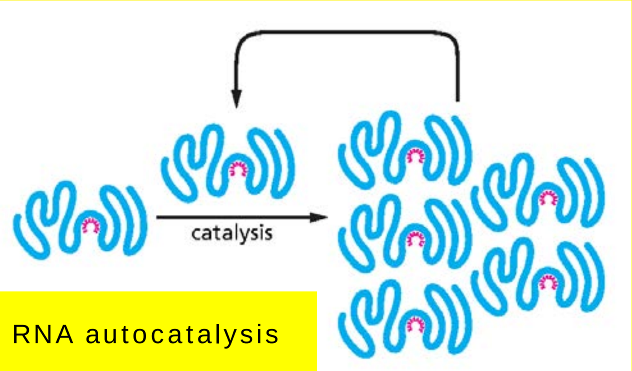
(1) EXTERNAL ENERGY: For mysterious reasons, the universe began in a highly ordered state – going back to the Big Bang. What keeps it ordered is gravity – which collects matter into stars and galaxies. Stars emit energy which can be used to drive chemical reactions, which can create complex molecules. Specific molecules, & even certain forms like right-handed molecules, can be selected in this way.



2 'enantiomers'; identical molecules except for their 'chirality' or handedness.

(2) AUTOCATALYSIS: We've seen that catalysis will speed up certain chemical reactions, and favour the production of specific molecules – but Nature also has another trick up its sleeve. In some cases the product of a reaction can catalyze the same reaction – ie., a molecule can catalyse its own creation, and thereby multiply. Crucially, RNA molecules can do this. In this way it is believed that an early 'RNA world' was created on earth.

The RNA would have been competing with many other autocatalysed molecules, but in the v specific conditions pertaining on earth at that time, RNA and eventually DNA molecules won out – giving our 'DNA world'.



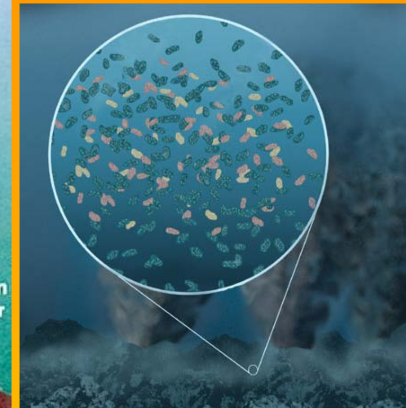
RNA autocatalysis

Note that different conditions & different accidents would have given very different results – but the result would still have been increasing complexity.

ORIGIN of LIFE on EARTH

* 4.5-4.1 Gya ago: Formation of solar system; asteroid bombardment, formation of moon & oceans.
* 4.3-3.9 Gya ago: complex molecules appear – amino acids, then peptide chains, finally RNA & DNA evolve, in ‘primeval soup’. Energy source is UV light from primitive sun.

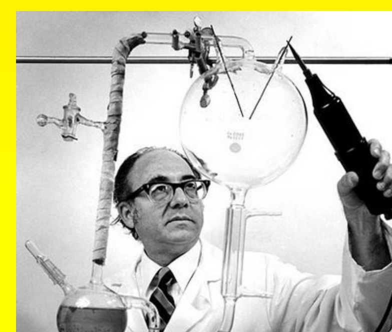
3.7 Gya ago: first evidence of microbial life, formed around volcanoes and undersea vents (thermophilic bacteria, stromatolites). These metabolized using H, CN, & S (not O), and did not require solar radiation.



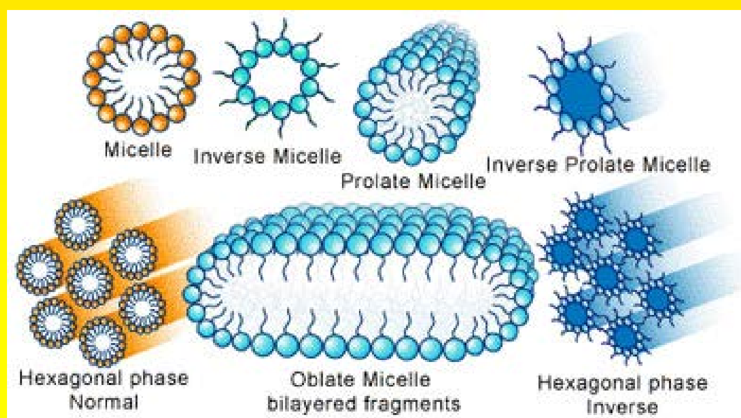
ABOVE: Stromatolite ‘bacterial mat’.
LEFT: An undersea volcanic vent

Early work of JBS Haldane (UK), Oparin (Soviet Union), & Miller & Urey (USA) showed how rich arrays of organic molecules could form on early earth – and that formation of vesicles could then create closed chemistry labs & primitive cells. Cells were the key – they allowed increasing self-organization inside the membrane.

ABOVE: VV Oparin
BELOW: S Miller



The primeval soup – supplied from earth & space.



Primitive ‘vesicle’ cellular structures, formed spontaneously by self-assembled lipid layers.

