



Jan Brueghel the Elder,
*The Entry of the Animals
into Noah's Ark, 1613,*
detail



The laws of life

Charles S. Cockell

Notwithstanding the awe-inspiring diversity of living creatures, the forms and processes of life are limited by universal principles that act at large and small scales.

Perhaps the questions were too speculative for his time, but Charles Darwin never considered whether another evolutionary experiment exists in the universe or what such an experiment might look like. Once life emerged on Earth, it proliferated across the planet, assumed remarkable forms, and wrought the extraordinary changes that have now inextricably linked the biosphere and geosphere. The oxygen that you and I breathe originated as the result of photosynthetic activity so pervasive and so productive that it eventually reached levels sufficient to drive a complex multicellular biosphere.¹

At the heart of understanding the phenomenon of life is explicating the extent to which the laws of physics narrow the range of possibilities at all levels of hierarchy in the structure of living things. Ultimately, to properly meet that challenge, we may have to find other evolutionary experiments and make a statistically valid comparison. A great deal of research on plausible alternative structures of life has been motivated by astrobiology, the science that encompasses the study of how life originated, evolved, and covered the planetary surface and whether and in what form it exists elsewhere.² Even in the absence of observed alien life, however, we can still learn a great deal from Earth's evolutionary experiment.

Wings and wheels

Look at the menagerie of life—for example, as depicted by Jan Brueghel the Elder in the painting to the left. The casual viewer could easily conclude that life is

limitless in its scope, that its forms and shapes are constrained only by the imagination. But however trite the observation may be, life must conform to the laws of physics. Science still does not know how many possible solutions there are to building a self-replicating system within those laws, however, or to what extent physics constrains the products of the evolutionary process.

At the scale of organisms, physical laws certainly do limit the engineering solutions to life's problems. For example, consider locomotion. In a now classic paper,³ Michael LaBarbera addressed a question that has been a favorite at biologists' café tables since time immemorial: Why doesn't life use wheels? People use them in a vast diversity of forms of locomotion. Why did biology reject them? Apart from the biomechanical problems of evolving rotating muscles and veins, wheels have an inherent physical problem in that they are limited in the landscapes they can navigate: They cannot overcome obstacles with a height greater than



FIGURE 1. WHEELS AND LIFE.

No life form is yet known that has wheels instead of legs, but in areas of the world where the land is dry and flat, evolution does explore spheres and wheel-like contraptions as means of efficient transport. Here, a dung beetle rolls its riches home. (Images by Charlesjsharp/Sharp Photography.)

their radius unless they are lifted up.

For the diminutive ant, terrain is more irregular than for larger creatures. But even at the human scale, legs are much more efficient than wheels for overcoming barriers. Furthermore, many substrates, such as sand or wet soil, present

considerable resistance to wheel movement. Interestingly, in regions of the world characterized by flat dry plains, dung beetles push balls of dung (see figure 1), and nearly spherical balls of tumbleweed roll across the landscape. Biology does explore spheres and wheel-like architectures in places that offer the potential for their success for rapid transport.

On an alien world, one might expect, the cracks, crevices, and irregularities that inevitably come with a planetary landscape would cause the selection of legs over wheels. Physics, rather than serendipitous, contingent quirks of evolution mandates that selection.

Another form of locomotion offers witness to the unyielding barriers of physics. The aerodynamics of insect flight is now an exquisitely developed subject in biophysics.⁴ The simple laws that underpin aerodynamic lift in an atmosphere have been explored by biological evolution, and the characteristic airfoil shape needed to produce a low-pressure region above a wing has been finely honed (figure 2). However, that evolutionary sculpting is not enough to lift many insects whose bulky bodies require extra help. Over the past 20 years, research has revealed how insects manage to garner every bit of lift and thrust from their tiny wings. One such mechanism is called clap and fling. As the wings are pushed into their back stroke, they are clapped together, a maneuver that forces air out from between them and provides additional thrust. The wings are subsequently flung apart as they begin their front stroke; the air that rushes in to fill the gap enhances circulation over the wing surface and thus improves lift.

Advances in high-speed photography and computer modeling have only in the past two decades allowed researchers to understand the fine-tuning that enables insects to exploit every nuance of the physics of aerodynamics.

