Chapter 9

Biological evolution: Real Correlations and False Coincidences

Religious worldviews held center stage in biology well after they had slinked backstage in other branches of science. Is the Earth created for the benefit of mankind? This is the premise of Judaism and most of the religions derived from it. (The view is not universal. Hindus view life as an opportunity to do good works amongst suffering. The Greek Gods toyed with mankind.) Divine Providence was a given in 1800 England despite the fact that the universe had grown beyond that of the time of Bruno. To this point, the worst fears of Galileo's inquisitors had proved unfounded. The evidence seemed irrefutable. Wasn't the Earth a very suitable place for humans? Aren't humans very well suited to live on the Earth?

Natural Theology to natural selection

By 1800, the resurgence of anatomy and biology showed that the human body is very complex. William Paley documented complex structures in animals and plants that fit them for their environments. All this could not be a coincidence. Paley's argument was that if we find a watch, there must be a watchmaker. A watch is just too complex to form on its own. Life is obviously very complex. Thus the Creator must exist. Buckland followed Paley's lead, supplying more careful observations including those of fossil organisms in the 1830's. All this changed by 1900 after careful attention to the meanings of "coincidence" and "chance" by nonmathematical men.

In his time, Paley's work had the positive effect of encouraging people to look at nature. Recently Creationists resurrected his ideas as "Intelligent Design." Debased forms of his Natural Theology appear in K-12 science books, like animals having assigned roles in the environment, such as predators being here to weed out sick prey.

The practice of finding the very moral lessons from nature that one wants is the dangerous downside of Natural Theology. This practice became the basis of Nazi racism. It persists today usually in more benign forms. *The Grasshopper and the Ants* is a nice children's story, but one that tells us little about real grasshoppers and ants. Such reasoning sometimes makes it into K-12 science books. The selective lesson from the spider is typically that hard work in making a web pays off, not that wives should kill and eat husbands.

Daily coincidences. Coincidences come up every day especially if we look for them. A lot happens every day and we have good communications. For example with a little afterthought by the news media, the collision of a tar truck with a feather truck would be widely reported.

Scientists need to winnow information out of the myriad of coincidences. They seek real correlations from cause and effect and correlated effects from a common cause. In daily life, you are most likely to have out the recipe that you are cooking, not one of the thousands of other ones in your cookbooks. The fraction of women over six feet in *Tall*

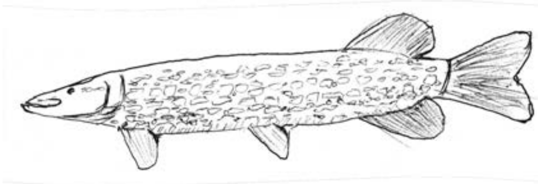
Girl or on a basketball team is likely to be higher than in a grocery store. Few commercial fishermen toil at their trade in the middle of a desert.

Other coincidences come after the fact. Any person can say they are 1 in 7 billion. The chance of getting any bridge hand from a fairly shuffled desk is the same as getting all 13 spades. One can easily create astronomically small probabilities in this way. Take for example the census list of a tiny village in China. There are 10 names listed in order. The chance of any one name occurring from the 1 billion population of China is 1 out of 1 billion (1 with nine zeros). The chance of the whole list in order is 1 in 10^{90} (1 with 90 zeros). However, we can say this about any ordered list of 10 people from China.

Some coincidences, like flies having wings, come after the fact from the human endeavor of giving names. (Otherwise they would be called "walks.") Lou Gehrig died of the disease named after him. Bookworms eat books. Fruit bats eat fruit. Flycatchers catch flies. *Ad nauseam*.

Yet the type of coincidence orchestrated by Paley remains. Houseflies are obviously well suited to find their food sources like open garbage cans and dog manure.

Spontaneous generation and begetting. The worldview that complex life generates spontaneously made discussion of the origin of life irrelevant in the Renaissance. Spontaneous generation was to be sure unusual. Like begets like. No farmer, even in the Dark Ages, waited for chickens, sheep, cows, pigs, and goats to spontaneously generate in his farmyard. Christians regarded their purported virgin birth as a divine miracle, not a mundane event. Yet Izaak Walton (1593-1683) discussed spontaneous generation with only a whiff of skepticism.

"'Tis not to be doubted, but that they are bred, some by generation, and some not: as namely, of a Weed called Pickerel-weed, unless learned Gesner be much mistaken; for he sayes, this weed and other glutinous matter, with the help of the Suns heat in some particular Moneths, and some Ponds apted for it by nature, do become Pikes."

The Compleat Angler Or the Contemplative Man's Recreation by Izaak Walton

When Walton published in 1653, biology was just becoming a new science. Both the people and the learned believed that complex organisms generated spontaneously from lifeless matter. Walton acknowledged that some pike beget pike in the ordinary manner, by generations of spawning. Yet some formed spontaneously from weeds. Geese formed from barnacles, mice from sacks of grain, and maggots from rotting meat. These ideas were not totally absurd. Strange transformations do occur, like butterflies from caterpillars.

In 1668, an Italian anatomist wanted to check for himself. He was familiar with the work of the Englishman William Harvey that mammals grow from small fetuses and presumably from even tinier "seeds." Francesco Redi (1626-1679) did a simple

experiment in the hot Italian sun. He left some meat to rot in open jars and some in jars covered with gauze. The powerful stench soon attracted swarms of flies that covered the open meat. Frustrated flies could not get through the gauze. Soon maggots swarmed over the exposed meat. Further work confirmed that maggots hatch from tiny fly eggs and grow up to become more flies. (You have already done part of this experiment when you put a lid on your garbage can.) It was less clear whether decay microbes come in and reproduce or spontaneously generate. As I noted in Chapter 4, spontaneous generation of microbes festered until 1859 when Louis Pasteur did careful experiments analogous to Redi's experiments.

