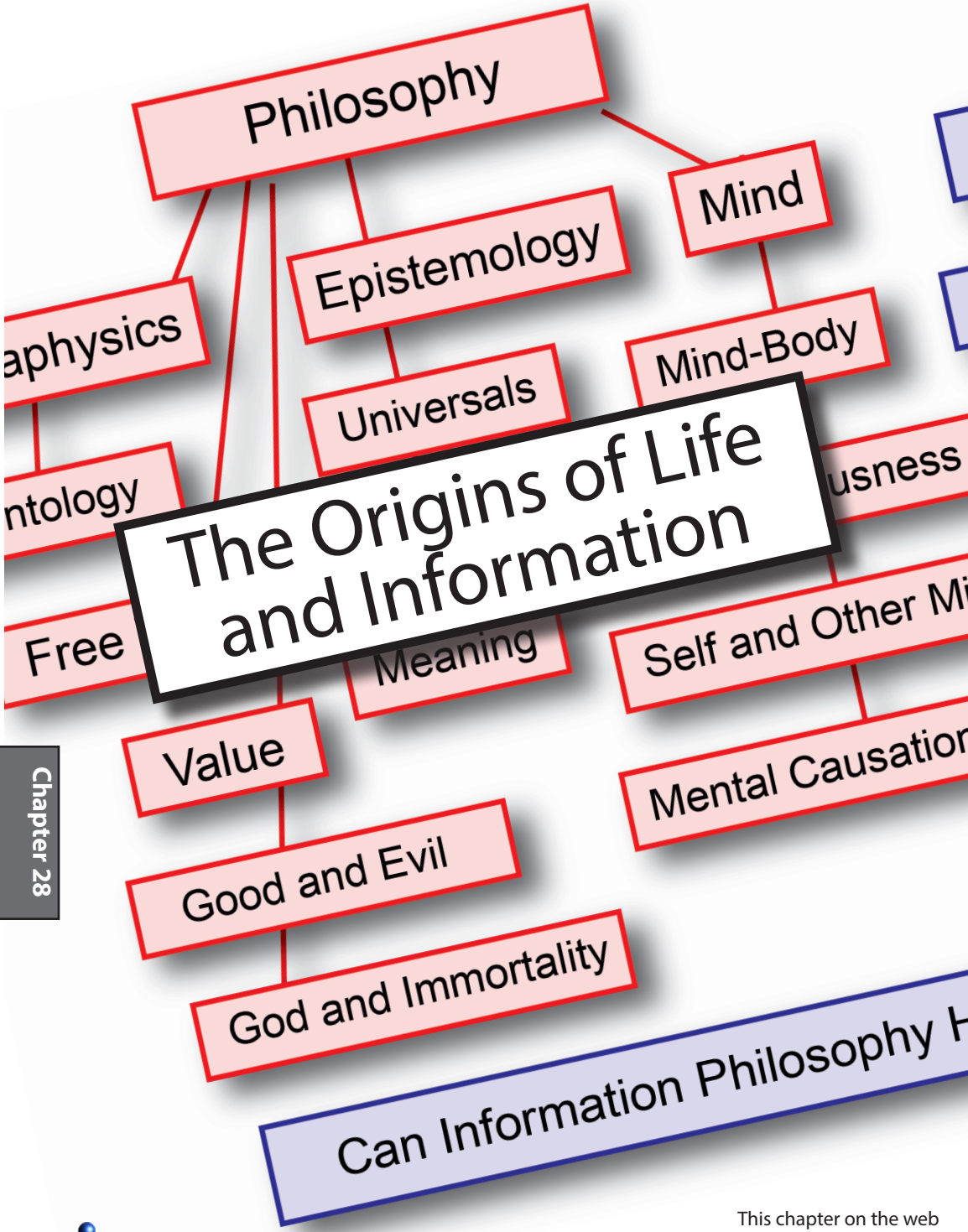
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Origins of Life and Information

Despite many controversies about the role of information in biology over the past several decades, we can now show that the creation of information is not only necessary to understand biology, but that biology is a proper subset of information creation in the universe, including the evolution of human minds, which have created the knowledge about how abstract *immaterial* information and concrete information structures (material, but also energy flows with low entropy that is called free energy) have been and are now being created in the universe.

A new story of biological evolution is needed, integrating it into the cosmological story and illustrating the total dependence of life on cosmological sources of negative entropy (free energy and information structures). We cannot appreciate the origin of life without first understanding the origin of information.

The first information *structures* formed in the early universe. Elementary particles, atoms and molecules, galaxies, stars, and planets, are all the result of microscopic quantum cooperative phenomena and macroscopic gravitational forces. These are the very special anti-entropic processes that we call *ergodic* (information *creating*) .

But it is not until the *emergence* of life that information *replication*, information *processing,* and information *communication* begins. Living things are *biological information processors*, forms through which matter and energy flows, with capabilities far beyond the electronic digital computers that cognitive scientists think provide a "computational theory of mind."

Most important, living things have "purposes." They engage in high level communications of information with other living things and with the environment. Their messaging is meaningful, allowing them to be active users of information, compared to passive material things, whose structural information is largely inert and meaningless. Living things also have *histories*, unlike physics and chemistry.

