Chapter 4

Interlude: What is Science? What is Life?

Astrobiology is the science that attempts to find extraterrestrial life. It is also the science that studies the origin and evolution of life on a planetary scale. We know life exists on the Earth and it is certainly wise to use this experience as a guide. The scope of our ignorance, however, is huge. We need to try to define the target of our search – life.

Some judgment based on common sense, worldview, and what science already knows needs to come in. I begin by discussing how science functions and more importantly how it can cease to function. I then return to recognizing life in extreme terrestrial environments and elsewhere in the universe.

Science and imagination

The Porcupine Dialogue. Campfire in mining camp in northern Ontario.

Cast:

Rustico, an outfitter

Eudoxio, another outfitter

Lithophilo, a young mining geologist

Lithophilo: I saw my first porcupine today. Its quills looked very sharp. How do they mate without impaling themselves?

Rustico: Very carefully!

Eudoxio: No amount of care will help. Their quills are just too sharp. The Spider Fairy Arachne comes to hold back their quills.

Lithophilo: Come on now. I was not born yesterday. We can figure this out. Rustico, you must have eaten porcupines. Aren't their organs just like other mammals?

Rustico: Yes, I even caught a pregnant one once.

Eudoxio: But you have never seen porcupines mate. No man has. The Spider Fairy gave the porcupine quills so that it could protect itself from wolves. She now helps them mate. Woodsmen have handed down this knowledge since the world began. They reveal their wisdom only to a chosen few.

Lithophilo: We must watch porcupines more carefully. We shall surely see them mate.

Rustico: We start at first light.

Eudoxio: That won't work. Arachne will project an illusion that looks like porcupines mating. Your eyes will fool you.

Rustico: Lithophilo, don't you have some high-tech equipment, like the surveying lasers, that will shine right through an illusion. We will see porcupines mate if we persist.

Eudoxio: No! Porcupines don't mate when anyone is watching. Watching will scare them away from Arachne. The porcupines will die out if they cannot mate. Arachne protects all the animals in the woods. She put animals here for the benefit of mankind. For example, she put spiders here to protect us from mosquitoes with their webs.

Rustico: Then why are we not benefiting from being bitten by all these mosquitoes?

Lithophilo: Right on! I am getting in my tent now before I get bitten any more.

Eudoxio: The mosquito's role is to provide food for spiders. Arachne is especially concerned with spiders. Her ways may seem mysterious. Mortals cannot fully comprehend them.

Exeunt.

The practice of science after the death of Galileo in 1642 would have been unrecognizable to Bruno even though he would have found the behavior of the Church frighteningly familiar. By Newton's death in 1727, astronomy and physics were recognizably modern. Why did science progress so slowly in classical and medieval times? The lack of imagination associated with magical thinking was one major obstacle.

Magically thinking. The methods of science in actual practice differ from those of pseudoscience and religion. Eudoxio captures the traits of pseudoscience. He stops scientific inquiry at every turn. He is quick to invoke magic. He distrusts even careful observations. When pressed he retreats to a reference to the authority of ancient woodsmen. He is unwilling to abandon tradition. Further pressed, he insists that any attempt at serious study will lead to disaster and that the woods were created for mankind's benefit. Finally, he contends that nature is inscrutable. He is able answer everything. For him, all problems are solved without taxing his brain.

The circular reasoning that the role of spiders is to protect us from mosquitoes and that the mosquito is here to feed the spider is still common in K-12 science books but not in serious ecology. It is the Natural Theology of William Paley. The most common K-12 form is that altruistic predators are here to prevent the prey from overpopulating and starving and to improve the prey by weeding out the old, the weak, and the sick. Never mind that some predators do starve for lack of prey or even that there is seldom enough weak and sick prey to go around. Do sharks regularly invade hospitals to avoid having to eat young healthy strong surfers?

Rustico and Lithophilo on their own could come up with a clever scheme for monitoring porcupines in their dens. Eudoxio would never think about one. A lack of imagination is a hallmark of pseudoscience and magic. Check out the *Iliad*.

> [Patroclus has fallen and Hector has captured the armor Patroclus borrowed from Achilles. The Greeks are in big trouble. Thetis, Achilles mother, goes to fetch new armor from the God Vulcan.]
>
> First he [Vulcan] shaped the shield so great and strong, adorning it all over and binding it round with a gleaming circuit in three layers; and the baldric [belt] was made of silver. He made the shield in five thicknesses, and with many a wonder did his cunning hand enrich it.
>
> [I skip a long discussion of the heraldry of the shield.]
>
> Then when he had fashioned the shield so great and strong, he made a breastplate also that shone brighter than fire. He made a helmet, close fitting to the brow, and richly worked, with a golden plume overhanging it; and he made greaves [lower

leg armor] also of beaten tin.

Achilles has the full resources of a Greek God. Yet this magic gets him only an improved version of the shields and armor already on the field. His multilayered shield is sophisticated; modern bulletproof vests are based on the same principles. Still an atomic weapon or even a Civil War cannon would have been more effective but would have required inventive genius, not magic.

(D5.1. Magnetic tape) You may be saying: The *Iliad* is poetry. Fantasy and science fiction serve only to create remote and therefore politically correct venues for adventure, poetry, and social commentary. Thus technology and magic need merely not be so ludicrous that they spoil the plot. No, look at the early *Star Treks*, a series where there was a serious attempt to present a self-consistent advanced technology. The computer has numerous tape drives, now after over 40 years antiques. Checking with freshmen, many younger viewers of reruns think that these tapes portray unknown advanced alien devices. Read the original H. G. Wells *War of the Worlds*. The Martians' poison gas, heat rays, and tripod walkers are still formidable, but not overwhelming 114 years later.

A belief in magic was not all that hindered the progress of science before 1600. Such beliefs continued afterwards that but did not halt science. Kepler practiced astrology. Newton considered that God tinkered with planetary orbits. Biological Creation was the standard before Darwin. The lack of modern technology and equipment is obvious but less limiting than one might suspect. For example, we estimated the distance of the stars without a telescope in Chapter 2.

Ancient and medieval science. Classical science suffered from two serious structural problems. The first was saving the phenomenon, rather than seeking a simple unified theory, like Newton's laws. A convoluted explanation, like geocentric astronomy, with some predicting power was fine since the heavens were beyond the ken of man. The second was the lack of the modern penchant for measuring, introduced by men like Galileo. Classical and medieval scientists rarely improved or checked existing measurements or even made new ones.

This attitude persisted in the early Renaissance. I describe well-known events in Spain in 1491 to provide an example. A brash Italian proposed to sail west to the Orient and bring back gold, silk, and spice. This voyage would be very expensive. Unlike the sanitized K-12 version with the royal jewels, the Queen would have to sell the loot seized from expelled Jews. In either case, the source of wealth was nonrenewable.

The learned men of the realm were summoned. No one was ignorant enough to contend that the Earth was flat. It is round, but they did not know its circumference. Was Cathay just over the horizon beyond known islands, as claimed by the navigator, or an unreachable distance away?

The scholars had the measurements of the Greek mathematician Erastosthenes (276-194 BC) and those of Ptolemy. Erastosthenes estimated using the distance that a camel could travel in a day, which left a lot to be desired. Ptolemy's measurement over open water between Rhodes and Alexandria was faked. The scholars did not know this but it did not matter. The big problem was the unit of measurement, the stade. Just what was a stade? No one knew for sure, but no one thought to accurately repeat the experiment with a known unit of measurement. In fact, there had been only two repetitions since classical times, one in the Muslim world and one in China. They were not much help either because the unit problem remained. The matter resolved itself when the Italian threatened to go to France with his services. Columbus (1451-1506) was wrong about his small circumference of the Earth. That became evident from observation in a few years.

In contrast to classical and medieval practice, modern science includes empiricism with many careful systematic measurements. It also includes logic, including mathematics. One uses logic to generalize from the data and then to make specific testable predictions. Nothing is sacred, but practically one must presume that some things are understood, like the balance or that a microscope works, in order to test others. Practical ancients, like Archimedes (287-212 B.C.) and Galen (131-200 A.D.), the physician to the gladiators and the Roman elite, successfully formulated scientific hypotheses. Archimedes' principle describes the behavior of floating bodies. Galen's medical text was used well into the 1800s. Gladiators were so expensive to train that wounded ones got excellent medical attention, like modern professional athletes. Having even half the contestants die in each show would have been prohibitive.

The Venerable Bede (672-735) made careful observations of tides, the position of the Moon, and seasons along the North Sea coast. His work firmly linked tides to the Moon. However, it like all medieval science had no lasting immediate effect, as few people attempted to test and expand results already in hand.

Galileo often operated like a modern scientist, but he retained the ancient notion that scientific propositions must be proven, not just supported by overwhelming observations. Making the Copernican system a testable hypothesis for further study was not an available compromise in 1616 and it certainly was not one in 1629.

> "Science, it cannot be too often repeated, deals with tangible phenomena. The man of science like the man in the street has to face hardheaded facts that cannot be blinked and explain them as best he can."

-- James Joyce, *Ulysses*, 1922

As Galileo had hoped, science has reached an uneasy truce with much of organized religion in much of the world. Science is methodologically materialist; it deals with what can at least potentially be observed. One cannot invoke magic. Science is agnostic, but scientists may be religious, agnostic, or atheists. Science, like U.S. courts, stays out of matters of faith. It gets dragged in when objective claims are made or when it comes under religious attack.

Organized pseudoscience. Pseudoscience is a relatively new phenomenon dating from the rise of the prestige of science in the seventeen hundreds. It dons the trappings of science, but is bound by tradition and magical thought. Its guises when disrobed are more appropriate to the dark ages.

Mysticism rejects both experiment and logic often selectively. It has resurfaced in academic raiment with Brobdignagian words like postmodernism and in more medieval garb as new age healing and astrology. Its absolute relativism of no objective reality can become doctrinaire. “We cannot show which idea is correct so mine must be right.” Yet there must be some order to nature even for an oxcart to work. Typically, mysticism involves a quotidian reality, like one should not stand in front of a moving bus, and a more lofty reality where anything goes.

> “A man might as well go into a gravel pit and count the pebbles and describe the colors. How odd it is that anyone should not see that all observation must be for or against some view if it is to be of any service."

-- Charles Darwin, letter to W.W. Bates on Nov. 22, 1860

Blind empiricism rejects generalizing from the data. A penchant for measuring often pays off especially when the level of ignorance is too high to begin theorizing. Some caution is always warranted in generalizing from data. A collecting-data-before-thinking approach, once common in geology departments, is inefficient. I have seen students with this philosophy fail to gather the relevant information at remote inaccessible field areas. When they come back and then learn some additional physics, they could not easily get back to their remote study areas to reconsider their observations. In practice, their field programs were slave to some outmoded theory.

In the end, blind empiricism is simply impractical. It is impossible to do all conceivable experiments. For example, we cannot check out all sequences of 150 DNA base pairs. (This would be a pitiful start at empirical science. Our genome alone has 3200 million base pairs.) There are 4 possible base pairs so there are 4 multiplied by itself 150 times or about 10^{90} (1 with 90 zeros) possibilities. There are not this many atoms in the observable universe. The practicing scientist needs some sort of theory to make observation tractable.