However, the idea of cleansing with heat predates the knowledge of microbes, rot, and disease. The Roman physician Galen treated his surgical instruments in fire. Jews cleansed pots by boiling them over hot coals. Pasteur deserves credit for cauterizing spontaneous generation. Unfortunately his later dogmatism (to self-promote pasteurization) delayed the discovery of spores that can briefly survive boiling and "thermophile" (heat-loving) organisms. By convention the term *thermophile* is anything that grows above 60°C and *hyperthermophile* is anything that grows above 80°C, the usual temperature of pasteurization. The distinction is a vestige of dogmatism that nothing could live above pasteurization at 80°C. It is not useful in most astrobiology discussions. I use thermophile to include anything living above 60°C.

Seeking the plan of nature. Explorers continued to discover (for Europeans) the great diversity of plant and animal life in the 1700s. It was evident that "apting" a pond for pike outside their normal range involved stocking them, just like King Charles II

(1630-1685) had to stock his parks with Canada geese. Biologists designated the origin of higher organisms as species to the Creator. They set out to deduce his plan. Carl Linnaeus (1707-1778) classified animals, plants, and fungi into a natural order. He was a good enough observer to start the basis of modern taxonomy (the science of classifying organisms). At first, he considered species to be God-given forms dating from Creation. Later, he recognized hybrids and that introduced species may change with acclimation. He willingly accepted some change over time, but not wholesale evolution. The geologist Hutton shared this view.

The Linnaean classification works for macroscopic organisms. At one end, plants, animals, and (later) fungi are natural kingdoms. At the other, species are a natural, but fuzzy concept. Intermediate taxa group various species. Many, like birds and fish, date from antiquity. All Linnaeus did was to assign their Greek or Latin names. (Politically dead languages do not invoke the wrath of nationalism. Dead languages also provide stable meanings.) Parts of the classification required careful study. For example, vertebrates have backbones and share numerous other characteristics. Dicots have two seed leaves (like peas) and a common flower structure. Humans fit well into the classification. (Omitting several intermediate groups) Our species, *Homo sapiens* (man wise), is part of the great apes. The apes in turn are part of the primates, which includes monkeys and lemurs. The primates are mammals. Mammals are vertebrates and the vertebrates are chordates (vertebrates and animals including sea squirts with a notochord, which is analogous to a backbone).

Fossils fit well into the classification, especially the more recent Cenozoic ones. Many recent fossils tend to resemble living organisms. It is obvious that a mammoth is a type of extinct elephant. There are numerous extinct groupings, some ancient, like trilobites. There are, however, intermediates between modern taxa, like mammal-like reptiles.

Darwin: insight and hesitation. I have already mentioned Darwin and natural selection with regard to the geological time scale. The story of the voyage of the *Beagle* is quite well known and I will be brief. When the ship left port, Darwin had trained to be a naturalist. He had also trained for the day job of a country parson. By the time the ship reached the Galapagos Islands, he had recovered numerous fossil specimens from Patagonia and visited tropical, steppe, subarctic, and mountain climates. He was well aware of the great diversity of life on the South American mainland and the wide ranges of many mainland organisms.

On the Galapagos, Darwin collected biological samples. At first, he just labeled specimens "Galapagos", as he did not expect to find differences between nearby islands. A local then pointed out the differences between similar species on adjacent islands. Darwin quickly found numerous other examples of *endemic* (local) species on the island group. In fact most of the land birds are endemic to one or more of the islands.

The finches play a large part in the legend and a part in Darwin's thinking after he got back to England. They resemble the native finches of the South American mainland. Darwin did not realize they were all finches while he is on the island. They differ from the finches he was familiar with and have somewhat different habits. Strikingly, one functions as a woodpecker eating insects from the tree bark. There are no native woodpeckers on the island.

Darwin's thoughts turned to evolution and he started a notebook soon after the ship reached England. The finch example is straightforward enough (though complex when examined closely) to get to a result. A wayward flock of finches ended up on an island in the Galapagos and some did not fly back. Initially they found things to their liking. There were plenty of insects and seeds to eat and few other land birds eating them. The finches multiplied and settled various islands and various environments. There was some inheritable variation within the finches. The "fitter" finches survived to multiply. However, different variations proved beneficial in different environments and finches specialized for one environment did better than generalists. Eventually the isolated populations became separate distinct species. In general, biologists call this adaptive radiation.

The woodpecker finch evolved because no real woodpeckers existed to compete with it. (On the mainland, a finch that tried to act like a woodpecker would find very slim pickings.) There were plenty of insects on or just under the bark. As the finch acquired the habit and eventually the instinct to act like a woodpecker, traits that made it more suited for the task became selected.

The finch argument is not far beyond what Hutton, or even Linnaeus, would have accepted. Limited natural selection was a common heresy dating from Aristotle that Paley attempted to refute. Darwin continued much further to having all life evolve from one or at most a few common ancestors. He was not comfortable with this concept and realized that it needed to be fully documented. After reading a book by Thomas Malthus (1766-1834) on the impending human population explosion, Darwin, like Paley, realized that all organisms produce far more offspring than can survive. They need not breed like rabbits to do this. Slowly reproducing species, like humans and elephants, would overrun the Earth before 1,000 years was up if all offspring survived. The death of some of Darwin's own children drove in the point that survival is not guaranteed.

Darwin continued to amass data and think. He discussed the issues with his friend Charles Lyell (1797-1875), by then the most noted geologist in the world, and with the botanist Joseph Dalton Hooker (1817-1911). Both were initially skeptical but supportive. Later they urged Darwin to publish on evolution. However, Darwin did ordinary science, like explaining corral reefs and studying barnacles and orchids, to get a better hold on the larger issue. He avidly associated with plant and animal breeders.