The solutions to the problem of flight are found again and again in different insects and birds.⁵ Some biologists call the replication convergent evolution, but convergent evolution is often just a biologist's way of saying convergence via physical laws. The ways in which a wing can be engineered to provide sufficient lift in Earth's atmosphere derive from physical constraints that radically narrow the number of solutions observed in the natural world.

Molecular limits on life

Underlying all creatures, from winged birds to walking ants, are the molecules from which they are constructed. Those, too, are limited. When they began in the 1970s to explore the bewildering variety of proteins from which life is assembled, biochemists, it seemed, like their colleagues in zoology, were confronted by a mind-numbing variety of possibilities. Twenty amino acids strung together in a chain of just 200 provides the potential for some 10^{260} proteins. Lengthen the chain and the



FIGURE 2. INSECT WINGS. The structure of the dragonfly wing is not a serendipitous quirk of evolution. Rather, it is an evolutionary result channeled by physical laws that mandate certain solutions to extract every possible amount of lift and thrust. (Photo courtesy of Michael Palmer.)

number is even more mind-boggling. How many centuries of biochemical work would be necessary to make sense of all those molecules? Yet as researchers sequenced proteins and studied the way they folded, it became apparent that no matter what the sequence of amino acids, the number of shapes that sections of proteins could adopt was very limited indeed⁶ (see figure 3).

Disassembled into individual parts, proteins display four main types of folding arrangements. Forms called α -helices are right-handed helical arrangements of amino acids held together by a hydrogen bond between a hydrogen on an amino group ($-\text{NH}_2$) and the carboxyl group ($-\text{COOH}$) of an amino acid three or four amino acids earlier in the sequence. Pleated sheets termed β -sheets are long, parallel amino-acid chains held together by hydrogen bonds. The third and fourth categories are hybrid motifs assembled from helices and sheets that occur separately along the amino-acid chain. For a generic sequence of helices and sheets, the hybrid is called $\alpha + \beta$; the special case of alternating helices and sheets is called α/β . Subclassifications called TIM (triosephosphate isomerase) barrel, sandwich, and roll motifs define particular ways in which the helices and sheets are assembled.

One explanation for the limited repertoire of folds is that specific forms sufficient to assemble something competitive in the struggle for survival became locked into biology early in its evolution. A house-building analogy might serve to clarify the point. You don't go to a builder's yard and use every type of brick you can find. Out of the diversity available, you select a few that will do the job. Once you ascertain that those bricks make a nice home, you have them mass produced.

Compelling though that contingency argument may be, it is possible that fundamental physical laws are at work to select for specific protein forms.⁷ Amino-acid chains, like molecules, tend to fold in such a way as to arrive at their lowest energy state. Each successive folding step is driven by thermodynamics to seek the most stable state. The steps are not independent, and different parts of a folded protein exert an influence on the folding patterns of other parts of the protein. Still, it seems that even in a holistic context, proteins seek out a limited number of thermodynamically favorable configurations.

Even the number and nature of the amino acids that form proteins may be a consequence of specific physics considerations. Proteins are generally constructed from 20 major amino acids, though in rare cases organisms use two other amino acids, selenocysteine and pyrrolysine. It is tempting to think that the selection of the core 20 from among the hundreds of amino acids that exist naturally was mere chance, an example of a pattern that physics cannot predict. In that case, protein analogues in life on another planet would be formed from a different randomly selected set of amino acids. However, the hypothesis that amino acids should be spread over a broad range of size, charge, and hydrophobicity (their tendency to be repelled by water) suggests that nature's amino acids do not occur by chance.⁸ Even the genetic code itself, the assignment to specific amino acids of a three-letter word whose letters A, G, C, and T represent the four nucleotides in DNA, appears to be a noncontingent result of optimizing the efficiency of minimizing translation errors among other factors.⁹

Some biologists have long debated whether there exist laws of biology or if the field is better viewed from a Darwinian per-

spective of evolution, in which order is not preordained and mutation and selection define the vast landscape of biological possibilities. The two views are not only compatible, they are inseparable. Darwinian evolution, through mutation and selection, experiments with a great diversity of forms, but the resulting organisms conform to the laws of physics and are tightly constrained by the universal principles that operate at whatever scale one chooses to observe. For example, Darwinian evolution generates an enormous number of proteins useful for different structures and functions that are selected because the processes in which they are embedded are beneficial for survival. However, thermodynamics greatly restricts the number of motifs from which that menagerie of molecules can be assembled.