A hard-to-teach skill of practicing scientists is how far to push generalizations from the data. Having a range of opinions from conservative to wildly speculative probably helps. Stating that nature is unfathomable and that we should not try to figure it out is an admission of defeat. Today, selective excessive empiricism is a fallback of new-age mystics. “You did not show that my cat can’t levitate. It only had a bad day.”

The medieval scholastics reasoned from biblical premises that they would not question no matter what the evidence. To function, scholastics selectively invoke excessive empiricism. The more open-minded prosecutors of Galileo were willing to believe their eyes with a telescope, but unwilling to generalize that the phases of Venus and the moons of Jupiter were strong evidence for the Copernican system that they contended conflicted with the Bible. So-called Creation Science keeps this tradition alive and well.

Eudoxio invokes secrecy, another hindrance to scientific progress. There are of course military and trade secrets today, but most of basic science is public. Conversely, secrecy serves to hide ignorance and incompetence. The military does this some, but a quack doctor is a better example. If he really had a cure for all types of cancer, wouldn’t he publish and patent it, live in luxury, and collect the Nobel Prize?

In the early days of astronomy, the ability to predict seasons and planetary motions gave the illusion of control, like with B-grade movies where the Westerner escapes cannibals by threatening to shut off the Sun just before an ellipse. By the time of Galileo, claims of control of the visible sky, as opposed to theological Heaven, were no longer a problem in Western Europe. The power of the guilds was waning. Overall, secrecy was not a significant impediment to the development of astrobiology after 1600.

Yet secret ceremonies can be fun. For example, when the need for stonemasons waned as cannons rendered castles useless for defense, the Freemasons maintained and enlarged their rituals. The few practicing stonemasons did not. The demand for their trade has continued to decline. Personally, my grandfather trained my father. But my father had to do other lines of work to live. He made no attempt to train me beyond recognizing which rocks are good to put in stonewalls once he realized I was interested in geology.

Recognizing life

> *Hotspur*: … No, Percy, thou art dust,
> And food for— [*Dies.*
>
> *Prince.* For worms, brave Percy.
>
> *The First Part of King Henry the Fourth*, Act V. Scene IV.
>
> William Shakespeare (1564–1616).
> The Oxford Shakespeare. 1914.

Shakespeare, like Bruno and Galileo, had no problem defining life. Percy, many of his troops, and many of his horses, were alive at the start of the Battle of Shrewsbury and dead at the end. Everyone was familiar with the basic necessities to sustain life. Man, worm, and horse had to eat. Horses and people definitely begat offspring.

Microbes. This all changed when Anton van Leeuwenhoek (1632-1723), a Dutch draper, became interested improving the microscope. Lenses had existed from late medieval times and there had been crude microscopes with two lenses before the invention of the telescope. Van Leeuwenhoek developed single lens instruments that could magnify a few hundred times.

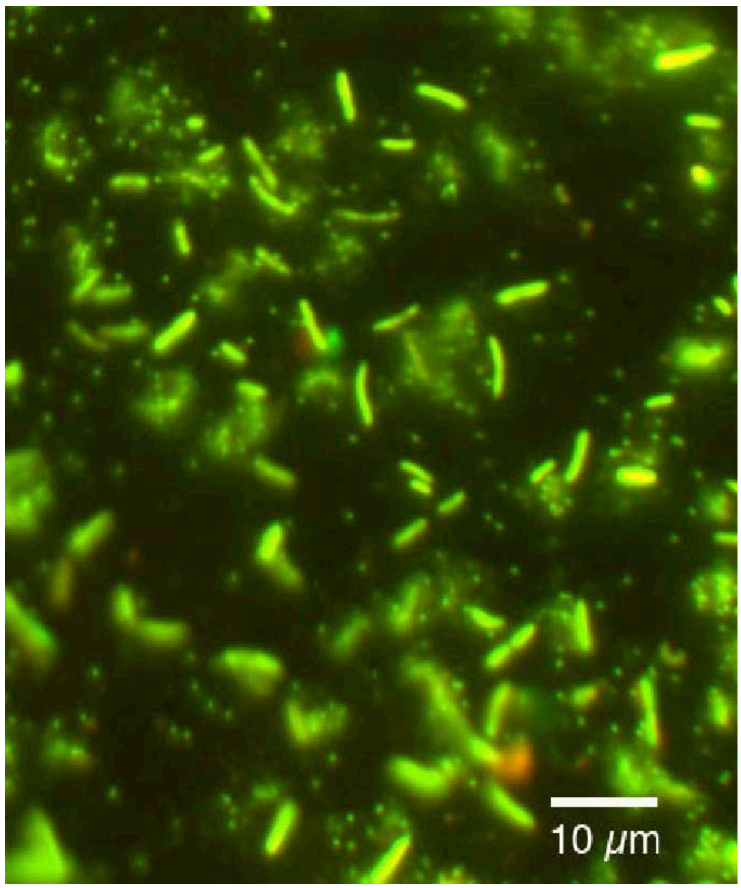

Figure 1: Rod shaped and small dot shaped microbes colonize a mineral surface placed in a spring coming out of serpentine. As discussed below, the building block ribose for DNA may have originated in this environment. The microbes have been strained green to make them more visible. Photo by Onion Johnson.

Like Galileo, he pointed his instruments looked for what would turn up. The water in rotting grass teemed with small moving organisms. The larger ones resembled tiny insects. The smaller ones were barely resolved. The number of microbes on the Earth is vast. There are more of them in a handful of soil from the field of Shrewsbury that people on the Earth.

Figure 2: Dry grass in water becomes a rotting mess in a few days. Such “hay infusions” are a good way to obtain teeming microbes and nearly microscopic animals for viewing by microscope. The microbes persist as inactive spores on dry grass; the animals have similarly inactive adaptations. Both become active when water is available. Photo by author.

Van Leeuwenhoek communicated his findings to the Royal Society in London, then the leading scientific organization in the world. These learned men were naturally skeptical and demanded more evidence. Van Leeuwenhoek welcomed scrutiny. He immediately enlisted the services of his townsfolk. Anyone who came to his house could see his organisms. The Royal Society sent a representative who immediately verified the results. Strong evidence and repeatable experiments held the day. The Royal Society made van Leeuwenhoek a member.

Two questions immediately arose: (1) Were the organisms found by van Leeuwenhoek really alive? Yes, the larger organisms could be killed quickly by boiling and the smaller ones by prolonged boiling. (2) Did they need to reproduce or did they arise spontaneously from rot? This question persisted into the late 1800s. Lazzaro Spallanzani (1729-1799) showed that the microbes in rot come from the air. However, this opinion was not established until Louis Pasteur (1822-1895) published the results of careful experiments in 1862. The advent of molecular biochemistry in the last half of the twentieth century showed that microbes are extremely complex. Modern scientists would have no trouble recognizing microbes as alive once they had them in their laboratory. The situation would not be as easy with a robotic probe on another planet.

Semantics and obscurantism surrounding life forms. I discussed the functional criteria that life gathers energy from its environment and that it begets itself. I have implicitly added complexity as a criterion. The criterion that the living can be killed is helpful. Even this rudimentary terminology can lead to confusion. I quickly outline some of the semantic difficulties that tend to cloak real scientific issues.

A mule is a hybrid between a horse and a donkey. Male mules are infertile and usually gelded as are oxen. Female mules can rarely give birth. The workers in a honeybee hive also do not reproduce. It is simplest to stick with common practice regard worker bees and mules as alive. A farmer would certainly claim I killed his mule if I shot it for a deer.

Viruses pose another problem. They reproduce in countless numbers like when we get the flu. Our immune system has evolved to kill them. They are complex. Their amounts of genetic material and their sizes overlap with those of microbes. Yet when viewed narrowly, viruses do not gather energy from the environment. They enter a living cell and hijack its genetic material to make more viruses. I regard this a just another way to gather energy and material to reproduce.

Going into the staples of science fiction, a consortium of self-reproducing machines may even be aware of its own existence and capable of conscious thought. They certainly gather energy and materials. They get killed, that is rendered nonfunctional, at the end of sci-fi movies. There is also the possibility of energetically engineered and cloned life. In all these cases, ordinary life, like us, has to evolve first.

Life as chemistry

Astrobiologists try to identify auspicious venues for life, particularly within our solar system. They need to be able to recognize both living and fossil life, probably on a planetary surface with a robotic probe. They want to see how non-life became life, particularly on our own planet. Chemistry, discussed more in Chapter 7, is the center of this activity.

There is no way to keep a scientific discussion of the origin of life devoid of complex chemistry. I give chemical names for those who wish to find out more from other sources and those already familiar with chemistry. You will at a minimum get an appreciation for complicity of even the basic molecular building blocks for life. I concentrate on aspects that relevant to the early Earth and other cosmic objects. It is inappropriate and impossible to present here the vast biochemical and biomedical knowledge on the workings of earthly life.

Basic chemistry. I present a primer on chemistry for those who have not had this subject or are rusty. It also serves to put terminology in context. To begin, matter is made of atoms. The dense nucleus of an atom contains protons (by convention) with positive charge. An equal number of negatively changed electrons "orbit" the nucleus. An electron's mass is much less than a proton's mass. There are also neutrons with no charge within all nuclei except hydrogen, which has only a single proton. Neutrons have about the same mass as a proton. The number of protons or equivalently electrons is called the atomic number. It defines a chemical element and determines most of its chemical properties. The mass number is the sum of the number of protons and neutrons. It has a minor but measurable effect on chemistry. Atoms of the same element (same number of protons) but different mass numbers are called isotopes.

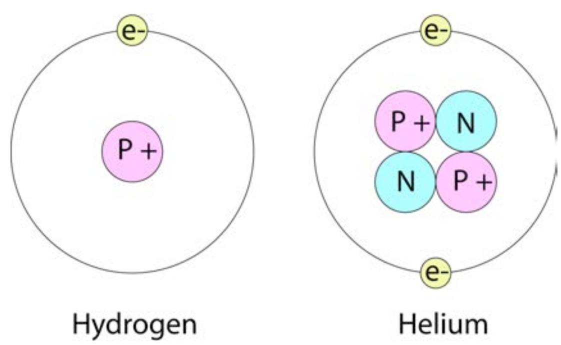

Figure 3: Hydrogen and helium are the simplest atoms. Hydrogen has one electron that orbits the nucleus (1 proton). Helium has two electrons orbiting a nucleus with 2 protons and 2 neutrons. Quantum mechanics represents the electrons as being in energy levels called shells. The orbiting electrons have the properties of a diffuse wavelike cloud, rather than following a well defined paths, like planets.

A key result of quantum mechanics at the start of the twentieth century is that the electrons orbiting an atom can be in only a finite number of energy states. It is still difficult to compute these states from first principles except for the simplest atoms. A phenomenological theory giving the results works well and illustrates the basis of chemistry.

The electrons exist in energy levels called shells. Hydrogen and helium have only one shell with room for two electrons in their lowest energy state.