Publication. All this changed in 1858 when a museum collector caught malaria in what is now Indonesia. Alfred Wallace was already a proponent of limited evolution. In the delirium of his fever, he grasped the real power of evolution by natural selection. He communicated his result as a paper to Darwin. Darwin was unwilling to betray Wallace, but did not wish to be scooped. He communicated his predicament to Hooker and Lyell. They arranged for Wallace and Darwin to publish companion papers. Darwin published *The Origin of Species* in November 1859. Any educated person should read some edition of this book.

I summarize some of Darwin's arguments with simplification and modern hindsight:

(1) Organisms share common characteristics because they descend from common ancestors. Species groups with recent common ancestors, like the Galapagos finches, share many obvious traits. The similarities between distantly related species, like

sharks and insects, are subtle. The Linnaean classification is really an attempt at constructing a family tree. Modern taxonomists group organisms in this way. The fossil record provides valuable information on descent with modification. The geographic distribution of organisms also makes sense in this regard. There is an inherent tension between keeping the classification stable for communication purposes and having it reflect descent as more is learned. The fact of evolution from common ancestry as opposed to its mechanism raised the least controversy at the time.

(2) The primary mechanism of evolution is natural selection. There are far more individuals in any generation than can survive. All organisms thus face a struggle for existence. There are heritable variations in natural populations. The individuals with variations that make them more suited for their mode of life have a greater tendency to survive and breed. The "fit" variations built up in the populations through time. Darwin used artificial selection of domestic plants and animals to show both that variations really exist and that they can be selected for. Darwin had little idea how heredity actually works. He did recognize linked genetic variations and heritable instincts.

Figure 2: Maize (corn for most Americans) illustrates the great changes that occur after domestication. The organism is even unable to reproduce unless the farmer plants its seeds. Photo by the author.

(3) Rudimentary organs, like the wings of flightless insects, played a large part in Darwin's arguments as the result of descent. Such structures were once useful to an ancestor of the organism but later proved useless or harmful. Darwin was familiar enough with shipwrecks to know the disadvantage of being able to swim halfway to shore. It is best to be a very strong swimmer or to stay with the boat. Similarly weak-of-flight insects on windswept islands risk being blown out to sea if they take off. Selection reduces both the instinct and the ability to take off. Once rendered useless and harmless by natural selection, rudimentary wings are highly variable. Natural selection cannot act to check or enhance variations that do not affect the fate of the organism.

(4) Chance plays some part. For example, the Galapagos finch ancestor may have been blown off course. Darwin emphasized the chance nature of colonization of isolated islands. On a larger scale, selection is statistical. A single organism with

"good adult" genes may never make it beyond being a larva. However, a large number of individuals with the good gene will have a larger tendency to survive.

Figure 2: Western poison oak (Rhus diversiloba) illustrates the fuzzy concept of "species." This species occurs along the Pacific Coast. The closely related species poison ivy (Rhus radicans) occurs widely in eastern North American. The ranges were disjoint during the Ice Age. However, they now overlap near Missoula, Montana, where they form a stable hybrid complex. This implies there is still a slight amount of gene flow between the two species. Photo by the author.

(5) Species are fuzzy entities from the ongoing process of evolution. It is a matter of semantics when the variation and breeding isolation of two populations are enough to elevate them to species. Organisms often continuously vary over their ranges so the individuals at each end appear different enough to regard as species. The process of continual species formation is particularly evident in the tropics where both Darwin and Wallace worked. It is less evident in recently glaciated areas, like England, which were colonized by a limited number of wide-ranging species after the ice melted.

(6) Geological time is vast. The slight amount of variation in each generation can

built up over time to vast differences like between birds and lice. The geological record is incomplete. Paleontologists have found lots of fossils since Darwin including those of early man. Each missing link closes one larger gap and creates two smaller ones. Still there seemed to be sudden changes in the fossil record that Darwin had trouble attributing to an incomplete record. I will return to the issue of mass extinctions in the Chapter 11.

(7) Ecology is quite complex and was not well understood in 1859. Darwin used the example that mice raid bumblebee nests and cats eat mice. Thus the abundance of cats influences the abundance of flowers pollinated by bumblebees. Overall, he made the argument from ignorance of the natural that it was premature to invoke the supernatural. He opened the entire field of ecology to study.

Backlash and debate on evolution. The strong reaction that Darwin expected occurred when his book hit the streets. It did not take long for every ideology to find the moral message that it wanted to promote or wanted to fear. Conservatives justified the plight of the poor as beneficial selection. Socialists pointed out that the poor merely lacked opportunity.

Darwin stayed out of the religious discussions. He had been brought up to believe that it was rude for a gentleman to denigrate another's religious beliefs. Tactically, it is not good to insult people you are trying to convince. What one believes on Sunday need not affect what science one does on Monday.

The implication of natural selection to Paley's watchmaker argument was obvious. There is simple cause and effect. Organisms are suited for their environments because they have evolved to be fit. Natural selection can refine an organism over generations just like breeders improve horses for speed. The lack of a role for the Creator chafed the religious minded, as had it initially troubled Darwin. Moralists feared that if men are animals they would behave like animals.

Some scientists attacked natural selection on mostly scientific grounds, including Richard Owen (1804-1892) and (after 1870) St. George Jackson Mivart (1827-1900). I discussed the length of geological time in Chapter 5. Mivart, like Paley, focused on organs of great perfection, like the eye. Surely it needed the Creator. To boot, half an eye could never form by natural selection because it would be worthless.

Darwin replied politely to Mivart in later editions of his book. First, the human eye is not perfect. Otherwise there would be no opticians. The half-an-eye argument owed to Mivart's lack of imagination, analogous to porcupines being unable to mate. Darwin was a geologist. He had already compared oceanic islands in various stages of their evolution from volcanoes to atolls. He did this with the eyes of various organisms. At one end, night crawlers have a weak sensitivity to light. If you want to catch one (jack one if you are in Maine), you need to keep it in the dim edge of your flashlight beam. Other organisms have eyespots connected to their brains by optic nerves that function to tell light from dark. At the other end, cephalopods (for example, squid and octopus) and vertebrates have complex well-developed eyes. A continuous sequence exists between the worm's feeble vision and a hawk's with each step serviceable to the organism. At each step, natural selection may drive further sophistication. To boot, the cephalopod and vertebrate eyes are different. They evolved independently. This is what the argument was until a few years ago. We now know from molecular genetics that the squid eye, our eye, and the compound eye of flies all evolved from a very simple eye of a common ancestor.