The elements of life

Physical principles may work to limit the very elements from which life is constructed. Imaginative scientists have conceived of various alternative chemistries for life, with some of the most pervasive being based on silicon.¹⁰ Compared with its sister element carbon, which lies just above it in the periodic table, Si has an extra set of electron orbitals. For that reason, it tends to be somewhat more reactive than C and less capable of forming stable, long-chained structures analogous to the many millions of C compounds. One exception is its ability to form the silicates, extraordinarily stable structures with oxygen.¹¹

Silicon chemistry experiments have been naturally carried out in Earth ever since our planet formed 4.54 billion years ago. The diversity of Si-based compounds produced has been impressive, but they are all minerals, glasses, and various amorphous structures that together make rocks. Figure 4 shows some examples. Laboratory work has produced complex Si

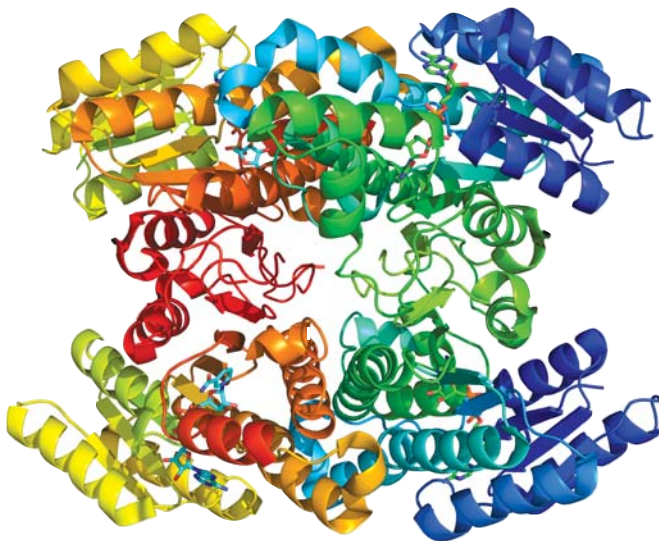


FIGURE 3. LIMITED PROTEIN ARCHITECTURE. The enzyme butanediol dehydrogenase is involved in oxidation-reduction reactions with particular organic compounds. Despite its complexity, it is primarily made up of α -helices (curved ribbons) and β -sheets (flat arrows) connected by flexible amino-acid strings. Its structure illustrates how proteins are arranged from simple motifs. (Image courtesy of ChemPro.)