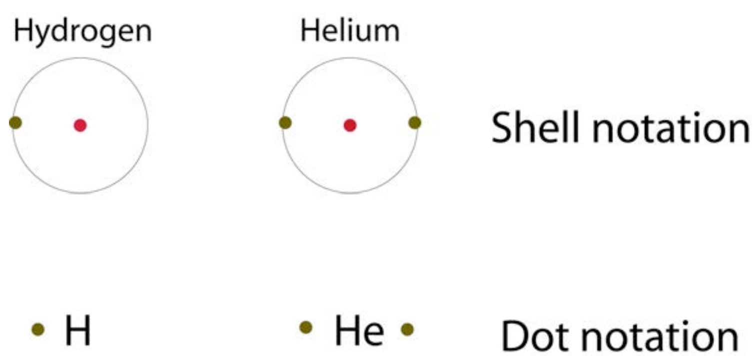

Figure 4: Two ways to represent hydrogen and helium atoms. Shell notation shows that the electrons are in a single shell with room for 2 electrons. Dot notation shows only the electrons in the outermost shell, which in this special case is the only shell.

Atomic hydrogen has 1 electron in its shell. Helium's shell is filled with 2 electrons.

All the remaining elements have a filled inner shell like helium that has little effect on their chemical behavior. The electrons in the outermost shell govern chemistry. The next two shells contain 2 and 6 electrons, respectively. They fill as if they were a single shell with room for 8 electrons.

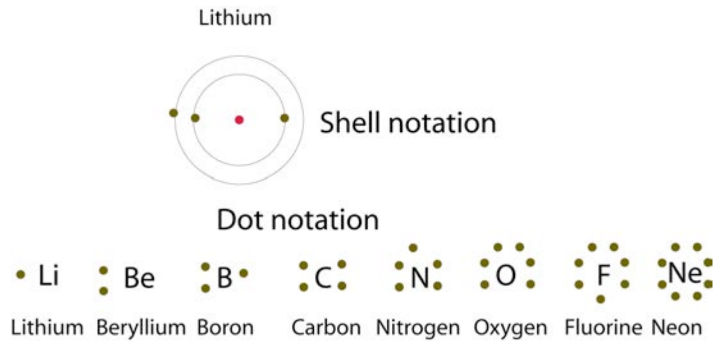

Figure 5: Atoms from lithium to neon fill their second shell with room for 8 electrons. Their inner shell is filled with 2 electrons. Chemists use the dot notation because shell notation becomes bulky.

In increasing atomic number, lithium, beryllium, boron, carbon, nitrogen, oxygen, fluorine, and neon have 1, 2, 3, 4, 5, 6, 7, and 8 outer shell electrons, respectively. Remaining elements have filled inner shells, with the electron configuration of neon. The next two shells with 2 and 6 electrons again fill like a single shell with 8 places for electrons.

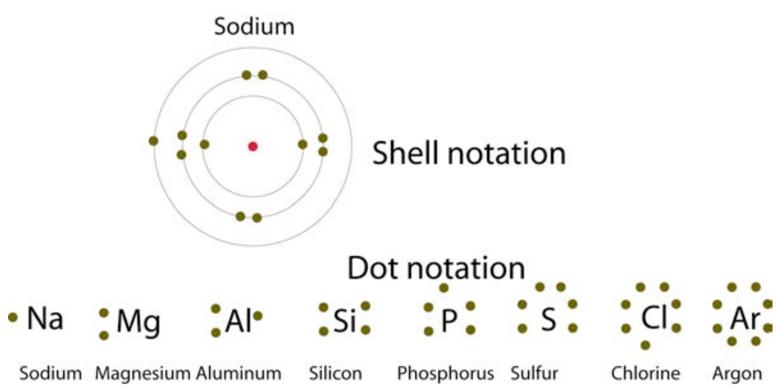

Figure 6: Atoms from sodium to argon fill their third shell with room for 8 electrons. Their inner shells are filled with 2 and 8 electrons.

The elements, sodium, magnesium, aluminum, silicon, phosphorus, sulfide, chlorine, and argon have 1, 2, 3, 4, 5, 6, 7, and 8 outer electrons respectively.

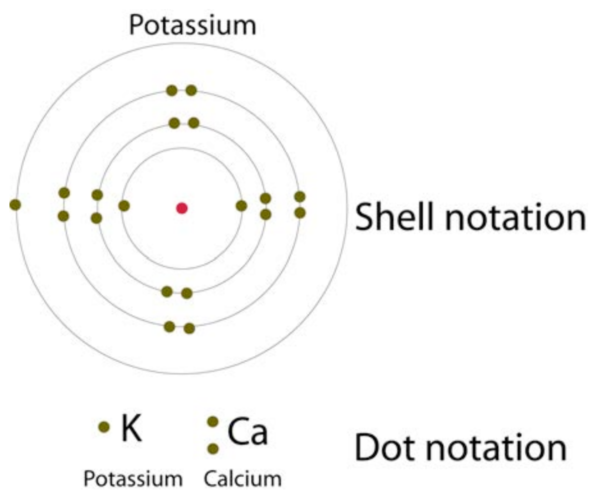

Figure 7: Potassium and calcium atoms begin to fill their fourth shell. Their 3 inner shells are filled with 2, 8, and 8 electrons. Elements with higher atomic numbers fill additional inner shells as well as their outer shell. This leads to complicated chemical behavior.

The next elements, potassium and calcium, have the inner shells with the configuration of argon and 1 and 2, outer electrons, respectively, The chemistry for elements with higher atomic numbers is more complicated because additional inner shells fill along with outer shells. I return to this when I discuss iron in Chapter 9.

Atoms with filled outer shells are the most stable, that is, the rare gases helium, neon, and argon. They do not form compounds at room conditions. Other atoms join to form molecules to obtain filled outer shells. They may either share or acquire electrons to obtain fill their outer shell. They may give away electrons to empty their outer shell so that their remaining inner shell is full.

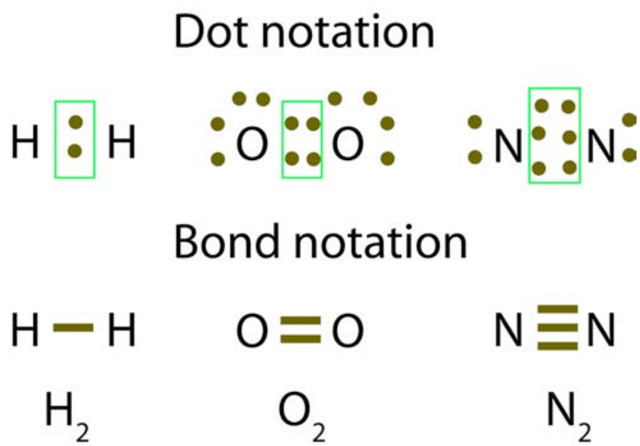

Figure 8: Like atoms bind to form diatomic gases. The green box encloses the shared electrons that give both atoms filled outer shells. Bond notation is less bulky. The number of lines indicates the number of shared electrons. For those with advanced chemistry, the actual bond in oxygen is more complicated.

I begin with electron sharing, as it is important in biochemistry. Atoms may join with like atoms of the same element. Hydrogen does this; two hydrogen atoms join to form the molecule H_2. For those unfamiliar with chemical notation the chemical formula lists the symbol for the element, here H for hydrogen, followed by the number of atoms of the element in the molecule, here 2. The 2 shared electrons have the effect of filling the outer shell of both hydrogen atoms with 2 electrons. If you are worried that this is some form of cheating, it is a quantum effect; there is no good analog at a macroscopic scale.

Oxygen also joins with itself to form a molecule. Here each oxygen atom has 6 outer electrons. Each atom shares two electrons, so the outer shells of both atoms have 8. The molecule is O_2, which makes up 21% of our air. Nitrogen shares 3 electrons from each atom to form N_2, which is 78% of our air. To make drawings legible, organic chemists often replace dot notation with bond notation: a single line represents a bond form a pair of shared electrons one form each atom, here between the hydrogen atoms. A double line represents a double bond made by sharing 2 electrons form each atom, here between oxygen atoms. A triple line represents 3 shared electrons here between the nitrogen atoms. I use both dot and bond notation for simple compounds so that the reader can become familiar with them with simple molecules. I use bond notation with complicated compounds. The effect of both notations is to project the three-dimensional shape of a molecule onto two-dimensional paper.

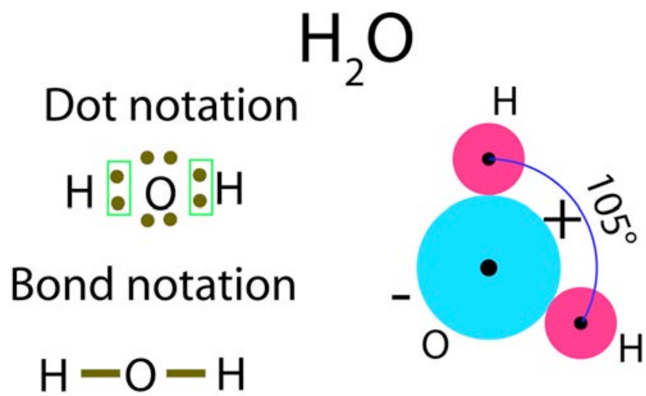

Figure 9: The water molecule in dot and bond notation. The hydrogen atoms form an angle of 105° with the oxygen atom. A net positive charge exists on the oxygen end of the molecule and a net positive charge on the hydrogen end.

Molecules also form by combining atoms of different elements. Water H_2O is a familiar example, the most widely known chemical formula. The oxygen atom shares an electron with each hydrogen atom. This serves to fill the outer shell of the hydrogen atoms with two electrons. Each hydrogen atom shares its electron with the oxygen. This acts to fill the outer shell of the oxygen with 8 electrons.

Sluggish reactions: a food for life. Water has less available energy than the mixture of hydrogen and oxygen to make it. Do not try this, but if we put a mixture of 2 parts hydrogen and 1 part oxygen in a closed jar at room temperature, they could sit there indefinitely with nothing happening. However, if we set off a spark the mixture explodes violently turning the stored chemical energy in heat and the “kinetic” energy of the flying jar fragments and expanding hot gas.

Returning to quantum theory, the hydrogen and oxygen molecules can have only certain energy states. I illustrate the effects of this feature with a much simpler system in two dimensions, a quantum “ball” on an undulant surface. The hydrogen and oxygen molecules are like the ball oscillating within a local depression. To react, the ball needs to climb over the barrier to drop down to the lower energy level representing water. At room temperature, almost all the molecules are in a low energy state and they do not jump the barrier.