Scientists and historians sometimes criticize Darwin for telling a just-so story about how some organs evolved. This is off base. Mivart contended that no evolutionary path by natural selection is possible. Darwin needed to only point out one feasible path. Clearly, the task of finding the actual evolutionary path is more difficult.

Mivart's perfection argument is the staple of the Intelligent Design movement. The argument now comes from a self-imposed selective lack of imagination. These professional Creationists have mostly shifted away from macroscopic organs where the refutation involves familiar organisms to biochemistry where the function for many substances is still unknown. Chemical names make the Creationist sound erudite to the congregation. These Creationists have never produced a single positive result. They have not even produced a criterion for recognizing the product of genetic engineering.

Ironically, the opposite argument (also from Mivart) gets made that natural selection cannot occur because the change over each generation is minute. I heard it from professional paleontologists in my youth, but it does not seem to come up much from Creationists. Consider the giraffe, which is popular in K-12 books, but too big and rare to leave a nice fossil record. In fact, there is no useful fossil record, so we have only a thought experiment. The height of giraffes may have increased a meter over (for simplicity) a million generations. The microscopic change (being one-millionth of a meter taller than the other giraffes) over each generation could not affect evolution.

This argument ignores the observation that evolution occurs erratically on a short time scale. This maintains a wide range of variability. For example take Darwin's finches. A modern visitor would note little change from Darwin's specimens. However, resident scientists on the island witness rapid change. Drought-tolerant forms dominate during the dry years. Wet forms dominate during wet years. Overall, the rapid change adds up to very little net change on a historical time scale.

Back to giraffes, the variability in height at any time was far greater than a millionth of a meter as it is today. Countervailing selective pressures may serve to maintain variability. A tall neck allows grazing high up trees. (We do not know enough about giraffes in the wild to state that reaching high leaves is the main use driving natural selection, so on with the thought experiment.) It is particularly useful during times of dearth to be able to get just above the other giraffes. The tallest giraffes would then dominate. The added height, however, might be useless or even harmful during subsequent times of bounty.

In addition, the neck of a giraffe is a highly complex structure. One cannot scale up organisms like giant grasshoppers in a 1950s movie. (Galileo began the science allometry of how different parts of an organism scale with its size.) Rather, many different features, like those to get blood to the head, needed to evolve to let the giraffe be taller. There was selection both for efficient giraffes and tall necks. Frustratingly for Darwin and his supporters, Mivart presented these arguments but still rejected natural selection as the main cause of giraffe evolution.

Evolutionary contrivances. Paley's design arguments contain a thread of testable hypothesis. He correctly contended that many organisms are very suited for their environments. Complex structures, like the eye, do look like the products of design. Darwin saw that it is easier to demonstrate evolution where it has yielded a kludgy but functional organism, something that no designer working from scratch would ever produce.

Inelegant adaptations occur because natural selection acts one generation at a time on the variation actually present. It cannot produce a line of unfit organisms over many generations with an ultimate goal in mind. To give a contra-possibility outside of the supernatural realm, a selective breeder could produce many unfit generations with an ultimate goal in mind, like a winged horse or a centaur. A genetic engineer could conceivably do that from scratch, but not during her lunch hour.

Natural selection also acts through the conditions that organisms actually experience. It does not anticipate changes. For example, armor-plated deer did not evolve to be ready for the invention of firearms. The land biota of isolated islands are a striking example. These animals often evolved in the absence of serious threats from land predators. Their traits often proved wanting in the changed environment. Introduced cats, rats, and mongooses made quick work of the native organisms on many islands by Darwin's time. Island animals appeared ridiculous and contrived to Europeans familiar with their biota that had evolved along with fearsome predators like wolves. The extinct dodo is synonymous with stupidity. It takes great faith to contend that it was the specially designed work of a benevolent Creator for the island of Mauritius.

Darwin studied orchids. Their complex flowers trap insects that go on to pollinate other flowers. The trapping and pollinating mechanisms have evolved from other parts of the flower. They work, but do not resemble anything designed from scratch.

Darwin used rudimentary organs as examples that have no place in design from scratch. The webbed feet of upland geese that rarely if ever alight on water betray their aquatic ancestors. The teeth in embryo birds expose their reptilian ancestry. The gills in the human embryo unmask our fish ancestors.


For readers of the sports page, the human knee is notoriously prone to injury. Our bipedal stance is geologically recent (a few million years). Natural selection from a quadrapedal knee has occurred over that time from individuals breeding success being lowered by a knee injury or a slow gait from an inefficient knee. At the present, it has produced a serviceable but troublesome organ. Minor "design" problems exist even in the human eye — Mivart's favorite. Its lens hardens and most adults need reading glasses by age 50. The optic nerve comes into the retina in a manner to form the blind spot. The squid eye does not have this "flaw."

If you want to learn more about contrivances read *The Panda's Thumb* by Stephen Jay Gould (1941-2002). The thumb is really a modified wrist bone that aids it in eating its vegetarian diet of bamboo. The panda is taxonomically a carnivore, a group also including cats and dogs. Its ancestors ate meat and its body structure reveals that fact. It is closely related to bears and raccoons, carnivores that that often stray from their taxonomically assigned diet.

Microbes and genes

Darwin saw teeming life everywhere he went. However, he focused his studies and discussions on macroscopic organisms. This was an excellent tactic for the evolution debate. Both scientists and the public relate to what they can actually see. Logistics were a more telling constraint. One can learn that microbes exist in an optical microscope, but not a lot more. The science of biochemistry exposed the great diversity and extent of life on the Earth in the twentieth century.