History and Evolution in the Universe

Long before there was life, the galaxies, stars, and planets had a rich developmental or evolutionary history of their own. Astrophysics tells us that stars radiated energy into space as they dissipated the energy of gravitational collapse (the photons carried away positive entropy to balance the new spherically symmetric order). The stars paused their collapsing when their interiors reached temperatures high enough to initiate thermonuclear reactions, which convert the lightest elements (hydrogen and helium) into heavier elements. Matter is converted to energy ($E = mc^2$). When the fuel is exhausted, the stars resume collapsing, some exploding catastrophically and spewing out into interstellar space their newly formed elements, especially the heavy elements needed for life.

Geophysics tells us that the surfaces of planets also go through heating, then cooling, as they radiate away the energy of gravitational binding. Chemical processes produce ever more complex molecules on planetary surfaces, and astrobiology now finds prebiological organic molecules everywhere in space.

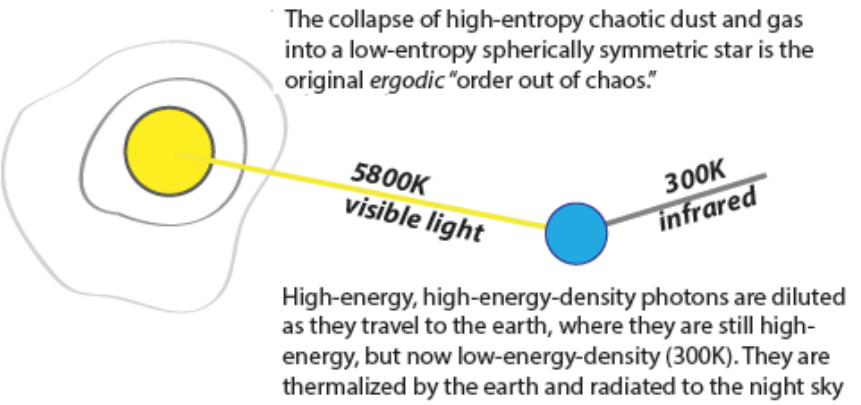

Figure 28-1. Photons are the major source of negative entropy on the earth.

When a planet is bathed by radiation from a nearby star, the radiation field is far from equilibrium. The high-temperature photons leaving the solar surface (5800K) are spread out over a huge volume of space. The energy density of the radiation falling on the Earth corresponds to a much lower temperature (300K), but the high-color-temperature photons cannot cool down without interacting with matter. This temperature difference provides a heat engine in

which the out-of-equilibrium photons are a source of free energy, energy with negative entropy, that is potential information.

When they do interact with the planetary surface, photons provide the necessary stream of free energy to form complex information structures, the macromolecules that are the chemical basis for life. An alternative stream of free energy with negative entropy comes from inside the cooling planet.

Whether from the Sun or high-temperature vents in the planetary surface, it is these out-of-equilibrium conditions that lead to the first living things. They are negative entropy (free energy) flows which are potential new information generators.

The Origin of Life

Early theories of the origin of life were based solely on physics and chemistry, from the 1920's hypotheses of A.I. Operin and J.B.S. Haldane that the early atmosphere of the Earth was reducing (hydrogen and not oxidizing), to Melvin Calvin's 1930's suggestion for autocatalytic cycles, and the famous 1950's experiments of Harold Urey and Stanley Miller that showed many organic molecules could form spontaneously (especially critical amino acids, the building blocks of proteins) in Haldane's "prebiotic soup."

In the last several decades, theories of chaos and complexity have led to the idea of "self-organizing" complex adaptive systems that combine various autocatalytic cycles, for example, the hypercycles of Manfred Eigen. The Nobel-prize-winning physical chemist Ilya Prigogine identified irreversible processes in systems away from thermal equilibrium that he called "dissipative."

Examples of "dissipative systems" include whirlpools and Bénard convection cells. They exhibit what Prigogine called "order out of chaos" and are an example of "emergence."[1] All living systems are "dissipative," so Prigogine and the complex adaptive system advocates thought they might explain the nature of life.

Complexity theories were popular because they added an element of *unpredictability* (really only human ignorance) to otherwise deterministic physics, without accepting the *indeterminism* and ontological chance of quantum physics.

1 See chapter 27 for the three kinds of emergence.

All these complex, dissipative, autocatalytic processes depend on a stream of free energy and negative entropy for their operation. But if all that they produce is a "passive" information structure, it is the just the same kind of "order out of chaos" that gravitation produces in the galaxies, stars, and planets. It is not yet life.

The most sophisticated example of an autocatalytic system is one that can generate large quantities of prebiotic molecules, such as the amino acids that combine to form proteins. This is the citric acid cycle (or Krebs cycle) used by all living systems today. It was almost certainly a precursor of life, before the information replication we associate with complex nucleotides and genetic code (DNA and RNA).

Metabolic cycles do not *use* information in the sense of processing it, but they do use the negative entropy flow to increase information in the form of the amino acids. A large quantity of amino acids can create proteins, but only randomly. Proteins cannot recreate themselves precisely. They cannot transfer hereditary information.