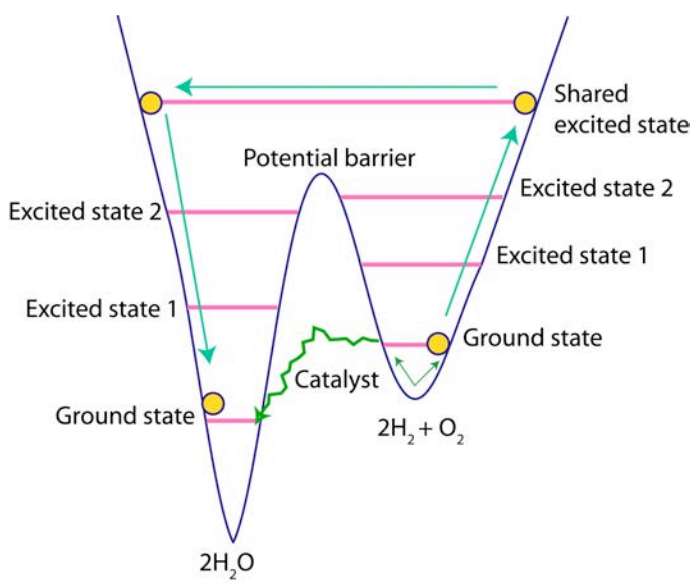

Figure 10: A quantum surface and quantum ball simply represent the reaction of $2H_2 + O_2$ to form water ($2H_2O$). The ball oscillates in the bottom of the traps. The top of the oscillation can be at only certain specific energy levels. At room temperature, the ball is in its ground state and rarely in the first excited state. It is trapped on its side of the barrier and the reaction does not occur. At high temperatures, the ball frequently enters a shared excited state and can cross over the barrier. The ball releases energy to the gas when it falls down to the ground state of the reactants. A catalyst lets the reactants circumvent the energy barrier but does not change the energy difference between the starting and final ground states.

The spark is a local region of high temperature. The molecules move fast and collide hard. Many of the molecules are in high-energy states and able to jump the energy barrier. The heat from forming water increases the temperature, speeding the reaction into an explosion.

Microbes living in the hydrogen-oxygen gas mixture cannot benefit by setting off an explosion. They do benefit, however, if they can lower the energy barrier so that the molecules can peacefully make the energy jump on their own. They also need to harvest the reaction energy into something useful for their mode of life, like making organic matter from methane and carbon dioxide. (I discuss these compounds below.) The net process can be viewed as linked balls on undulant surfaces. The ball representing making organic matter from methane and carbon dioxide needs to jump an energy barrier and land in a higher energy state. It cannot do this on its own. The molecular chemistry of the organism both links the production of water with the production of organic matter and lowers the energy barrier for making water. The actual process in a real microbe is much more complicated but has this net effect.

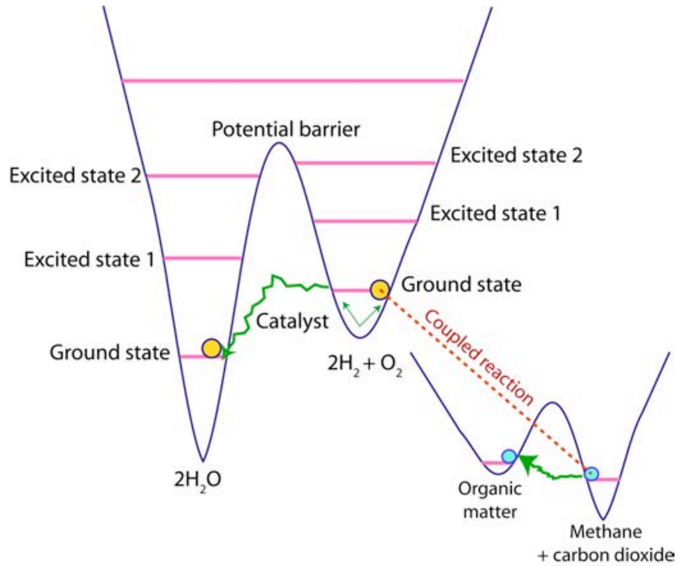

Figure 11: Linked quantum balls and surfaces represent a coupled reaction. The catalyst lets hydrogen and oxygen react quietly to form water. It uses much of the energy of this reaction to form organic matter from carbon dioxide and methane.

Hydrogen fuel cells, as proposed for cars, also gain useful energy by controlled production of water from hydrogen and oxygen. They produce an electric current. We could conceivably use the current to make organic matter and have the same net effect as our organism. In general, chemists refer to any substance that lets a reaction circumvent an energy barrier as a catalyst. Fuel cells require sophisticated catalysts.

These examples yield the chemical definition of life as an orderly collection of many catalysts that can self-replicate and gather energy from its environment. We can see from this concept why Bruno was wrong to expect life on the scorching surfaces of stars and why we do not expect to find life within the hot interiors of planets. There is little to eat (that is available energy to gather) at high temperatures because there is enough heat energy that many molecules are at high energy levels. Most reactions have already jumped their barriers to the most stable low-energy molecules. In more technical terms, the system is at its lowest energy equilibrium for its temperature. Even if an organism did produce some complex molecules needed for its existence, they would continually jump energy barriers and go back to uninteresting simple molecules.

Water: the base of life. Life on the Earth depends on liquid water confined within cells. The bulk of our bodies is water. Since Galileo, there is a tendency in astrobiology to focus attention upon environments were liquid water can exist. Water does have neat properties. I examine them to point out other possible biological liquids.

Returning to the water molecule, the sharing of electrons is not equitable. The electrons spend more of their time about the oxygen atom than the hydrogen atoms, giving the oxygen a net negative change. The hydrogen atoms each have a net positive change. They arrange themselves to form an angle of 105° with the center of the oxygen atom. This has the consequence that that the oxygen end of the atom is negatively charged and the hydrogen end is positively charged. This makes water an effective solvent. In addition, the unlike charges attract causing adjacent water molecules to stick to each other. This process allows water to be a liquid at room temperature and ice to form below 0°C.

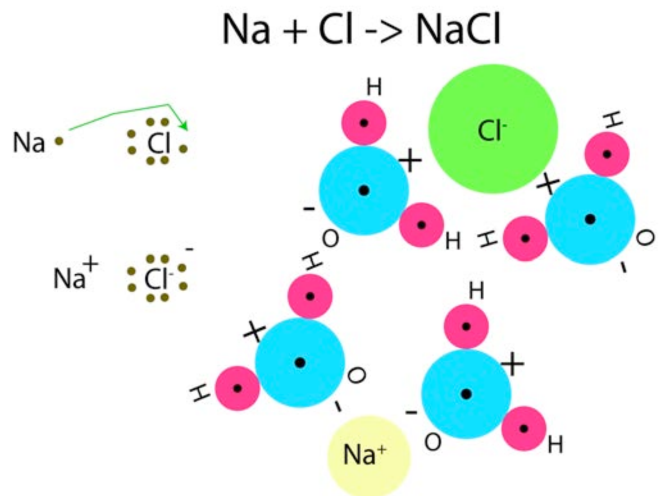

Figure 12: A sodium atom gives its outer electron to a chlorine atom. This empties the outer shell of the sodium atom and fills the inner shell of the chlorine atoms. The charged ions of salt readily dissolve in water. The hydrogen ends of water collect around the chlorine ion and the oxygen ends around the sodium ion.

To show this, I return to electron exchange and basic chemistry. Table salt is NaCl. The sodium Na atom has a single electron in its outer shell that it would "like" to get rid of. Chlorine Cl has 7 electrons in its outer shell and would "like" 8. Both atoms have filled outer shells when the sodium atom gives its electron to the chlorine atom. This leaves the chlorine with a negative charge from its added electron and the sodium with a positive charge from ridding itself of an electron.

Salt dissolves when placed in water. Unlike charges attract. The negatively charged chlorine atom (called an ion) attracts the hydrogen ends of water molecules and the positively charged sodium ion attracts the oxygen ends of water molecules. This keeps the sodium and chlorine atoms apart and in solution. In general, substances that separate into charged ions or have positively and negatively charged ends (polar molecules) are soluble in water.

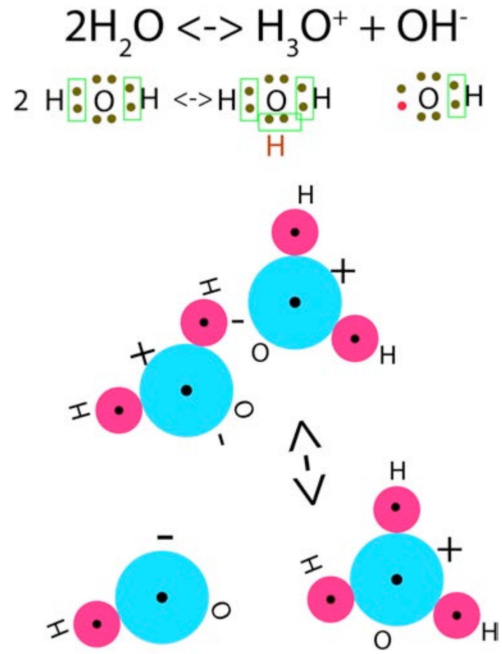

Figure 13: A hydrogen atom jumps from one water molecule to another to form the charged ions hydronium H_3O^+ and hydroxyl OH^-. These ions then quickly recombine to form uncharged water molecules. The processes occur continually maintaining about 2 out of a billion of the water molecules as ions. Chemists often use the symbol H^+, the hydrogen ion, to compactly represent what are actually hydronium ions in solution.

Water contributes some ions on its own. Some water molecules ionize into OH^- and H_3O^+. At room temperature and pure water, about 2 molecules out of a billion are in this state. This may not seem like much but it is enough to make water reactive with many other substances. I return to water after I discuss the other basic ingredient of life carbon.

Carbon, organic chemistry, and information storage. The complex chemistry of life on the Earth involves large molecules with many carbon atoms. In particular, carbon forms the backbone of the genetic information molecule DNA. To store information, like the text this page, the large carbon-containing molecules need an orderly complexity with some predictability. In analogy, the scribbling of a three-year-old is complex, but disordered and unreadable.

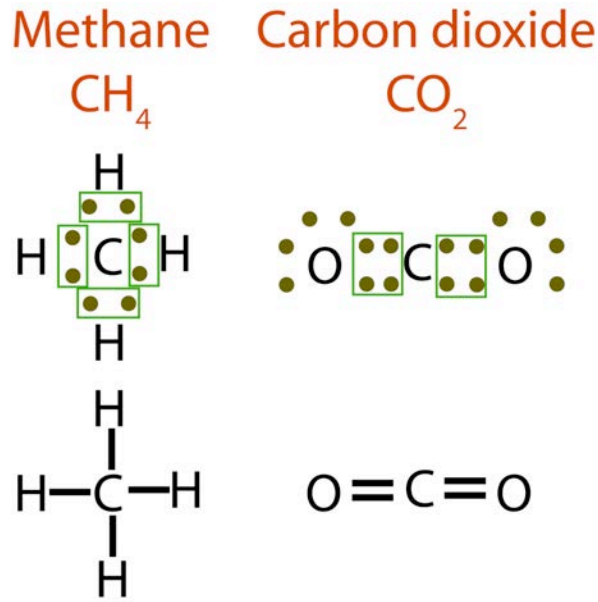

Figure 14: Methane and carbon dioxide are simple carbon compounds. All the electrons in the hydrogen atoms and carbon atom of methane are shared. Four electrons in each oxygen atom are not shared in carbon dioxide. In general molecules where all the electrons are shared, like methane less reactive than molecules with unshared electrons, like carbon dioxide.