Life at elevated temperatures. Medieval warlords used fire as a weapon. The ability to survive fire required magic. Salamanders had this alleged talent. A salamander in a fire is appears on numerous coats of arms including that of Sarlat, France. Salamanders in fire play minor roles in the *Harry Porter* series.

This superstition has some basis of fact. Salamanders hibernate sometimes in fallen logs. They get out quickly when the fire starts to get hot. That is when you see them. Most people do not go looking for salamanders in the woods. The fact that many salamanders (that is, newts) are toxic if eaten may have added to their mystique.

OK, salamanders do not live in fire, but what are the limits to life? Temperature is clearly one. I have already noted that the use of heat for sterilization predates knowledge that high temperatures kill microbes. Pasteur was correct that it is an effective method to kill pathogens and organisms that foul wine and milk.

We can see why pasteurization works with human pathogens. The pathogenic organisms need to survive temperatures in a person with a fever up to 40°C and they often spread through filth at "room" temperatures. Such organisms rarely experienced (in pre-sanitation times) high temperatures and when they did the temperatures were quite high, like boiling pots and fires. There was no advantage for a microbe in being able to withstand a slightly higher temperature than its relatives.

Conversely, real thermophile organisms, like those in hot springs, are highly adapted to that mode of life. They rarely get swallowed by animals or end up in wine vats. If they do somehow end up there, they find that these environments are quite different than hot springs and already teeming with well-adapted microbes. It is unlikely that any survive to evolve into pathogens.

Dogmatism following Pasteur delayed the discovery of thermophile organisms, or relegated them to curiosities. Petroleum geologists knew as early as the 1920s that bacteria inhabit oilfields. Over time the bacteria degrade oil in the ground, at temperatures to at least 80°C. For example, they cause oil to react with sulfate, which produces sulfide and CO_2. The degraded oil contains a smaller fraction of the compounds that are easier to use in making gasoline. The problem becomes more serious when petroleum engineers pump surface water into the oil-bearing rock to drive out the oil. This introduces sulfate (if seawater is used) and dissolved oxygen. Numerous microbes eat the oil, making it react with sulfate and dissolved oxygen. Some corrode the drill pipe. A cottage industry exists to eradicate oilfield microbes before they can do much harm.

Microbes exist on land in boiling hot springs. Such organisms are valuable to the biotech industry. For example, the enzyme used in criminal DNA analysis came from microbes in a Yellowstone hot spring. One can produce enzymes in industrial quantities that withstand boiling. One can heat the culture to get rid of unwanted microbes.

Interest in thermophile organisms took off with the discovery of marine hydrothermal vents. There were initial claims of living organisms at 350°C. None held up, but it is clear that life thrives up to 122°C, the current record. (The high pressures at the bottom of the ocean keeps water from boiling at this temperature, like in a pressure cooker.) Here we have a real limit to terrestrial life. Temperatures increase gradually with depth away from the vents and rapidly with position within the vents. An organism that could withstand a slightly higher temperature than its relatives would get first crack at the life-giving vent water. Yet this has not happened even though vents have existed since the Earth formed.

Other "extreme" environments. Cold is no barrier to microbial life as long as liquid water is sometimes present (Figure 3). When my oceanographic voyage docked in Mexico, both the scientists and crew warned me of the dangers of tourist disease from ice cubes tainted with pathogens. In fact, we preserve living microbes by freezing them.

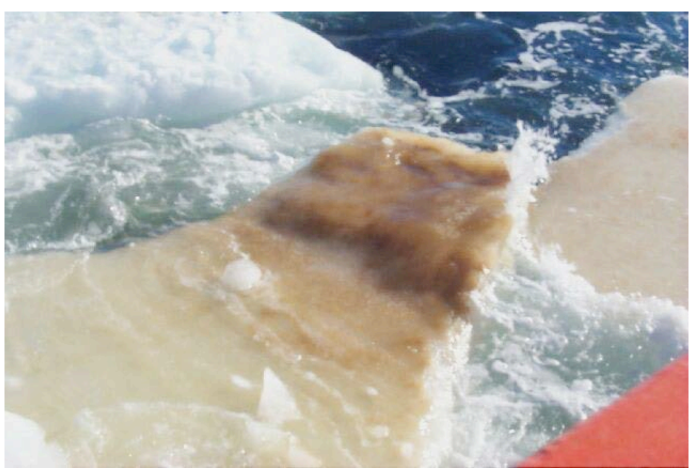


Figure 3: Overturned ice block exposes an interesting Antarctic microenvironment. Photosynthetic microbes, mainly diatoms, live at the base of the sea ice. Enough light gets through for them to do photosynthesis. The block is about a meter across. Photo by Kevin Arrigo.

Microbes inhabit very acidic water from mine drainages, alkaline springs, saturated salt brines, and the driest deserts. As noted in Chapter 4, there are more microbes in a handful of good soil than people on the Earth. On the other hand, there are more microbes in a 100-m square than the human population of Earth at the current level of detection. The only generalization is that microbes that we know about require liquid water that is not too hot. Pressure is no serious problem. The deepest ocean teems with animal and microbial life. However, the pressure at the bottom of the ocean can be lethal to organisms that evolved at the surface and vice versa.

There are some potential environments on the Saturn moon Titan for which we do not have viable organisms. They include liquid methane-ethane at the surface at ~90 K and a liquid water-ammonia solution in the shallow subsurface at temperatures down to 235 K and even 153 K if methanol is present. Like with armored deer, there has been no selective pressure for terrestrial organisms to evolve the ability to inhabit environments that have never existed on the Earth.

Garden peas. Darwin considered heredity to be a blending of characteristics. This is certainly a valid overall description of the offspring of animals and plants. Look at yourself and your parents and siblings. He was aware that hidden traits could emerge after several generations. He also believed use and disuse affected heredity.