So alongside a working metabolic cycle we need information replication. The earliest such information structures were probably duplicated on an external template (a catalyst). Before DNA appeared, there was an RNA world in which RNA could perform the enzyme functions that proteins perform today, as well as the self-replication that DNA gives us.

The central dogma of biology today is that DNA generates RNA which generates the proteins from amino acids. And today we see the clear central role of information, specifically the messaging and processing of information via "messenger RNA" and "transfer RNA."

To be considered life, information philosophy expects an "active" information structure that is *processing* information, communicating messages among the components to maintain its structure.

The first person to articulate the information processing aspect of life was Lila Gatlin, who wrote in 1971

> Life may be defined operationally as an information processing system—a structural hierarchy of functioning units—that has acquired through evolution the ability to store and process the information necessary for

its own accurate reproduction. The key word in the definition is information.[2]

At some moment, a primitive macromolecule replicated itself. To do this, it created new (duplicate) information, so positive entropy equal to or greater than the new negative entropy must have been carried away from the new information structure (for it to be stable).

Mere replication should not yet be seen as life. And anything like metabolism would just be the flows of the low entropy solar photons or geothermal free energy that get degraded in the process of providing the available energy needed to form the new molecule. But we might anthropomorphize a bit and say that the *apparent* purpose of the molecule appears to be replicating itself, increasing *its own kind* of information structure in the universe.

Now at some point the replication might have been less than perfect (note the element of *chance* here).

Imagine now that the new molecule might be even more efficient than the original molecule at replicating itself (it has greater reproductive success). Note that the new molecule has more, or at least *different*, information in it than the original. Now we might say that this is the beginning of Darwinian evolution, which *appears* to have a goal of building richer, more robust, living information structures.

We now have both primitive inheritance (of the information) and a form of variability. Some of these molecules might not only be more successful replicators, they might have chemical properties that allow them to resist being destroyed by environmental conditions. The energetic extreme-ultraviolet photons, for example, or destructive cosmic rays, which might have been the source of the original variations.

The result might be a runaway exponential explosion of the concentration of those molecules (an important characteristic of living systems) as well as alteration of their environment. Early life generated an oxygen atmosphere that protected it from the ionizing ultraviolet rays that may have led to life in the first place.

Replication could lead to populations of the molecule that are well beyond the normal populations that would be expected in chemical

2 *Information Theory and the Living System*, p.1

equilibrium. Chemists might view this as simply an autocatalytic process, in which the molecule catalyzes its own production. But because it is *information* replicating itself, it is qualitatively different from mere chemical autocatalysis.

At the atomic level, it will be quantum cooperative phenomena that pull the constituent atoms into the desired molecular positions. It is the overall shape (form, information) that produces a dynamical interactive constraint well beyond the mere *aggregation* of individual atoms.

Loosely speaking, the new, more successful species of molecule has "learned" something, storing the new information internally and passing it on to the next generation.

Jumping now to human evolution, we see a species of multimolecular, multi-cellular organism that has found a way to externalize information, storing it in the environment (culture), where it can be shared with new generations of humans, who continue to add to this external store of knowledge we call the *Sum*, enabling them to dominate the planet, for better or worse.

The Origin of Information

Passive information structures formed in the universe from the first few moments of time. But these elementary particles could not even form a lasting atomic structure until nearly 400,000 years after the expansion of the universe had begun. The universe had to cool significantly more, taking millions of years, before the galaxies, stars, and planets could form.

Although these magnificent astronomical bodies are the dominant contents of the universe, their information is essentially inert and meaningless until astronomers have appeared to study them, *extracting* their information. It is said that an astronomer is one galaxy's way of knowing about other galaxies, the universe's means of self-contemplation. These of course are mere metaphors, because the flow of information is one way, from the passive structures to the information-processing minds.

Claude Shannon[3] analyzed the communication of information in terms of senders and receivers, exchanging coded messages through noisy channels. It applies to the extraction of any kind of information, for example the yes/no answers to questions put to the physical world by scientists making quantum measurements.[4]

We can think of the Sun as sending its photons to Earth, although since they go out in all directions, less than one in a billion is received here. But where astronomers do not return any information to the stars and galaxies they study, even the smallest organism *interacts* with its environment and *exchanges* information in meaningful ways. All organisms and their components are "interactors" exchanging information.

All life draws its nourishment from the stream of negative entropy, the matter and free energy that flows though every organism. But living things also excrete matter and degraded energy into their environment, a return information flow that alters, in many ways creates, their local world - the biosphere.

Information in Biology

The major question for information in biology is this, are the communications between biological systems (organisms) and between their components (cells, organelles, macromolecules) *semiosis*, the exchange of signs?

Major textbooks on biology have always used terms like signaling, coding, transcribing, translating, communicating, messengers, recognition, even language, but they almost always insist that these are only metaphors, that they are not the kind of intentional and meaningful exchanges of signs that humans use.[5]

Consider what happens in a cell when a particular protein or enzyme is in short supply. A messenger enters the nucleus with a signal that more of the protein is needed. Responding to the signal, an enzyme (synthetase) travels to the exact segment of the DNA that contains the sequence of nucleotides for the needed protein.