To start again with basic chemistry, carbon has 4 outer-shell electrons. It typically gets eight by sharing with other atoms. It makes carbon dioxide CO_2 by sharing 2 electron pairs with each of 2 oxygen atoms. It makes methane CH_4 by sharing one electron pair with each of the hydrogen atoms. These compounds are the most stable states of carbon in gas at room temperature and pressure.

A vast number of compounds of carbon with hydrogen and oxygen are possible. To start, carbon forms the compound formaldehyde H_2CO by sharing a pair of electron with two each of 2 hydrogen atoms and 2 pairs of electrons with an oxygen atom.

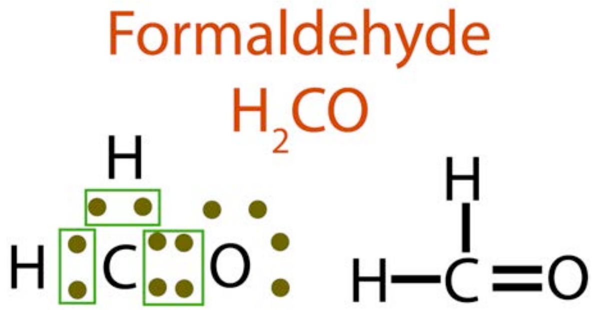

Figure 15: Formaldehyde is a simple compound that is a building block for more complex compounds.

Formaldehyde is toxic to many bacteria. It was once a widely used preservative for biological specimens. It is highly volatile. Biology departments reeked of its fumes when I was in college. Parkinson's disease from long-term exposure was then an occupational hazard for biologists. Despite its toxicity to modern life, the tendency of carbon to share electrons with itself makes formaldehyde a building block of life. Astronomers have detected it in interstellar space (See spectra in Chapter 6).

I work up in complexity. I double the number of atoms in the formula and again make molecules. Acetic acid gives vinegar its sour taste. Glycolaldehyde has the same composition as acetic acid but a different structure. Both molecules occur in space.

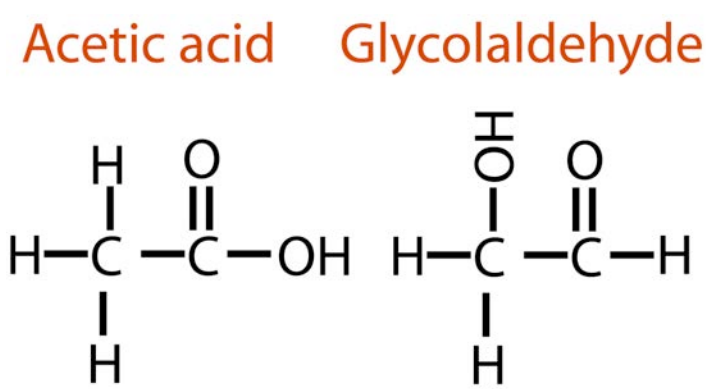

Figure 16: Acetic acid and glycolaldehyde have the same empirical formula but different structures.

In general, a group of atoms including a few of carbon can typically form several different molecules. Organic chemists use structural (dot and bond) formulas for this reason. I distinguish the structural formula from the "empirical" formula, which is $C_2H_4O_2$ for both acetic acid and glycolaldehyde. In the case, there is also a simplified empirical formula obtained by dividing the coefficients by 2. This formula for formaldehyde, acetic acid, and glycolaldehyde is CH_2O. That is, it is equivalent to one carbon atom and one water molecule. Chemists call more complex compounds with this simplified empirical formula carbohydrates. This includes sugars and starches. Some of these compounds are necessary parts of our diet, even though "carbs" have got bad press lately because gluttony can lead to obesity.

Water, carbon, and sugar. The property of carbohydrates that their simplified empirical formulas are equivalent to a number n formaldehyde molecules, $n(CH_2O)$, allows for orderly complexity. Interestingly, complex molecules of this type can form abiotically in conditions that are likely to have been present on the ancient Earth. As discussed in Chapter 8, rocks in the Earth's mantle (the region from several to 2900 kilometers deep) contain the oxygen compounds (oxides) of magnesium, silicon, iron, and calcium. These rocks locally outcrop on land and beneath ocean basins. In both cases, water circulates through the rock at low temperatures as well as temperatures to a few 100°C.

Again looking at the electrons in the outer shell, magnesium has two outer electrons. It gives them to an oxygen atom filling its outer shell forming MgO. A calcium atom also has two outer electrons to give to an oxygen atom to make CaO. Silicon has 4 outer electrons. Like carbon, it shares electrons with 2 oxygen atoms making SiO_2. At the temperature (~1200°C) where mantle rocks are partly molten, the oxides of magnesium and silicon combine to form the mineral olivine, so named because of its greenish color. Its formula is Mg_2SiO_4. Transparent gem quality olivine is called peridote. Movements within the Earth (see Chapter 8) bring the cooled rock to the surface.

There are minor amounts of Ca_2SiO_4 in natural olivine. At room temperature, the oxides of magnesium and silicon combine with water to form a complicated mineral called serpentine. Calcium, however, does not enter the serpentine. It remains in solution as a positively charged ion. The oxygen ion derived from CaO has two excess electrons; it combines with water to form 2 OH^- ions (each called a hydroxyl ion). The ions in solution are thus 1 Ca^{++} per 2 OH^-. You may have purchased this substance as quick lime or agricultural lime to put on your garden.

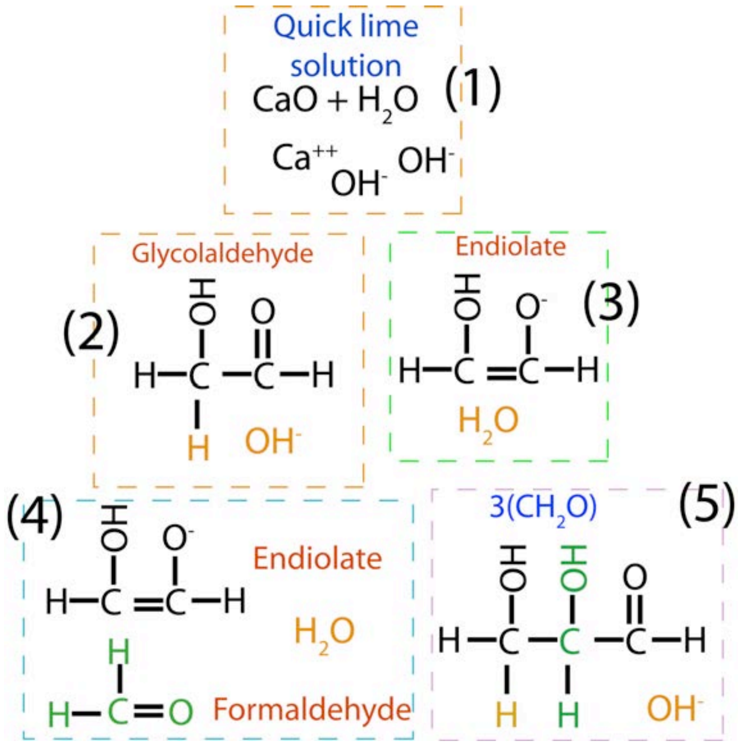

Figure 17: Five steps to make complex organic molecules from glycolaldehyde and forma;dehyde. (1) Calcium oxide dissolves in water liberating hydroxyl OH^- ions. (2) The hydroxyl ion attaches to a hydrogen atom in a glycolaldehyde molecule. (3) This forms an endiolate ion with a negative change and a water molecule. (4) The endiolate ion reacts with a formaldehyde molecule. (5) The produces are a 3-carbon molecule and a hydroxyl ion. The hydroxyl ion is a catalyst as it enters the reaction at the beginning and emerges at the end. In general, catalysts work by allowing a series of intermediate reaction steps with low energy barriers.

These ions Ca^{++} and OH^- are powerful catalysts for reacting formaldehyde with glycolaldehyde to form large carbohydrate molecules. The OH^- ions can form water molecules by attaching to a hydrogen atom in another molecule. In general, materials with the property of releasing OH^- ions or consuming hydrogen ion to make water are called bases. The substances that supply the hydrogen ions or consume OH^- are acids. You have acid in your stomach. The antacids you take are mild bases that release only a small fraction of their available OH^- into solution. It would be very dangerous to use quick lime, which releases most of its OH^-, for this purpose.

One of the hydrogen atoms in glycolaldehyde can attach to an OH^-. It does this in a complicated way. The carbon atoms in the product share 2 pairs of electrons with each other. Chemists call this a double bond. The oxygen accepts the electron from the OH^-. The oxygen atom now shares only 1 pair with the carbon as it got its 8th outer-shell electron from the OH^-. Chemists call this ion endiolate.

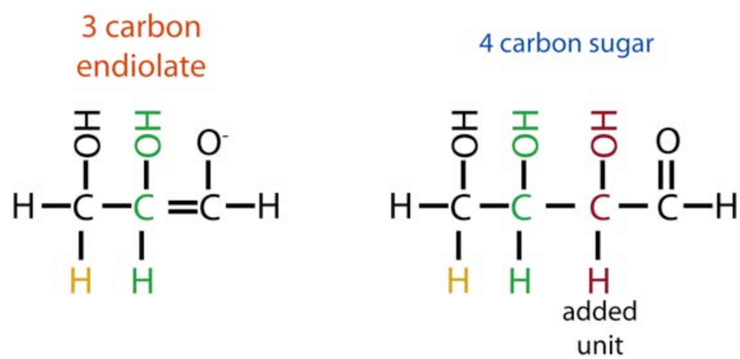

Figure 18: 3 carbon endiolate forms from a 3-carbon molecule by reacting with a hydroxyl ion. It reacts with formaldehyde to form a 4-carbon molecule. This process goes on indefinitely to form long chains of tar molecules.

Endiolate readily reacts with formaldehyde to form a compound with the empirical formula of $3(CH_2O)$. This molecule can react with formaldehyde to form a compound with the empirical formula of $4(CH_2O)$. It can react with glycolaldehyde to form compounds with the empirical formula of $5(CH_2O)$. These reactions go on indefinitely making long chain molecules with many CH_2O units. This material, black tar, is complex but not orderly. It is not a good starting point for life.

A building block of DNA and RNA is ribose with the empirical formula $5(CH_2O)$. It has 4 ends where it may attach to other molecules and form orderly complex chains. It too quickly decomposes to black tar in a quick lime $Ca(OH)_2$ solution.

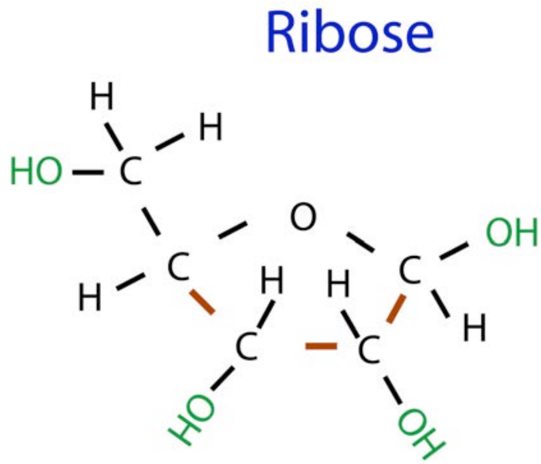

Figure 19: The sugar ribose has 5 carbon atoms. Four of the carbon atoms an oxygen atom form a pentagonal ring. The OH groups are reactive sites.