EVOLUTION of LIFE on EARTH

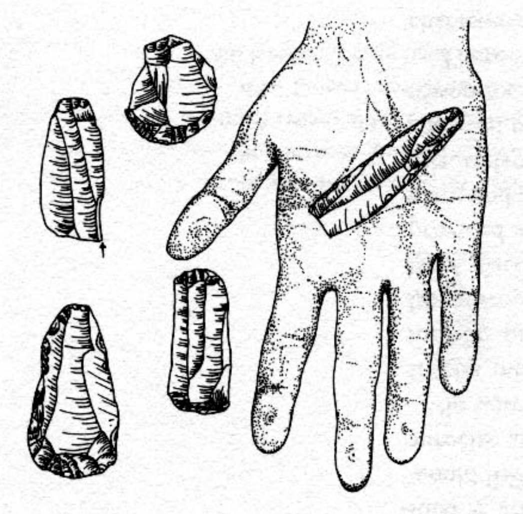
Cambrian animals from 570 Mya ago, found in the Burgess shale deposits

Biologists now discern various key transitions in the evolution of life on earth. Once complex molecules including long hydrocarbon chains and lipid molecules, and RNA had appeared, things went as follows:

RNA world → DNA world (4.0 Gya ago): RNA can replicate, can even make viruses, but DNA can encode info to make things like proteins.

DNA world → DNA in cells (4.0-3.9 Gya ago): Concentrates ingredients inside vesicles, allowing the first primitive cell factories to appear. The metabolism (ie., factory processes) are powered by chemical energy & heat from volcanic vents.

Chemical energy → photosynthesis (?? Gya ago): use of sunlight to drive reactions – notably splitting of H_2O → release of O into atmosphere (slow evolution of atmosphere). O breathing cells then slowly evolve into existence.



Not the first use of tools by animals. But this development was crucial for human evolution

Prokaryotes → Eukaryotes (?? Gya ago): absorption of viruses into cell to create nucleus, organelles (factory divides tasks into compartments); some of these eukaryotes lose rigid cell walls to become mobile bacteria.

Cell Mitosis → Sex (?? Gya ago): allows fusion of genetic material from 2 different cells.

Cells → multicellular organisms (600 Mya ago): In wake of ‘snowball earth’ phase, massive evolutionary change – in only 20-30 Mya, large (3m long) animals appear.

All of this could have happened differently. Not clear what the next big transition will be – maybe soon!

WHERE LIFE is GOING – on EARTH & ELSEWHERE

We have no reason whatsoever (except for antiquated religious arguments) to suppose that:

(1) what happened on earth is special – very complex organized systems have certainly formed in a huge variety of places in the universe.

(2) the kind of organization appearing on earth is even special. It actually arose from a very specific set of conditions (specific chemistry & geology, size of earth & distance from sun, particular characteristics of sun, etc). It is rather likely that highly advanced organized systems elsewhere would be almost unrecognizable as life to us – or if the term 'life' as we use it would even be meaningful.

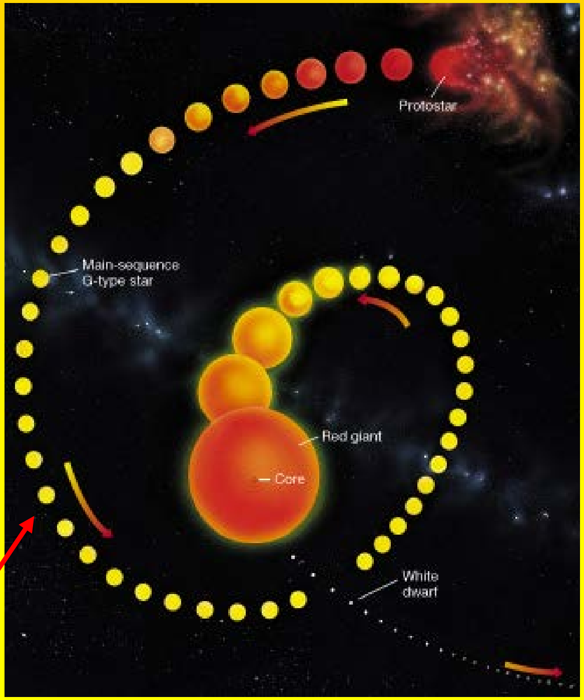
(3) humans as a species are anywhere near the most sophisticated forms of organized system – we are likely very primitive compared to some of what is out there.

In the short term, humans will likely ruin the earth. The causes: human overpopulation, resource depletion, species destruction, modern science & technology. Escape to other planets is not an option. The next 100 yrs will be crucial.

However life on earth has survived far worse disasters. It is impossible to predict what will evolve out of the current mess. In the very long term, the sun will slowly heat up – in 2 billion yrs the oceans will boil on earth; in 6 billion yrs the sun will go to its red giant stage (and then to a white dwarf). The earth will then vaporize.

ABOVE: One possible near-term scenario for the development of the earth – dominated by environmental pollution

BELOW: The evolution of the sun over a 12 Gya time period



Where we are now