3 *The Mathematical Theory of Communication*, 1948

4 See "Meaning in the Theory of Information" on page 142

5 See appendix G for the story of Biosemiotics.

The synthetase moves along the DNA, transcribing the sequence of nucleotide triplets (called codons) into a growing RNA with a message intended for the ribosome that manufactures proteins. Each codon refers to a specific amino acid in the protein.

The "messenger RNA" detaches itself from the DNA and travels through the nuclear membrane into the cell cytoplasm where ribosomes and a supply of amino acids is located. The amino acids are moving about randomly and very rapidly as a result of thermal and quantal noise. The long thread of mRNA enters the ribosome, which stops it to wait for the arrival of a "transfer RNA" carrying an amino acid and the three-letter "anticodon" that matches the codon in the mRNA for the next amino acid needed in the polypeptide chain.

When the one-dimensional linear protein leaves the ribosome, it folds itself into a three-dimensional shape that has enzymatic activity. If it does not fold correctly, it is swallowed by tiny "trash-can" shaped structures called "chaperones." The chaperone closes its cover and squeezes the protein, encouraging it to fold correctly.

If it does not, the protein is broken up into its amino acids. This is an amazing degree of error detection and correction.

The whole chain of communications between the signal that entered the nucleus, the syntax of the message, the semantic decoding of the mRNA by the ribosome, which refers to exactly the right amino acids as they fly around at high speeds connected to transfer RNA, looks like interpretation of the message, with reference to the amino acids. The message has pragmatic significance, leading to meaningful action (production of the protein). The later Wittgenstein tells us that "meaning is use." The cell is using all this communication of information for the purpose of staying alive!

Information philosophy looks at all this as the primitive prototype of the information communication and processing that we have today in human beings. In human language, the fundamental elements are syntax, semantics, pragmatics, and morphology (the shapes of the signs). Are not all of these already present in our smallest organisms?

Despite many calls to recognize the reality of information in biology, the reductionist view that biology is nothing but the result of physics and chemistry has prevented it. Here are some important calls over the years to accept information in biology.

> "Life may be defined operationally as an information processing system—a structural hierarchy of functioning units—that has acquired through evolution the ability to store and process the information necessary for its own accurate reproduction. The key word in the definition is information. This definition, like all definitions of life, is relative to the environment. My reference system is the natural environment we find on this planet. However, I do not think that life has ever been defined even operationally in terms of information. This entire book constitutes a first step toward such a definition."[6]
>
> "Evidently nature can no longer be seen as matter and energy alone. Nor can all her secrets be unlocked with the keys of chemistry and physics, brilliantly successful as these two branches of science have been in our century. A third component is needed for any explanation of the world that claims to be complete. To the powerful theories of chemistry and physics must be added a late arrival: a theory of information. Nature must be interpreted as matter, energy, and information."[7]
>
> "A central and fundamental concept of this theory is that of 'biological information,' since the material order and the purposiveness characteristic of living systems are governed completely by information, which in turn has its foundations at the level of biological macromolecules . The question of the origin of life is thus equivalent to the question of the origin of biological information."[8]
>
> "Information as the central concept in molecular biology:..Information, transcription, translation, code, redundancy, synonymous, messenger, editing, and proofreading are all appropriate terms in biology. They take their meaning from information theory (Shannon, 1948) and are not synonyms, metaphors, or analogies."[9]

Biological Machines

We have seen that biological communications, the information exchanged in messages between biological entities, is far more important than the particular physical and chemical entities themselves. These material entities are used up and replaced many

6 *Information Theory and the Living System*, (1971) Lila Gatlin, p.1
7 *Grammatical Man*, (1982) Jeremy Campbell, p.16, inspired by Gatlin
8 *Information and the Origin of Life*, (1990) Bernd-Olaf Küppers, p.xvii
9 *Information Theory, Evolution, and the Origin of Life*, (2005) H. Yockey, p.6

times in the life cycle of a whole organism, while the messaging has remained constant, not just over the individual life cycle, but that of the whole species.

In fact most messages, and the specific molecules that embody and encode those messages, have been only slowly varying for billions of years.

As a result, the sentences (or statements or "propositions") in biological languages may have a very limited vocabulary compared to human languages. Although the number of words added to human languages in a typical human lifetime is remarkably small.

Biological information is far more important than matter and energy for another reason. Beyond biological information as "ways of talking" in a language, we will show that the messages do much more than send signals, they *encode* the architectural plans for biological machines that have exquisite control over individual molecules, atoms, and their constituent electrons and nuclei.

Far from the materialist idea that fundamental physical elements have "causal control" over living things, we find that biological information processing systems are machines, intelligent robotic machines, that assemble themselves and build their own replacements when they fail, and that use the flow of free energy and material with negative entropy to manipulate their finest parts.

Coming back to the great philosopher of logic and language Ludwig Wittgenstein, who briefly thought of "models" as explanatory tools that can "show" what is difficult or impossible to "say" in a language, we offer still pictures of a few biological machines, with links to dynamic animated models on the I-Phi website.