How then would this process naturally stop at the useful biological product ribose? It turns out the minor element boron is important. It occurs in solution in natural waters within serpentine. Boron has 3 outer electrons. It shares them with 3 oxygen atoms. The oxygen atoms take 3 more electrons from OH^- atoms forming water. This results in a borate ion BO_3^{---} that has 3 negative charges. Borate attaches to 3(CH_2O) so that it can only react with glycolaldehyde to form 5(CH_2O) compounds and keeps 5(CH_2O) compounds from reacting. Here is stabilizes two ribose molecules.

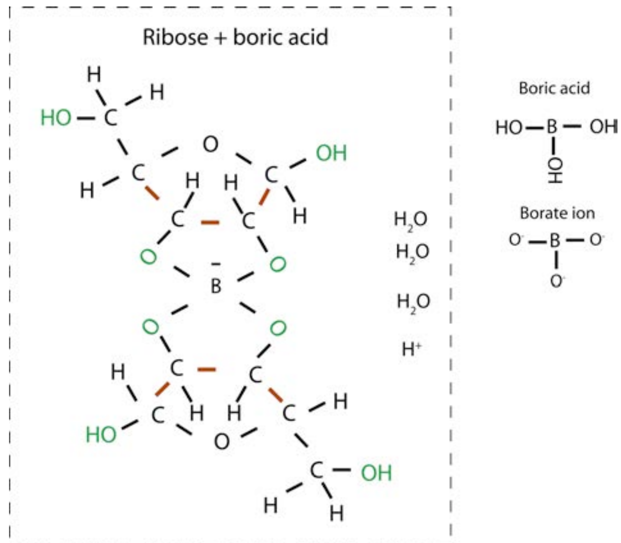

Figure 20: A borate ion reacts with the OH groups on the pentagonal structure in ribose. Each ribose molecule contributes 2 hydrogen atoms. The boric acid molecule contributes 3 oxygen atoms and 3 hydrogen atoms. The produces are 2 joined ribose molecules with a negative change on the borate ion, 3 water molecules, and a positively change H^+ ion. In general borate allows 5-carbon sugars to form and stabilizes them from turning large tar molecules.

The actual DNA and RNA chains used by organisms on the Earth contain additional complex blocks that include phosphorus and nitrogen atoms. Both these atoms have 5 outer electrons. Phosphorus shares its electrons with 4 oxygen atoms to form phosphate PO_4^{---} which has 3 negative charges.

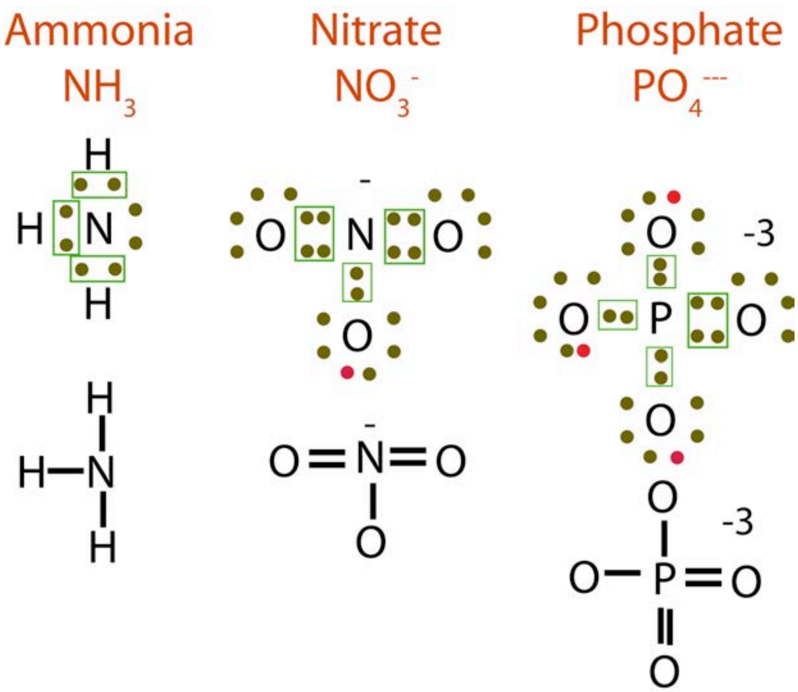

Figure 21: Three building blocks of complex organic molecules. Ammonia is a simple compound of hydrogen and nitrogen. Nitrate and phosphate ions are soluble in water. The 3 oxygen atoms share the extra electron in nitrate. The 4 oxygen atoms share the extra 3 electrons in phosphate. All the 5 outer electrons of nitrogen and phosphate are shared with oxygen in these ions.

Nitrogen shares electrons with hydrogen. It fills its outer shell with 8 electrons to form ammonia NH_3. Nitrogen, hydrogen, and oxygen compounds with carbon are complex, like carbohydrates. Amino acids are one class of these compounds. They contain carbon sharing one electron with NH_2. This fills the outer shell of the nitrogen atom with 8 electrons. Amino acids readily form chains including the proteins in our cells and our diets. Nitrogen can also share 2 electron pairs with each of 3 oxygen atoms to form ions with one negative charge called nitrate, NO_3^-.

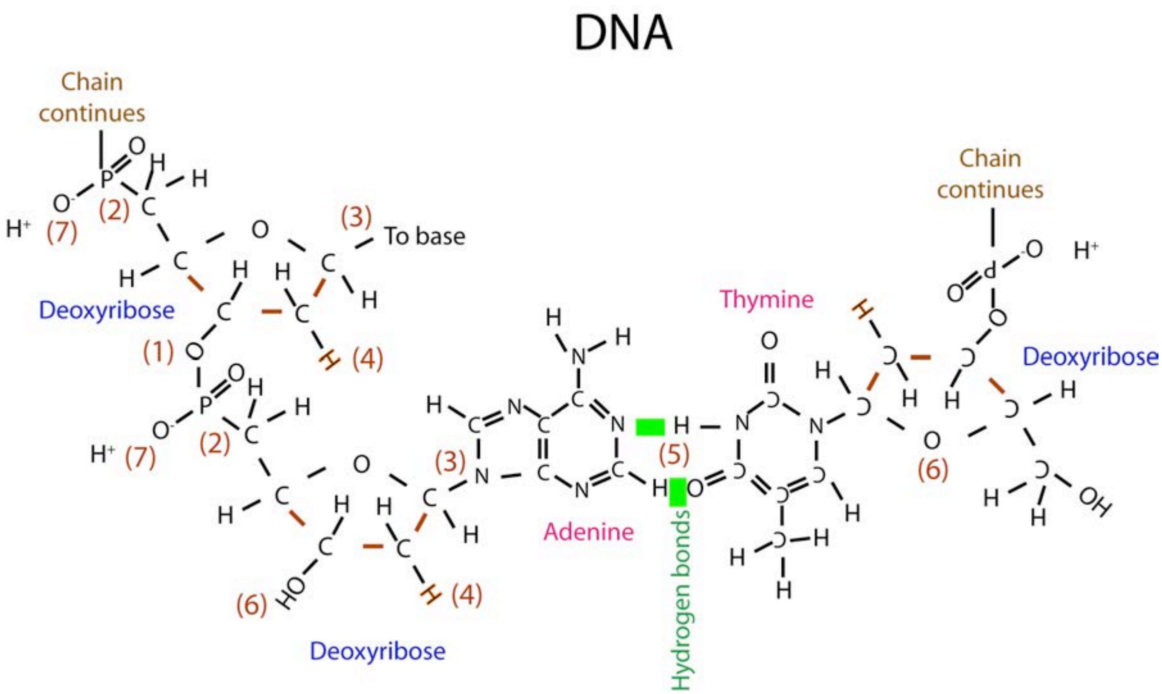

Figure 22: DNA (deoxyribonucleic acid) forms from simpler building blocks of deoxyribose, phosphate, and here the bases adenine and thymine. In the orientation of the left side of the drawing: (1) The OH group on the lower left side of the pentagon detaches and the carbon atoms bonds to an oxygen atom in a phosphate group. (2) The OH group on the carbon atom that is not in the pentagon also detaches and the carbon atom bonds to the phosphorus atom in the phosphate group. (3) The OH group in the upright right of the pentagon detaches and the carbon bonds to a nitrogen atom in the base. (4) An H atom replaces the OH group at the lower left corner of the ribose pentagon. "deoxy" in the name tells that an oxygen atom is missing. This substitution stabilizes a potentially reactive site. RNA retains the OH group. (5) Hydrogen binds link the two bases. (6) The ribose groups and bases point in the opposite direction in the other half of the chain. (6) The chain ends at the bottom of the diagram. The OH group is a potentially reactive site for the chain to grow longer. (7) One oxygen atom in the phosphate group is negatively charged. This has the effect of releasing an H^+ ion into solution in the cell. Hence DNA is an acid.

This drawing shows a single link in a DNA chain. Note that the deoxyribose molecules point in opposite directions. Chemists call the building blocks linking the two deoxyribose molecules "bases." The linkage occurs by hydrogen bonds where the molecules share hydrogen atoms. These weak bonds release when the DNA divides into two single chains when it replicates. Bases include ring-like structures made of carbon and nitrogen atoms and NH_2 groups. We each have two sets of chromosomes each with about 3200 million pairs of bases in our cells.

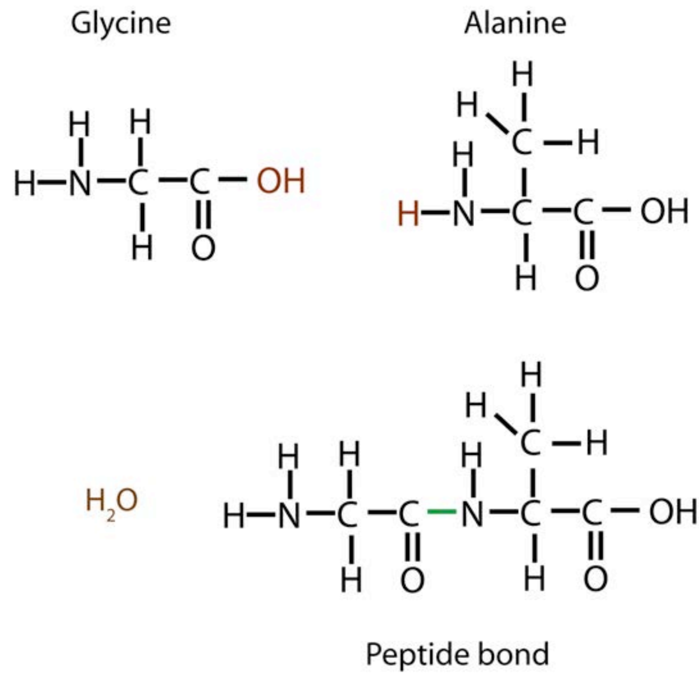

Figure 23: Glycine and alanine are simple amino acids. They form a peptide bond, releasing a water molecule. Proteins are long chains of amino acids formed by peptide bonds.