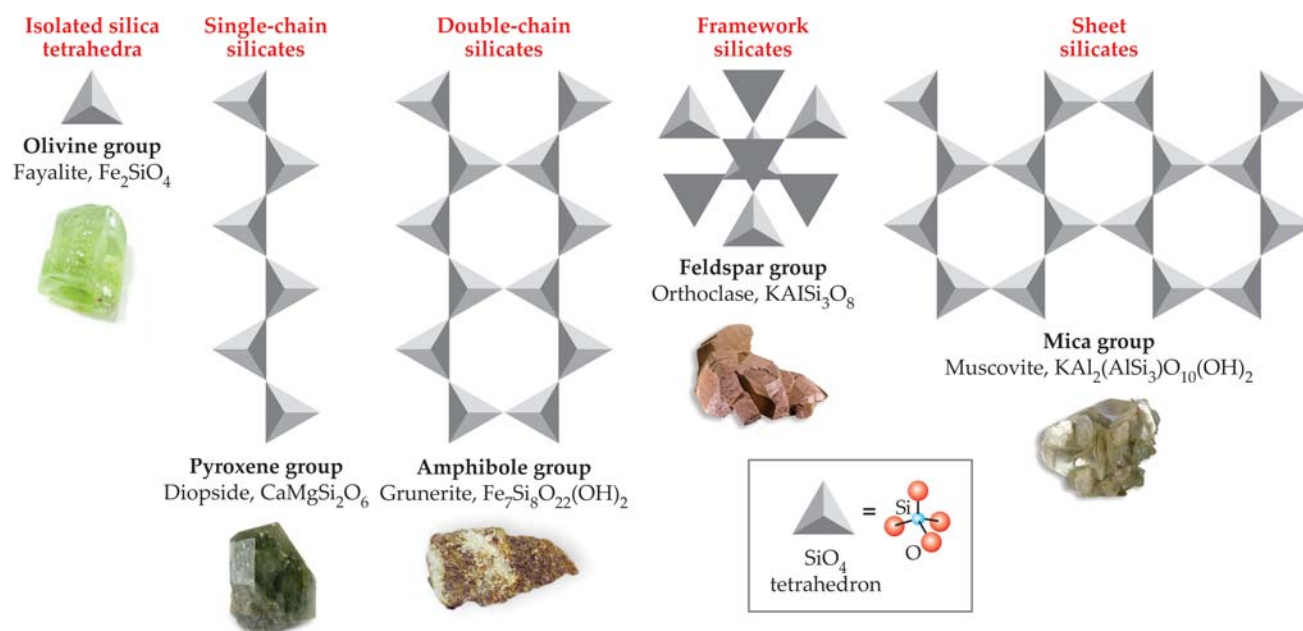


FIGURE 4. SILICON STRUCTURES. In combination with oxygen, Si forms a great variety of silicate structures from assemblages of silica tetrahedra linked through common O atoms. The silicates are highly regular, generally crystalline, and make better rocks than life forms. Shown here are general structures of silicates, with examples of specific groups in each structural class and specific minerals representing each group. The inset shows the schematic of a tetrahedron with the central Si and an apex O atom facing out of the page. (In the framework-silicate schematic, filled triangles represent tetrahedra with the out-of-plane O facing into the page.)

compounds that look less like rocks and more like the stuff of life forms. For example, the silsesquioxanes are a class of organosilicon compounds that form impressive chain- and cage-like structures that tantalize the mind with ideas of hybrid silicon-carbon life.¹² Yet as far as we know, they too are limited with respect to their complexity and diversity. The size of the C atom, which allows it to form stable single, double, and triple bonds, coupled with the atom's ability to form bonds with many elements and switch bonds among a range of elements with little energy cost or release, makes the element uniquely favorable for assembling a versatile zoo of molecules.

The above considerations are by no means limited to Earth. The field of astrochemistry, which intersects with astrobiology, investigates the chemistry of the cosmos. Its findings during the past two decades have been remarkable.

In various locations in the Milky Way, including diffuse interstellar clouds, giant molecular clouds, and protoplanetary disks in which new solar systems are formed, C-based compounds are everywhere being synthesized.¹³ Some of them are simple, such as the molecular species NH_2CN , CH_3SH , and CP, but many more-complex compounds are also being produced. Polycyclic aromatic hydrocarbons, like a sheet of stamps, have complex repeating units of linked structures—in their case, aromatic rings. Ultimately they are thought to form tubes, buckyballs, and structures layered like onions.¹⁴ Most significantly, isopropyl cyanide and other cyanide-containing compounds have been detected. The cyanide groups might act as precursors for biologically useful molecules with branched structures that are similar to those of biologically important molecules such as amino acids.¹⁵ Because space has a low density of matter and is cold, many of those compounds are

thought to form on siliceous and carbonaceous grains, whose surfaces can bring reactants close together. In some cases, interstellar radiation catalyzes the reaction.

Most intriguing has been the haul of C compounds found in meteorites that land on Earth.¹⁶ One class of meteorites, the carbonaceous chondrites, include some of the most primitive materials in our solar system. (See the article by Bernard Wood, *PHYSICS TODAY*, December 2011, page 40.) They have been found to contain sugars, from which carbohydrates are built; amino acids, from which proteins are built; long-chain carboxylic acids that behave like cell-membrane lipids when immersed in water; and even nucleobases, the informational units of the genetic code. Thus the evidence suggests that in the solar system's protoplanetary disk, the pancake-like swirl of dust and rock in which our sun and the planets were born, conditions were ideal for the synthesis of the basic units that combine to form the major classes of life's molecules.