The amazing operations of these machines are so far beyond man-made machines that it has called into question the ability of Darwinian evolution to create them by random trials and errors. But the most complex of these machines have been shown to be composed of dozens of smaller and simpler parts that did and still do much simpler tasks in the cell.

The five biological machines that we chose are

• the *ribosome*, a massive factory that manufactures thousands of different possible proteins when messenger RNA carries a request for one of them from the nuclear DNA,

• *ATP synthase*, which packages small amounts of energy into a nucleotide molecule that carries energy to any place in the organism that needs power to perform its function,

• the *flagellum*, a high-speed motor that moves bacterial cells to sources of matter and energy in their environment,

• the *ion pump*, which moves calcium and potassium ions to rapidly recharge the activation potential of a neuron so it is ready to fire again in a fraction of a second so the mind can make its decisions and take actions to move the body,

• the *chaperone*, an error detection and correction system beyond the ability of our finest computers to protect memories from noise.

Biology cannot prevent the occurrence of random errors. Indeterministic chance is the original source of variability in our genes that led to the incredible diversity of life forms, including us humans.

But the nearly perfect operation of our biological machines and the phenomenal fidelity of copying our many genetic codes over billions of years shows the stability and "adequate determinism" of biology in the presence of ontological chance, a consequence of the noise-immune *digital* nature of biological information.

Ribosomes

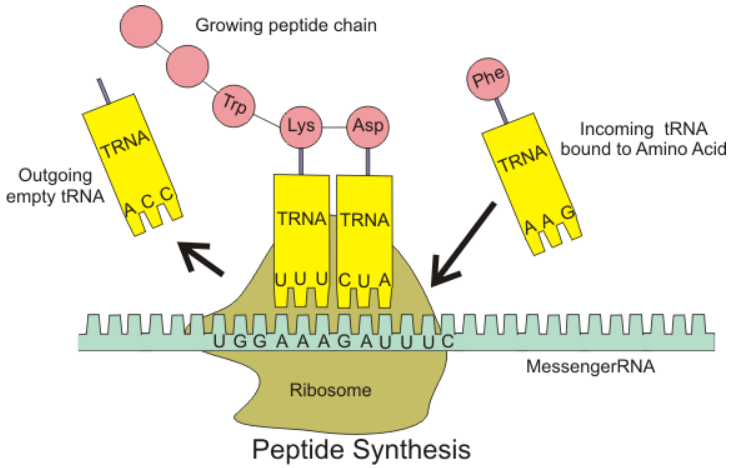

Figure 28-2. The ribosome waits for the right tRNA and amino acid to collide, then captures it to be added to the growing protein

The linear messenger RNA is a sequence of three-letter nucleotide "codons," each of which codes for one of twenty possible amino acids. The transfer RNAs are flying around randomly in the cell carrying an amino acid with the complementary anti-codon. When an incoming tRNA colliding with the ribosome is a match, the mRNA captures it and moves three letters into the ribosome. The amino acid is detached from the tRNA and attached to the growing peptide chain, and the mRNA advances three more letters, releasing the outgoing, now empty tRNA, who will capture a replacement amino acid.

Notice that the tRNAs are moving quickly and randomly, so a large number of incorrect tRNAs bang into the next position on the mRNA while it waits for the correct match. Nothing in the path of the tRNA is *determining* the new sequence, as some physical chemists think. Which particular tRNA and amino acid of the right kind is added next is pure chance.

The ribosome is an ancient machine, going back to the last universal common ancestor (LUCA) of the three domains of life - bacteria, archaea, and eukaryotes. It is built from a few RNA molecules that self-fold to become enzymes (ribozymes) and a number of proteins that provide a supporting structure for the RNA. The longest of these RNAs is at the middle step when the amino acid is released from the tRNA and attached to the growing peptide chain.

Comparing modern ribosomes in the three domains, the microbiologist George Fox, who with Carl Woese identified the archaea domain, reconstructed the likely earliest version of the ribosome, an important component of the RNA world's transition to DNA.

We shall see that reconstructing the earliest versions of important biological components, especially the biological machines, can provide deep insights into the origin of life.

By comparison, the efforts of complex adaptive systems theorists to guess at the earliest auto-catalytic chemical systems have largely been fruitless, since chemical systems do not process information about the different chemicals.