Amino acids are another building block for complex organic molecules. They have 2 hydrogen atoms at one end attached to nitrogen atom and an OH on the other end attached to a carbon atom. A hydrogen atom from one amino acid molecule can combine with the OH from another molecule to from a water molecule. The two amino acids join with a carbon to nitrogen bond, called a peptide bond. Proteins are long chains of amino acids formed in this away. I stop with DNA and protein at this point and return to them after discussing evolution in Chapter 9.

Enclosed cells. Microbes are single celled organisms. Our bodies are consortia of vast numbers of cells. There is some tendency to equate life with cellular life. It needs to be resisted. Cells are quite complicated and cannot be the starting point of life. We have already seen that viruses are a form of noncellular life.

Cells, like medieval walled cities, are advantageous to organisms, as the chemical compounds they gather and produce are not immediately dispersed into their environment or seized by competing organisms. They help keep viruses at bay. I briefly discuss the properties of water that allow cell walls to function.

As already noted charged ions and polar molecules with charged ends are soluble in water. Nonpolar molecules that lack charged ends are not significantly soluble in water. Octane a component in gasoline is an example. Nonpolar oils cause water to bead on a duck's back. Car wax is a nonpolar solid that repels water.

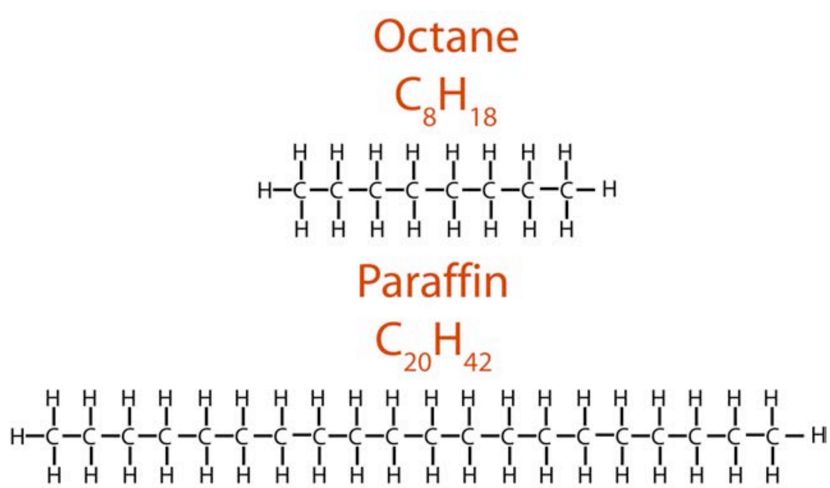

Figure 24: Octane and 20-carbon paraffin are simple nonpolar hydrocarbons. Octane is liquid at room temperature and paraffin is an easily melted solid. Both repel water.

Molecules consisting of several carbon atoms can have both properties at the same time. I use "sterol" to indicate a class of compounds with this property that includes those used in actual cells. (The formal definition of sterol "any derivative of cyclopentanoperhydrophenanthrene that possesses one or more hydroxyl groups" is not helpful to most people. I include it so biochemists (like one reviewer of this book) will not go ballistic.) One end of these molecules has a net charge and attracts water, hydrophilic for those wanting the chemical term. The other “hydrophobic” end repels water. Cells membranes are a double layer with the hydrophilic ends pointing out. They are highly evolved to allow the cell to control egress and entry of material.

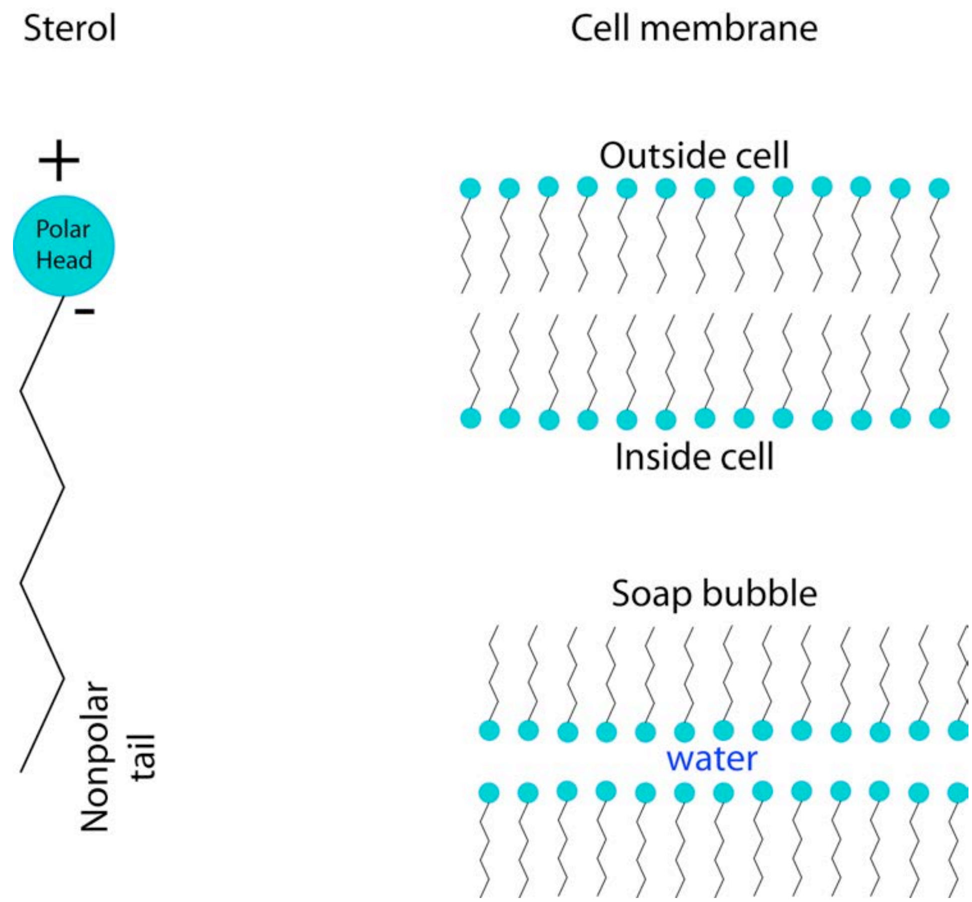

Figure 25: A sterol has a polar head here with the positive charge sticking out and a nonpolar tail. Sterols self organize into structures, like cell walls, with the polar ends pointing out. The polar ends point inward with soap bubbles. This arrangement might prove beneficial to cellular life inhabiting a nonpolar fluid.

Yet simple structures resembling cell membranes assemble spontaneously. Sterols also form spherical structures with the hydrophilic ends on the outside. Chemists have found stearols that do this in meteorites. Soap bubbles are an example on a double layer where the hydrophobic ends point outward and the hydrophilic ends trap a thin layer of water. Layers with the nonpolar ends pointing out form in nonpolar fluids like oil.

Weird Life

Carbon and water are the bases of life on the Earth. Astrobiologists seek other venues for life. They have amassed a shopping list. I discuss some promising examples.

Carbon and noncarbon life. Carbon is common on the Earth and in the universe. It forms long orderly chains by bonding with itself. I begin by tweaking carbon-based life from its terrestrial form.

Terrestrial life uses DNA to store genetic information. Some viruses use RNA. Prions are protein particles that act somewhat like viruses. The protein in a prion contains the information to make copies of itself at the expense of its host. Studies of prions indicates that they may evolve into closely related varieties that infect different species of organisms and hence may act as carriers of genetic information.

This opens the possibility of RNA and protein as alternative genetic substances. As discussed in Chapter 9, RNA is simpler than DNA and a more likely early genetic molecule. Proteins can form chain structures crudely similar to DNA. They are hence candidate early genetic molecules for the Earth.

Chemists have synthesized numerous carbon chains analogous to RNA and DNA. Some of these analogs do function as genetic substances. It turns out that RNA and DNA are among the more efficient genetic molecules. Ribose their building block, as we have already seen, forms abiotically. Phosphate may be a necessary component. For example, replacing it with sulfate SO_4^{--} does not yield an acceptable analog.

What about dispensing with carbon? Silicon is a favorite of science friction. It, like carbon, has 4 outer electrons. It is common in the universe. On the Earth, silicon occurs as SiO_2, a major component of rocks, including beach sand. Despite its ubiquity, silicon does not bond with itself or with carbon to form chains in terrestrial settings.

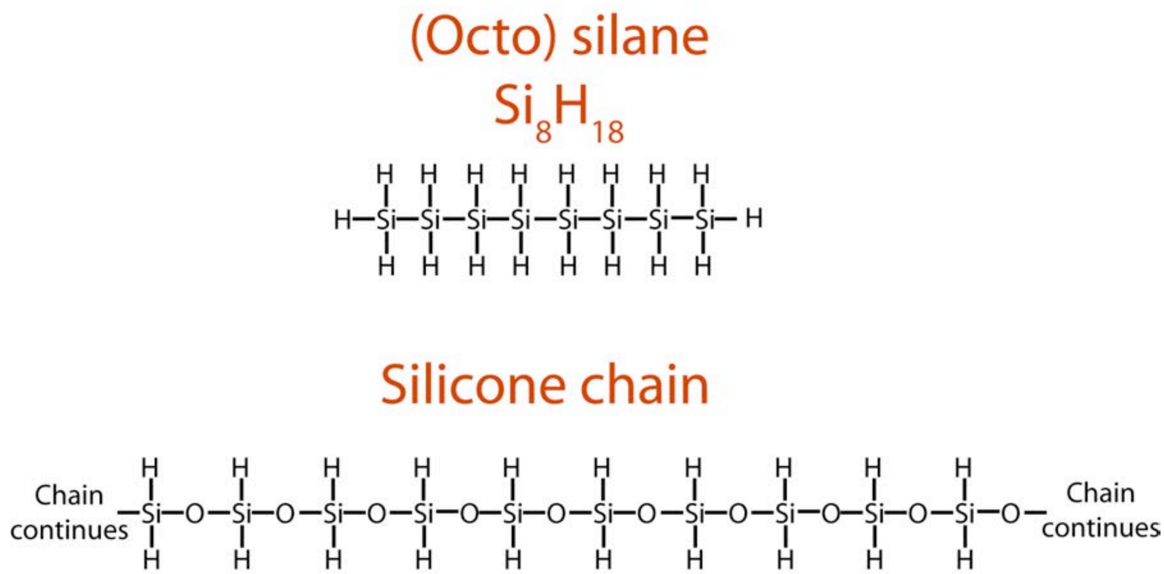

Figure 26: Silicon forms complex chains resembling organic molecules. Silanes resemble hydrocarbons. Silicones are chains formed by oxygen and silicon atoms.