Meteorites do not offer a large diversity of strange Si compounds. Some silicon carbides have been observed,¹⁷ but most of the Si-based chemistry in meteorites is again confined to minerals and glasses. The messengers from space that arrive on Earth may be attesting to the relative merits of Si- and C-based life. Certainly, they make plausible the idea that C-based life is universal rather than being a quirk of terrestrial chemistry.

Underlying all the properties that make C suitable as the atom of life is a simple notion: the Pauli exclusion principle, which ensures that electrons added to orbitals and suborbitals neatly pair up in twos. In particular, the Pauli principle mandates the sequential layers of electrons that determine an atom's radius and reactivity. Carbon's propensity to form a range of amino acids, whether in febrile living things or in the tumult-

tuous swirling gases of the protoplanetary disk, shows that Pauli's principle underpins biological assembly at a fundamental physical level that applies everywhere.

Darwinian evolution is not free to bound aimlessly through the periodic table and create an endless variety of form. Complex C chemistry is a feature of biology because it results from the laws of quantum physics. The unique capacity of C to generate variety in molecular products is as evident in a molecular cloud at 10–50 K as it is in a cockroach. One would expect a similar capacity in many planetary environments across the universe.

Life's mechanism for gathering energy

Even at the subatomic level, we find a beautiful simplicity of life rooted in physics. Biochemist Peter Mitchell first proposed the detailed mechanism by which life extracts energy from its environment,¹⁸ for which work he received the 1978 Nobel Prize in Chemistry. Life does not seem able to readily access energy from nuclear fission. Some have claimed that hypothetical life could use ionizing radiation as a source of energy, but such radiation generally causes severe damage to many molecules. Nuclear fusion requires too much input of energy to be a plausible way for living things to extract energy from it. The other parts of an atom from which an organism might extract energy are the relatively more accessible electrons, and it is those that life uses in Mitchell's chemiosmosis process.

Electrons are gathered up from the environment from electron donors, molecules that have a propensity to lose electrons, and travel within a cell or mitochondrion membrane on their way to being picked up by electron acceptors. In you and me, the membrane is mitochondrial, the electron donor is organic matter, and the electron acceptor is oxygen: Your lunchtime sandwich is a tasty way to eat electrons.

Figure 5 sketches the chemiosmosis mechanism. As the electrons, driven by an electrostatic potential difference, move through the membrane, a series of proteins that reside in the membrane use the electrons' energy to move protons from the inside of the mitochondrion to the outside. The result is a proton gradient. The external protons, under the action of osmosis, want to move back into the mitochondrion to neutralize the gradient. That they do, but not by randomly diffusing through the membrane, which is generally impermeable to them. Instead, they flow back through a complex molecular apparatus, an enzyme called ATP synthase, which makes ATP (adenosine triphosphate). As the protons move through the ATP synthase, they cause the components of the enzyme to rotate.

As pieces of the synthesizing contraption whirl around, the changing shape of the enzyme brings phosphate groups into association with adenosine diphosphate to make the ATP. The newly made, energy-rich phosphate bonds trap the energy of the electron-transport chain. The ATP can be shunted around the cell and those phosphate groups broken off to release energy anywhere it's needed—for example, to make new mole-