In the 1860s, an Austrian monk experimented on common garden peas. Gregor Mandel (1822-1884), like Galileo, did simple experiments, observing evident traits. Seeds may be yellow or green. Flowers may be purple or white. Inbred plants breed true for many generations; for example, white-flowered plants beget white flowered plants.

Like many breeders of his day, he crossed his plants. A cross between green-pea plants and yellow-pea plants, for example, yielded only yellow-pea plants. There were no yellow-green peas or green peas. When he interbred these hybrids, 1/4 of the plants produced green peas and 3/4 produced yellow peas. Again there were no intermediate plants. He had discovered that heredity is quantized in what we now call genes.

The explanation is mathematically simple. Each pea plant gets a gene for seed color from each of its parent. The purebred parents have the genes YY for yellow peas and yy for green peas. The upper case Y indicates that it dominates over the lower case "recessive" y. The first generation hybrids all have a gene from each parent (Yy) and are yellow. The second cross gets a gene at random from each parent. Putting the mother gene first, the possibilities are Yy, YY, yY, and yy. Only the yy plant yields green peas. It statistically occurs 1/4 of the time. Mandel did this with numerous traits. Each trait behaved independently. Modern science shows that genes join together on chromosomes. Traits governed by genes that are close together on the same chromosome are linked. The traits studied by Mandel are either on different chromosomes or so far apart on one chromosome that little linkage occurs.

Many biology books state Mandel's published results are too close to the expected theoretical ratios to be true. Mendel reported enough information that recent statistical analyses indicate that outright fraud or self-deception by Mendel or his assistants is unlikely. At the start of his work, he did not have the expected ratios, but clearly became aware of them later on. The statisticians, however, did not find the expected effect of bias: Mendel's later results are no closer to the expected ratio than his early results. In any case, any deviations of Mendel from optimal scientific practice are irrelevant to the scientific issue of the existence of genes. Anyone one can repeat his experiments; countless have done so.

Still it is worthwhile to examine sources of bias that crop up with experimental data. First, peas do behave as Mendel reported, so we can exclude complete fabrication. More subtle issues arise once an experimenter knows the expected result. Mendel was trained in mathematics and simple statistics. He did not, however, have access to modern probability theory on typical deviations of real trials from the expected ratio (1:3 in my example). For example, he repeated one trial that came out too far from the expected ratio for his taste. Recent analysis indicates that the deviation from the ideal ratio in his first trial was well within the expected range. Neither did he have a good idea of how many plants he needed to count to get a representative sample. Conceivably he could have stopped counting once the ratio approached the expected one. (He seems to have counted the whole samples.) He might even have failed to report trials on other traits that did not work out to the expected numbers. (He did report the trial that he repeated so this is unlikely.) There was some tendency to unconsciously bias results with traits that could not be determined with 100% accuracy. We then would find that hard to measure traits are closer to the expected ratio. No one has analyzed his work for this bias.

Mandel published in German, a language that Darwin did not read. Darwin never opened Mandel's reprint. Legend has it that biologists dismissed his work as extremely complex mathematics or as something that conflicted with Darwin. This is partly true. Yet three independent groups rediscovered Mandel's results in 1900 and submitted their papers to scientific journals. As customary, the journal editors sent the drafts to qualified scientists for technical review. The reviewers pointed out Mandel's paper. It had never been fully forgotten.

Genetic diseases. The genes for recessive genetic diseases, like sickle cell anemia and cystic fibrosis, provide a tragic example of an evolutionary contrivance, which is impossible to attribute to design. I have never heard of a preacher going to a cystic fibrosis ward to tell the victims that the divine Creator designed the disease for their benefit.

The cystic fibrosis gene n is recessive. (More precisely two independent mutations are involved in the disease.) The carrier with one normal gene N and one cystic fibrosis gene n appears normal. Actually having the mixed genes Nn provides some protection against dysentery, a major scourge in medieval squalor. If the n gene is rare in the population, Nn individuals mate only with NN individuals and produce (statistically) equal numbers of Nn and NN children. More of the Nn children, however, survive dysentery causing the n gene to become more frequent. Eventually some Nn individuals mate producing (statistically) 1 NN, 2 Nn, and 1 nn children. The nn child dies from cystic fibrosis (or with modern medicine at least does not breed). The frequency of the n gene in the population reaches equilibrium where the benefit of producing carrier children is negated by the deaths from cystic fibrosis. It does no good for individuals to recognize carriers at equilibrium since NN and Nn individuals have an equal chance, with all mating possibilities, of continuing their bloodlines.

At the present, dysentery is not a major problem in countries with good sanitation. The cystic fibrosis gene is thus essentially useless to carriers as well as lethal to those with the disease. A new equilibrium will eventually occur with the gene essentially absent. Its frequency would be determined by the very slow rate that it is produced from the normal gene as a mutation. There have not been enough generations of people dying from cystic fibrosis for this to happen. Actually, any mutation that makes the normal gene ineffective leads to cystic fibrosis. It is easier for a mutation to break a gene than to fix it. Just like it is easier to sabotage than fix machinery.

Genetic science. The existence of genes poses complications to natural selection. Some of these involve figuring out how evolution works. Biologists distinguish between *genotype* (list of genes) of an organism and its *phenotype* (actual structure). For example, a starved individual with “good” genes may be sickly. Natural selection, as I have already noted, is statistical. A gene or gene combination has an expected chance of survival, which changes with time as conditions change.

Mathematical genetics is a major field of current research. Geneticists distinguish between the behavior of genes in small and large populations. Vast number of copies of each gene exists in a large population so statistic methods that concentrate on the most likely outcome apply. Only a few or even one copy of a gene may exist in a small population. “Good” genes may be eliminated by bad luck and moderately “detrimental” genes may build up. Sometimes, the combination of several accumulated detrimental genes proves advantageous. The small population then may expand its range and displace the surrounding members of its species. The net effect is that the small population passes through somewhat unfit generations to a more fit state. It does this by chance and natural selection with no goal in mind.