Silicon, however, does form chains with itself including analogs to hydrocarbons and oils in the laboratory. Oxygen-bearing silicon chains, silicones, have numerous industrial applications. They are quite stable at room temperatures and do not react readily with carbon-based life. They are used for this reason to make implants in the human body. This inertness makes silicones poor candidates key biological molecules. Silicon carbide, a solid with the composition SiC, has the industrial application as grinding powder. It occurs naturally as a trace component in some meteorites. It is again inert at room conditions. Silanes at the other extreme react rapidly with water and are hence unlikely to be utilized by life.

Replacing water. Scientists suspect that liquid, like the water within cells, is an effective medium for life. Liquids can hold enough material in solution for the chemical reactions to proceed at significant rates. In contrast, gases can hold only volatile substances in solution, which makes it difficult to build up large complex molecules. Reaction rates are slow within solids because atoms cannot move around easily. I follow this lead by reiterating water's properties that make it an effective medium for life.

Water is a very abundant substance on the Earth and on other solar system objects. Its atoms, hydrogen and oxygen are very common in the universe. It is a liquid over a significant range of temperature, 0 to 100°C at room pressure. Life exists over this entire range. Organic molecules are somewhat soluble and ionic substances, such as sodium chloride, are quite soluble. Life exists in brines at least down to the freezing point of saturated NaCl solution, -21°C. It exists at high pressures on the ocean floor in hydrothermal seawater to at least 122°C.

Water shares properties with other polar fluids. Nonpolar substances are insoluble. This allows cell membranes to form. The density of the water is similar to that of large organic molecules. Gravity does not cause settling of material to the base of cells.

Ammonia NH_3 is a possible polar fluid in the cold regions of the outer solar system. It remains liquid down to –78°C. Ammonia is a starting point for making amino acids. With regard to complex molecules, an HN unit can share two electrons with a carbon atom, as does an oxygen atom in water-based life. An H_2N unit can share one electron with a carbon atom, functioning like OH units. Liquid ammonia clouds exist in the atmosphere of Jupiter.

Scientists often use absolute temperature (degrees Kelvin) rather than degrees Celsius for objects in the outer solar system, when liquid water is not being discussed. They also use it to represent high temperatures of stars. Conversion between Celsius and Kelvin is straightforward. The change of 1 degree Kelvin (abbreviated 1 K) is the same as a change of 1°C. O°C is 273.15 K. In the above paragraph rounding, -78°C is 195 K.

Liquid sulfuric acid clouds H_2SO_4 exist high in the atmosphere of Venus at room temperature. As noted in chapter 13, some terrestrial microbes inhabit highly acid water, but the insides of their cells are not acid. Complicated carbon chains analogous to those in terrestrial life can form abiotically in sulfuric acid.

Carbon dioxide liquid exists at seeps on the bottom of the terrestrial ocean. It dissolves many organic compounds. Industrial uses include dry cleaning and decaffeination of coffee. CO_2-based cells would need to have walls made of material that is insoluble in this liquid. This does not seem to be a serious limitation has numerous organic materials, including the wool and cotton in clothes, are in fact insoluble.

Methane forms a nonpolar liquid at low temperatures. It freezes 90.6 K. Methane rain falls and methane rivers flow on the Saturn moon Titan. Short chains of hydrocarbon atoms are soluble in methane. Methane has the attractive property that it, unlike water, does not react with complex organic compounds, causing them to decompose. For this reason, laboratory chemists routinely use hydrocarbons as organic reaction mediums.

Methane and hydrogen H_2 are gases and not good solvents at room pressure. However at higher pressures like at the bottom of the ocean, these gases are dense enough act somewhat like liquids and are candidate materials for filling cells. The vast quantities of methane that exist in natural gas fields are of biological origin from buried organic matter. Hydrogen and methane occur in abiotic seeps from serpentine. No hydrogen, methane, or CO_2 based cell has been found on the Earth, but there really has been no systematic search.

Executive summary: Science, life, ignorance, and bliss

It may seem strange, but much of science involves recognizing our ignorance. That is, a productive scientist needs to effectively pose questions. In astrobiology, a key question is how did aboitic molecules self organize into life. They wish to export terrestrial results to other cosmic objects. I defer more specifics until Chapter 9 on evolution.

The concept of catalysts frames the question. Pre-life started with complex organic molecules probably in water. The eventual product reproduced like the microbial life with which we are familiar. The intermediate stage involved autocatalysis. A collection or consortium of complex organic molecules existed. They did not reproduce faithful copies of themselves, but they did act as catalysts that aided the formation of similar molecules. Gradually some of the molecules in the "autocatalytic molecules" became more complex and adept at producing faithful copies of themselves, that is "molecular organisms." Seeking a criterion for when autocatalysis becomes life is like seeking one for the world's smallest giant.

It is productive to ask what the starting mix was for this process. It is productive to ask its source. We know that moderately complex organic molecules form in space; they fall to the Earth within meteorites; and they form in laboratory. Scientists have identified the mineral serpentine as a place on the Earth for organic molecules to form.

Scientists seek out likely sites for pre-biological chemistry. They can examine serpentine and other environments on the modern Earth. They carefully examine organic matter in meteorites. We will eventually be able to look for products of prebiotic chemistry elsewhere in the solar system. In the mean time, laboratory chemists study individual possible steps of prebiotic reactions in controlled conditions.

Chemists examine all these lines of enquiry with possible alternative forms of life. They seek ways to recognize such life if we found it. Scientists are beginning effort to seek nonstandard life on the Earth that may have escaped detection because of its small size and rarity.

> "Surely, God could have caused birds to fly with their bones made of solid gold, with their veins full of quicksilver, with their flesh heavier than lead, and with their wings exceedingly small. He did not, and that ought to show something. It is only in order to shield your ignorance that you put the Lord at every turn to the refuge of a miracle."
>
> Quote attributed to Galileo

Returning to the first part of this chapter, magically thinking does contain a grain of testable hypothesis. Do we see things like lead fish and lead birds that are so outlandish that it would be rational to take them as signs in the old theological sense of the word? No! If real magic worked, the makers of the *Harry Porter* movies would not have spent a fortune on special effects. Conversely, science would take notice if we could really make cats levitate by pointing a wand and saying *levitato felis* in broken Latin.

Going to the molecular level, we see components in terrestrial life like ribose that chemists expect to form abiotically on the early Earth. Terrestrial life contains common elements, like hydrogen, carbon, nitrogen, and phosphorus. Scientists expect similar conditions on other rocky planets.

Returning to the natural, I provide a prime example that a potentially true hypothesis, just like hiding ignorance with magic, can be a science stopper. We cannot exclude that some cosmic Johnny Appleseed introduced life on the Earth billions of years ago. We cannot even exclude that this life was genetically engineered. These hypotheses, called directed panspermia, replace productive inquiry into terrestrial and solar system conditions with unconstrained speculations on the social behavior and technology of unknown aliens. Invoking aliens pushes the origin of life back to unknown and unknowable conditions on their planet.

Overall, scientists bite off manageable problems by recognizing ignorance. Each answer poses new fruitful questions. A significant part of a scientist's training is to demarcate and act on ignorance. Embracing ignorance, rather than cloaking it goes against much of one's K-12 and undergraduate college training where ability to bluff on a test is richly rewarded. It goes against instruction to trust authority. Otherwise talented individuals fail in graduate school because they cannot make this switch.

Galileo began this trend toward manageable science by asking questions like "How does the velocity of a falling body change with time?" Scientists divide overly broad questions like how did life originate into smaller segments, like the stabilization of ribose by borate. Scientists eschew first-cause questions like what is the meaning of life. Pure speculation has no place: “If a bullfrog had wings would it fly?” “Would it land on unicorns?” Neither do matters of personal taste, like whether Gregorian chants are better than rap music.

Finally, modern science exposes ignorance with new concepts: Bruno saw that the Sun might be a star. It eliminates ignorance putting new equipment to use as with Galileo and the telescope. Both Galileo and van Leeuwenhoek found available technology wanting and improved it. Many scientific studies involve painstaking systematic observations. There is lots of ignorance to keep scientists productively employed.

Notes

I picked on Arachne as her cult that is unlikely to have any actual followers. Eudoxio means true believer. Eudoxio of Antioch died in 370 A.D. He was part of a Christian group called Arians who rejected the Trinity. The Church suppressed the Arian viewpoint, but the issue arose again during the Reformation and Bruno’s execution.

Pond water and hay fusions are excellent ways to get microbes and small animals for viewing. A small microscope will bring in the latter, which may appear like dots to the naked eye.

I condensed the biochemistry discussion from *The Limits of Organic Life in Planetary*

Systems, National Academies Press, 116 pp., 2007.

Salt is a familiar catalyst. It speeds up the rusting of cars where it is applied to the roads.

Serpentine is a group of minerals with an approximate simplified empirical chemical formula of $Mg_3Si_2O_5(OH)_4$. Ferrous iron replaces magnesium in the mineral so that the actual composition is a solid solution between $Mg_3Si_2O_5(OH)_4$-$Fe_3Si_2O_5(OH)_4$. The rock (formally serpentinite) often contains brucite, which is also a solid solution $Mg(OH)_2$-$Fe(OH)_2$. Calcium (CaO or $Ca(OH)_2$) does not enter these structures. Ferrous iron reacts with water to form hydrogen and magnetite $3FeO + H_2O \rightarrow H_2 + Fe_3O_4$. The rock thus contains magnetite. I refer to the rock as serpentine for simplicity.

Exercises

Designer life. If you are a science fiction buff, find an example of weird life. What is the life made of? How does its get energy? Do these seem at all plausible? If you are familiar with chemistry, a project is to put the sci-fi life into chemical context with reactions, information storage, and catalysts. There will probably not be the information to do this in most sci-fi, so you will have to use some imagination. You will see that design is not an easy way to get life even on paper.

Superstition and reason. Chapter 1 discussed how superstition can arise from overgeneralization and misinterpretation of valid observations. Think about superstitions that you have encountered (or find some on the Internet). Can you recognize the partial basis of fact in some of them? You can include religious tenets and taboos if you like.

Sampling biases — Man bites dog is more likely to make the newspaper than dog bites man. You may have heard that athletes and rock stars die young. While this may be partly true from their life styles, there is a reporting bias here. Most other 20 to 30 year olds are not important enough that their deaths attract national attention in the press. Come up with other examples of reporting bias that give a misconception on the real occurrence of events.

Pseudosciences. Clinging to tradition is a hallmark of a pseudoscience. If you are familiar with a pseudoscience, what are its traditions? How did they arise? Did they once have some basis of fact?

Postmodernism. Until well after 1950, some social scientists seriously thought that standardized tests for artistic taste and moral standards could be perfected to yield quantitative scores. Postmodernism arose has a reaction to such efforts to impose such quantitative rigor to topics that are inherently qualitatively. It also objected to the misuse of IQ tests in education. It includes the valid tenets that terminology and power structure can foreordain conclusions. It can become a pseudoscience when it imposes relativism on a physical or biological science where quantitative rigor is possible. If you are familiar with postmodernist literature, a workable exercise is to see when and when not resisting quantification is appropriate.