ATP Synthase

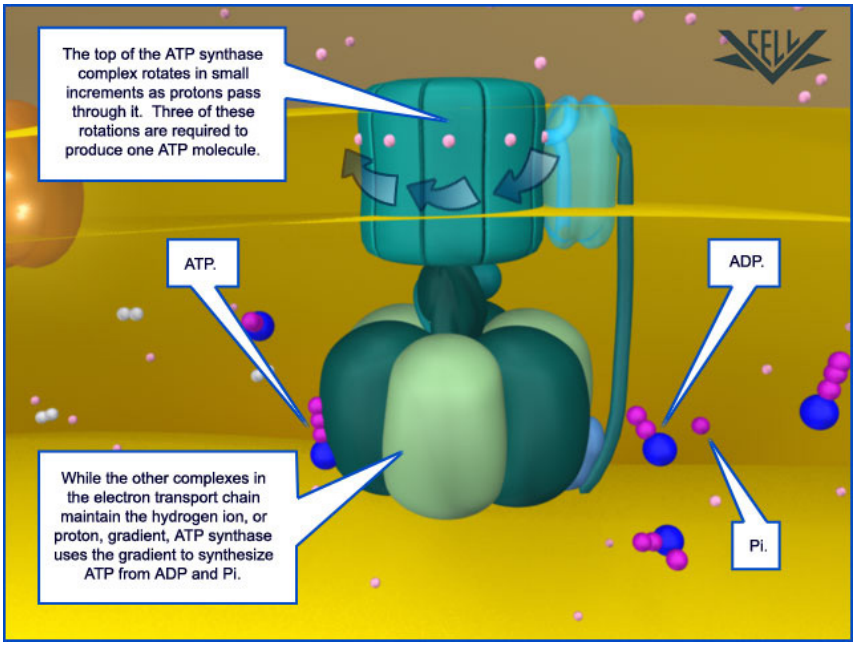

Figure 28-3. The rotating motor embedded in the membrane spins at 10,000 rpm.

The source of power for most biological machines is the ATP (adenosine triphosphate) molecule. Adenosine is one of the four nucleotides in the genetic code (G, C, A, T). The ATP synthase machine above adds an inorganic phosphate group P*i* back to a depleted diphosphate ADP, powered by "chemiosmosis," a flow of protons (hydrogen ions) across the semi-permeable cell membrane.

As each proton enters the top of the synthase complex, the top rotates by one of its segments. A fixed shaft (on the right) holds the lower part of the synthase in place while the rotating center shaft pushes lower segments to open and close, providing the energy to add back a P*i* to the ADP.

ATP contributes a jolt of power to other machines (see the ion pumps below) when the third phosphate group is detached and energetic ATP becomes depleted ADP.

But what was the basic power source before complex biological machines like ATP came into existence?

The Flagellum

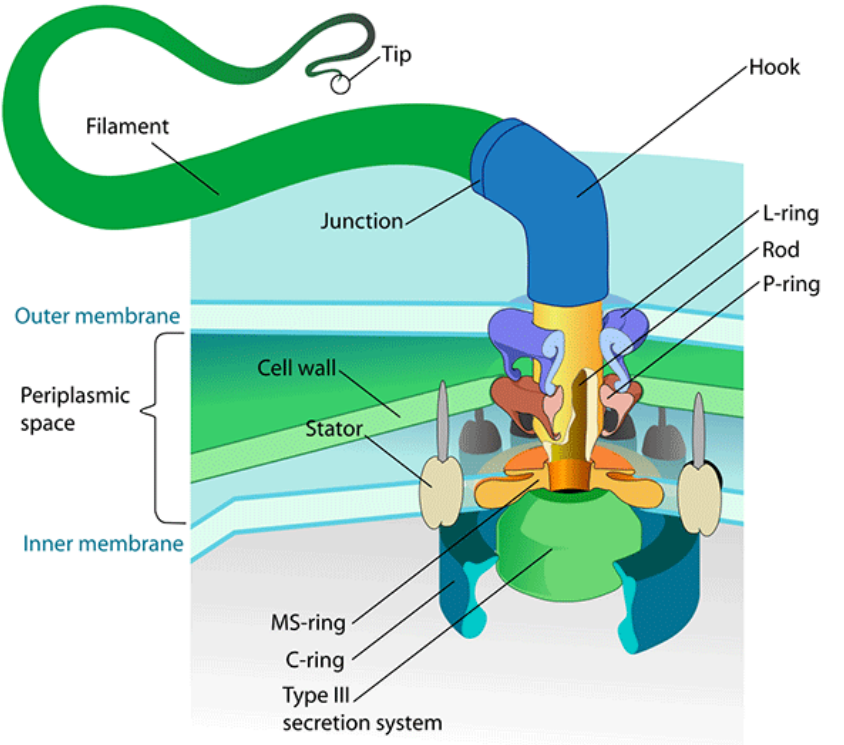

Figure 28-4. This motor can instantly switch into reverse, the bacterium tumbles randomly, then switches back to forward motion in a new direction.

Another rotating system embedded in a cell wall is the reversible motor that drives the flagella of mobile bacteria. The rotor has been measured at an incredible tens of thousands of rotations per minute. This system is so amazing it is considered the "poster child" of intelligent design advocates, but of its fifty protein parts, over forty have been identified as having simpler, but similar, functions that have "exadapted " for their role in the flagellum motor.

Bacterial flagella are powered by a flow of protons just like the rotating part of the ATP synthase, others by a flow of sodium ions, and some are powered by ATP flows. Some organisms have flagella only in their earliest development phase, for example, spermatazoa. But we can ask what produced the flow of protons before there was a molecule as advanced as ATP?