Casino gambling provides an analogy. The odds in games like roulette favor the house. The outcome for the house is positive as it depends on a large population of players. An individual player may beat the odds, like a small population, during an evening. Casinos games have evolved odds so that a minority of players typically win over the typical lengths of sessions. These winners are more likely to brag than the losers, providing an example of sampling bias. This draws people back to the tables.

(photo Gail Mahood) Both mutations that produce modified genes and sexual reproduction that redistributes genes are important. To get an idea of the power of sex on the genetic variation already in a natural population, you need merely watch a dog show. The vast array of dog breeds comes mostly from genes already present in their wolf ancestors. Show dog breeders do not practice genetic engineering. It would kill the sport value. They do use molecular genetics to confirm pedigrees.

Molecular genetic code breaking. After World War II, scientists returned to their peacetime day jobs. The war had brought both carnage and improved technology to Britain. Its end brought a sense of intense competition to some of the scientists. The story of James Watson and Francis Crick's discovery of the structure of DNA is well known. In fact, DNA is one of the most commonly recognized abbreviations. Watson and Crick received the Nobel Prize for their work in 1962 with Maurice Wilkins. By then, Rosalind Franklin who had done much of the X-ray work and got little of the credit was dead.

I have already discussed DNA as a chemical in Chapter 4. To cut to the chase, DNA is a complicated chain of similar molecules. It has two spiral chains linked by "base pairs." (The Double Helix.) The base pairs are the basis of the genetic code. There are four bases, adenine (A), thymine (T), guanine (G), and cytosine (C). C always pairs with G and A with T. To duplicate; the double helix unzips leaving the bases unpaired. The side of the single helix (with say CGAT) forms its matching helix with GCTA. The complementary side of the helix with GCTA grabs CGAT. The result is two double helixes that are copies of the original. This nicely explains like begetting like.

When my son Jacob was four, he took a phone message on the pad as he had seen us do many times. He did not yet know how to read and write. Neither he nor we could decipher his scribbling. The cell needs to read the information coded in the DNA for it to be any use. The mechanism is highly complicated. I give an overview.

The DNA functions as a genetic code to make proteins from chains of amino acids. Groups of 3 bases act as "letters" to code from 1 of 20 amino acids or a stop (analogous to a period in English) to end the chain. There are 4 times 4 times 4 or 64 possible letters. So more than one letter codes for the same amino acid. For example TCT, TCC, TCA, TCG, AGT, AGC all code for serine. Ribosomes composed of Ribonucleic acid (RNA) and proteins do the reading.

The code is almost but not completely universal. To see why evolution locks the code, consider the human genome. It has around 3 billion base pairs and 35,000 functional genes (that is, genes that make protein). A change in a gene that codes for the reader in the ribosome would cause all these genes to generate different chains of proteins than they did before. This gross change would be lethal to the cell. Yet minor differences from the standard code exist, showing that it can and did evolve. For example, humans have a nonstandard (21st) amino acid containing selenium. It occurs in 25 proteins.

It is useful to consider English as an analogy. It, like DNA, is a code intended to be read, even though first graders have some trouble. We could transmit English with the genetic code. We would instead have 26 caseless letters (like on an old telegraph or teletype) and a space and a stop. We would have several combinations code for vowels (in analogy to serine) and only one code for z.

> this would be easily readable. we could even drop the z and replace it with x. we would not park in the no parking xone when we visit the xoo. W cld vn mt vwls lk n hbr.

The point is that there is much redundancy in English writing. There is also considerable redundancy in the genome. Most changes are not lethal. The simplest mutation changes a single base pair. Often this does nothing, like replacing AGT and AGC. There are large parts of the genome that do not code for proteins. There are other parts of the genome that code for rudimentary or unimportant structures.

Another class of mutations involves omitting part of the genome. One or more complex genes may be lost. Typically, this does not benefit the organism. Yet changes of this type occur, particularly in microbes like pathogens that live within the cells of other organisms. The loss of a gene for an important function need not be lethal as the host may also do that task. Like organisms on oceanic islands, pathogens have many chance colonization events. For example, a strep throat microbe with a missing gene may start an epidemic. Once a complex gene is lost, it cannot be regenerated by evolution. A newly evolved gene that performs a similar function will be different, just like the mostly independently evolved squid and human eyes differ.

Reproduction sometimes leaves two independent copies of a gene where one existed before. Initially the genes do the same thing, but they can evolve to handle specialized purposes to the benefit of the organism. In analogy, numerous word pairs like "chef" and chief" exist in English. Gene families originate in this way. Biologists construct family trees of genes within a single organism.

I could not believe that immortal creatures were so careless with their lives

A World Without Time, Larry Niven

Immortality of genes. There are two meanings of immortal. One is like the Greek Gods that can never die. The other is like the elves in the *Lord of the Rings* or the children in *A World Without Time*. They can potentially live forever, but can be killed. Microbes that reproduce by dividing and genes are immortal in the second sense. So are plants and animals that reproduce by budding. We die because genes that precluded vegetative reproduction and mandated sexual reproduction proved advantageous to our distant ancestors, about 550 million years ago.

Figure 4: Ivy, like many house and garden plants, can reproduce both by seeds and budding. Sexual reproduction maintains a genetically variable population. This diversity itself is advantageous when conditions change, as some portion of the population is more likely to be fit for their new circumstance. In addition, a pathogen cannot evolve over many brief generations to optimally infect genetically identical hosts. Photo by author.

Typically the fate of a gene in a mouse is tied to the fate of the mouse. The immortality of genes and the coexistence of multiple copies give rise to exceptions.