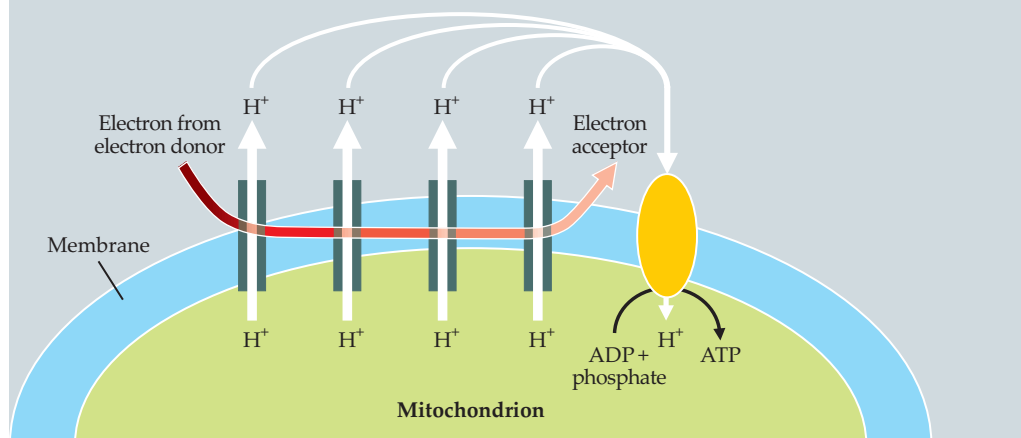


FIGURE 5. THE CHEMIOSMOTIC PROCESS. As described in the main text, life takes the energy of electrons from organic matter or some other electron donor and ultimately stores it in the phosphate bonds of adenosine triphosphate (ATP). As the donated electron is transported to an electron acceptor such as oxygen, it traverses a portion of a mitochondrion membrane (or in some organisms, a cell membrane). While there, it passes through a series of proteins that extract energy from the electron and use it to transfer protons (H^+) outside the mitochondrion. The expelled protons, under the action of osmosis, reenter through ATP synthase (yellow), which builds the ATP molecule from adenosine diphosphate (ADP) and a phosphate group. The physical simplicity of the process, despite the biochemical complexity of the proteins involved, suggests a universal mechanism for acquiring energy.

cules for growth and reproduction. And in case you think energy production is an on-again, off-again biological process, your body, in all of its cells, produces about 1.4×10^{21} molecules of ATP in a second. It has cost you about 2.5×10^{24} molecules of ATP to read this article. I apologize.

The beautiful simplicity of chemiosmosis is that swapping out the electron donors and acceptors enables life forms to grow in a whole variety of places. Change the electron acceptor from oxygen to sulfate and now you have sulfate-reducing bacteria that can live deep underground—they are the microbes that are responsible for cycling sulfur in the biosphere. Swap the sandwiches for iron, hydrogen, or ammonia as the electron donor and you've got the chemolithotrophs that can live in rocks, volcanic hot pools, and hydrothermal vents, chomping on the raw materials of planetary geology rather than relying on sunlight or organic food from other organisms.

Let's stand back and look at the process for another moment. It starts with readily accessible subatomic particles (electrons) that have some energy to give away. That energy is used to produce a gradient of another subatomic particle, the proton. The gradient is then harnessed, via osmosis, to produce a molecule that effectively stores the electrons' energy for release anywhere it's needed. Life might be able to use ions other than protons to make the gradient. Even on Earth, some organisms seem able to harness the power of sodium-ion gradients, but the principle is the same.

Chemiosmosis is a thing of remarkable minimalism. Is it contingent or universal? As we have seen, fission and fusion are more difficult to commandeer as sources of energy; the nucleus is a difficult beast to tame for the relatively trivial energetic needs of life. Granting contingent modifications in the

THE LAWS OF LIFE

molecules involved and maybe the use of different ions to generate a gradient, it seems likely that life anywhere would tap into the energy available in electrons, relatively easily yanked away from atoms to do work.

Physics or chance?

Life must be fashioned by the laws of physics. Birds must conform to the principles of aerodynamics, protein folding to thermodynamics, and energy acquisition systems that use electrons to the various energy states of those subatomic particles. What is less clear is the extent to which physics narrows the range of Darwinian possibilities. The physical principles that underlie the construction of life from predominantly C-based molecules instead of Si-based ones have long been understood. More recently, however, scientists have suggested that other choices that once seemed contingent are nonrandom events based on statistical probabilities, energetic considerations, and optimal arrangements for a self-replicating, evolving system. Examples include the structure of proteins or even the 20 amino acids that life chooses from the many hundreds of possibilities to build those proteins.

One job of physicists is to examine the extent to which contingency is possible in life at its different levels of hierarchy and to explore the predictability of the architecture of living systems. Astrobiologists' role in that quest is to try to determine whether we can find another example of an evolutionary experiment with which to test the hypothesis that life, from the machinery of energy acquisition up to the form and shape of whole organ-

isms, is constrained tightly into a few forms. I have suggested in this article and elsewhere that it is. Disappointing though it may be to many imaginative science fiction writers, if that hypothesis is ultimately accepted, we will have learned that life on Earth is unexceptional.

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