Ion Pumps

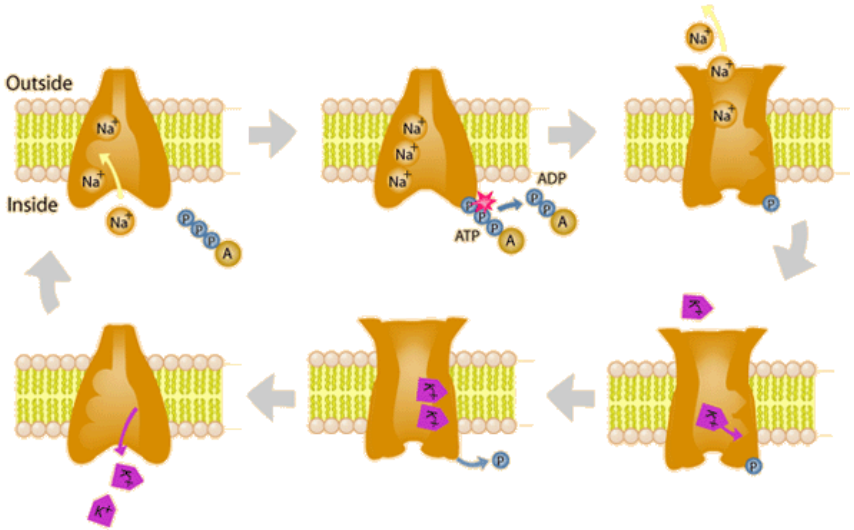

Figure 28-7. The ion pump uses ATP as its power source.

When a single neuron fires, the active potential rapidly changes the concentration of sodium (Na+) ions inside the cell and potassium (K+) ions outside the cell. Within milliseconds, thousands of sodium-potassium ion channels in the thin lipid bilayer of the cell wall must move billions of those ions from one side to the other. They do it with emergent biological machinery that exerts downward causation on the ions, powered by ATP energy carriers (feeding on negative entropy). Random quantum indeterministic motions of the amino acids drive them near the pump opening, and quantum collaborative forces capture them in a lock-and-key structure.

ATP hydrolysis provides the energy for a full cycle of opening and closing the pump, which pumps three sodium ions out of the cell for every two potassium ions pumped in. In neurons, the pump uses about 2/3 of the energy expenditure in the cell.

Before there were ion channels powered by ATP, could some primitive proteins have evolved to move specific ions across a membrane and create an electrochemical potential?

Chaperones

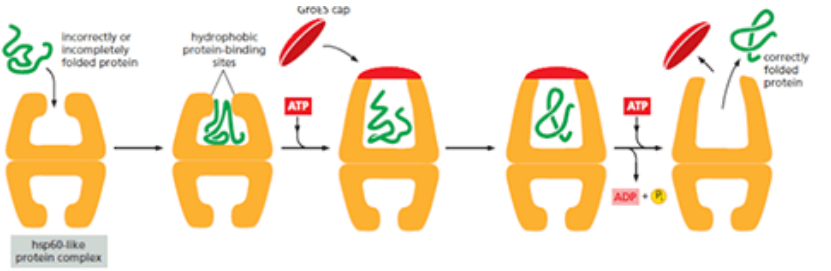

Figure 28-5. The error-correcting chaperone also uses ATP.

When a newly manufactured protein leaves the ribosome, it sometimes fails to fold properly to become an active enzyme that carries out its proper function in the cell. A well-folded protein hides away all its oily hydrophobic sites, exposing it hydrophylic sites to the water-based solution in the cell.

The incorrectly folded protein's hydrophobic sites are attracted to hydrophobic locations inside a chaperone. Once inside a cap is attached to the top and forces inside the chaperone encourage it to fold properly, in which case the cap opens and the normal protein is released. Once again, it is ATP that powers the chaperones.

Motive Power?

What ultimately powers all these machines? Of course it is ultimately free energy in a negative entropy flow, but what is the specific chemistry? If it starts with sunlight, it will be photosynthesis that extracts energy in the photons via redox reactions (simultaneous reduction and oxidation) that produce electrons and ions. For example water becomes H^+ and OH^-, with transfer of H+ ions (protons) across plant cell membranes. In mitochondria, it is the breakdown of food (sugars) in the citric acid cycle, with transfer of protons across the inner mitochondrial membrane.

In either case, an electrochemical gradient across a membrane is like a battery voltage (a tiny tenth of a volt) that powers all of life. It may have originated with amino acids randomly assembled into proteins that penetrated the bilayer phospholipids of proto-cells to act as proto-ion-pumps.

Life, Love, and Death

A few speculations about three topics - *bios*, *eros*, and *thanatos*[10] - that often raise origin questions - why are we living?, why sex?, and why do we die?

From the standpoint of information philosophy, biology seems to have been a series of cosmic accidents, some of which in retrospect can be seen as highly unlikely. Against the arguments that given the right conditions, life is highly probable, we can note that life remained unicellular for the first few billion years. The endosymbiosis of bacterial cells being hosted by an archeon, to form the eukaryotes who became multicellular, suggests that this critical step for the possibility of intelligent life was highly improbable.

The importance of chance is evident from the evolution of the deliberate randomization of genes in sexual reproduction, which seems to aim at creating unique individuals.

As human life is about to take control of the evolution of the human genome, a major objective may be to eliminate the chance elements that lead to cell death.

Working Backwards in Time

We saw in chapters 12 to 16 how *philosophers of mind* attempt to *reduce* mental states to bottom-up deterministic causation by the laws of physics and chemistry at work in the brain.

Most biologists today are also reductionists, feeling more comfortable with the materialist laws of the physical sciences than with *immaterial* ideas like emergence, purpose, and information. Most cognitive scientists and neuroscientists share this traditional and conservative view.

But information philosophers and scientists today should make the strong case that life is more than the conserved quantities of matter and energy, and more than the deterministic laws of classical physics and chemistry.

Life is matter and energy - plus *information*. Life is quantum physics and chemistry - plus the *new information* in the universe that would be impossible without the ontological chance of quantal indeterminism.

10 Or at the cellular level - *mitosis, meiosis, and apoptosis.*

Unlike physics and chemistry, life has a history - an information history. We are more likely to figure out the origin of life by working backwards to guess the most primitive elements of today's most universal parts (e.g., the citric acid cycle), than by trying to work forward from primitive chemical reactions of atoms and molecules that know nothing, that always lose any information about where they have been in the past.

We consider the origins of four increasingly sophisticated information-controlled processes - the metabolic cycle, chemiosmosis, the ribosome, and the genetic code. Our technique will be to strip them down to their primitive core elements. By reducing the amount of information in each process, we are working backward in time.

The current eight-step metabolic cycle uses sophisticated ATP as a catalyst. The earliest cycle would eliminate those steps.

Chemiosmosis moves protons or other ions across a membrane to create electrochemical potentials. This is done by multiple protein complexes in the current electron transfer chain. Today's proteins are produced by the ribosome, with RNA messages from the DNA. Let's work back to a time without either of these. It will still be proteins separating the electrons from the protons. They must do it without ATP, because they provide the power to create ATP. So let's look for the simplest components of today's proteins that can do this.

There are several different such complexes. The largest one uses a string of connected iron-sulfur clusters, each of which takes a small amount of energy from the electron and passes it, perhaps by quantum tunneling, to the next cluster. The presence of these FeS_2 clusters points to Günter Wächtershäuser's iron-sulfur world hypothesis of life forming on mineral surfaces near hydrothermal vents in the deep sea. Membranes over pores in rock surfaces would later become modern cells in the RNA world.

It was a study of the different ribosomes in bacteria, archaea, and eukaryotes that led to Carl Woese's discovery of the three domains of life. Woese's colleague George Fox and Hyman Hartman of MIT have worked backward in time to the most ancient parts of

the ribosome, specifically a central RNA molecule that encloses the center where a new amino acid is added to the growing peptide (protein) chain.

The current genetic code uses three nucleotides out of four RNA possibilities (G, C, A, U), giving 64 codes to choose one of twenty amino acids. But the third nucleotide often has no relevance for the amino acid. As long as the first two are GG, any one of the four will still code for glycine. GCx codes for alanine, CGx for arginine, and CCx for proline. All four of these amino acids are very common. Could there have been an early time when there was a simpler, two-base code and only four amino acids in the first proteins to be coded for, probably in a ribozyme with the hereditary information?

Hartman has connected this hypothesis back to the *reversed* citric acid cycle that was likely in the early earth's reducing atmosphere. He estimated the number of extra steps beyond the metabolic cycle needed to produce each amino acid, identifying the easiest to manufacture. Alanine, glycine, aspartic acid, and glutamic acid are one step away. Glutamine, asparagine, and serine are two steps away. Between those with the simplest codes and those with the mini mum number of steps to produce them, glycine and alanine were likely the earliest amino acids to enter the genetic code.

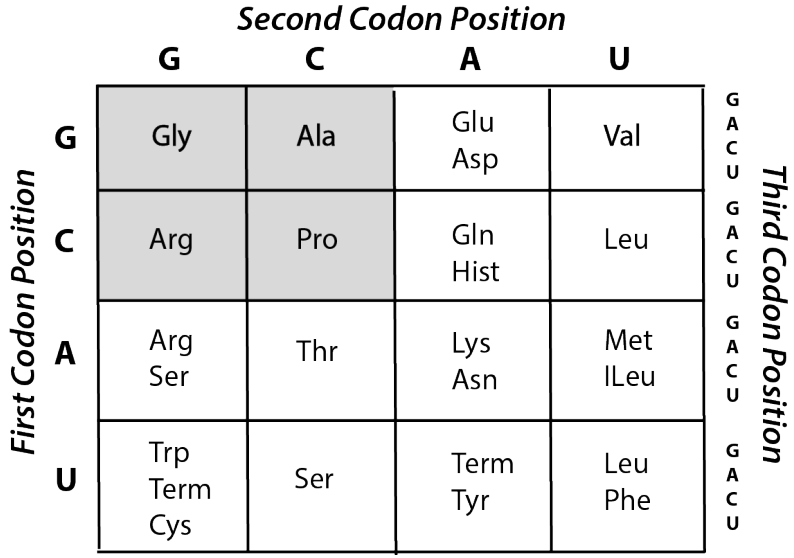

Figure 28-6. Was there an earlier time when only two nucleotides coded for fewer amino acids?