Some genes have evolved to preferentially duplicate themselves and jump between chromosomes. They are particularly abundant in maize (field, pop, and sweet corn for Americans, Figure 1). Barbara McClintock (1902-1992) began documenting these effects in the 1940's. Legend has it that she was universally regarded as a crackpot. She did have difficulties, but the National Academy of Sciences elected her in 1944. She received the Nobel Prize in 1983.

Self-duplicating genes are a form of parasite, but one whose fate is linked to the host. If they get too out of hand, they cause frequent mutations, in addition to making the genome excessively large. Either the unfit organism dies out with its jumping genes or evolves mechanisms for keeping them in check. There is thus a selective advantage for variants of jumping genes that do not get too greedy.

There are also jumpy genes that are readily carried by viruses between microbes, like one-celled photosynthetic cyanobacteria in the ocean. The exchangeable genes, the "core" genes of the cells that do not exchange, and the viruses are three nonstandard classes of organisms with a complex ecology. An exchangeable gene benefits by being readily picked up by viruses, by having its cell host easily infected by these viruses, and by not having the infection be lethal before the cell as had chance to divide. These traits are not necessarily advantageous to its host or to its virus. Natural selection thus acts on the core genes and the viruses, sometimes to the detriment of the exchangeable genes. An exchangeable gene, like many parasites, benefits when it is not a major detriment to its hosts, here the core genes of the cell, and its vector, here the virus.

Conversely, there are numerous copies of successful genes in the genomes of many individuals, say a population of butterflies. As the copies are identical, it is irrelevant to the genes, which butterfly actually reproduces. It is the net increase or decrease of the gene in the population that matters. A gene (or group of genes) that renders the butterfly toxic to birds and recognizable from its nontoxic relatives may spread in the population by group selection. A bird eats a toxic butterfly, killing that copy of the gene. It becomes sick and avoids the toxic butterflies in the future. This benefits the remaining butterflies that carry the gene.

The tree of life. My aunt recently had her membership in the DAR disqualified because the ancestor had fought on ships, not land, in the American Revolution. With some effort, she found an ancestor who had served in the Army and registered to collect his pension (and hence modern documentation). This aroused my curiosity and I did some looking on the web. There are two types of family trees, the ancestors of James Hatfield and the descendents of James Hatfield. Biologists from the advent of evolution dealt with both types of trees using morphology and the fossil record.

DNA provides a solid method of determining family trees. It has put an end to contested paternity suits. It is far more reliable in crime solving than eyewitness accounts of the "morphology" of the suspect. Scientists can sequence the DNA as a long list of AGCT's, sequence the amino acids in the proteins, or sequence the RNA in the ribosomes.

If we wish to use DNA to deduce the recent family tree, like in a paternity suit, we need to concentrate on parts of the genome that are highly variable. These are partly genes of traits for which there has been much recent natural selection, like skin color with latitude, and unimportant traits (including DNA that does not code for proteins). If we want to work out our relationships with microbes and plants, we need important DNA that evolves slowly. The ribosome is ideal. It occurs in all cellular organisms. Its failure is lethal in that the genetic code cannot be read. It is also quite complex. This alone shows that all cellular life has a common ancestor. It is easier to sequence the RNA in the ribosome than the DNA that codes for it.

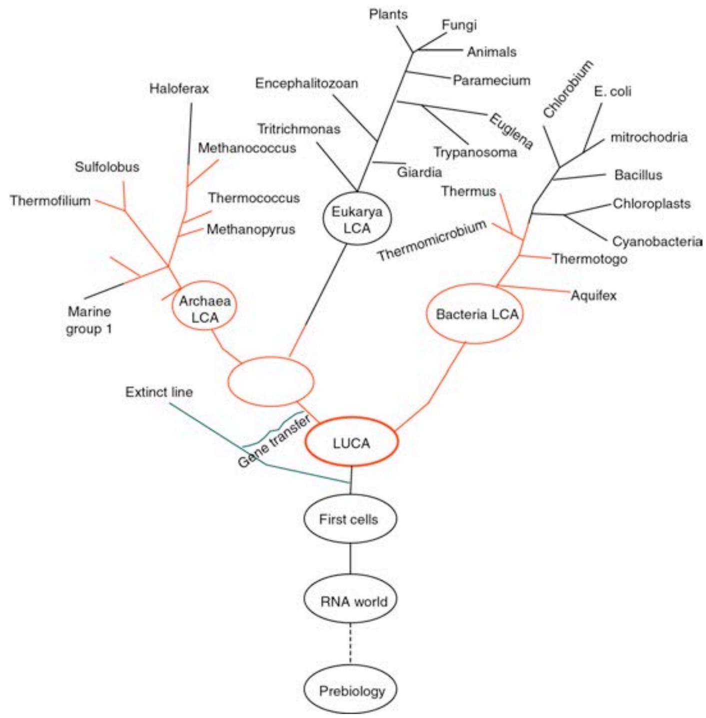


Figure 5: All extant organisms descend for the Last Universal Common Ancestor (LUCA). There are also last common ancestors of the three major branches, Bacterial, Archaea, and Eukarya. Plants animals, and fungi are closely related. Red lines indicate thermophile organisms and black lines indicate organisms living at lower temperatures. The last ancestors will change if organisms with lower branches are found. The truck below LUCA is poorly constrained. FYI: Aquifex, Thermotoga, Thermomicrobium, and Thermus are thermophile bacteria. Chlorobium is a non oxygen-producing photosynthetic organism. Tritrichmonas, Giardia, Encephalitozoan, and Trypanosoma are Eukaryotic pathogens. Euglena and paramecium are feed-living Eukaryotic microbes that can be easily observed in a microscope. Thermofilium, Sulfolobus, Methococcus, Thermococcus, and Methanopyrus are Archaea thermopphiles. Haloferax lives in saturated salt brine and does photosynthesis. I have pruned the tree to have a manageable number of branches. I omit the vast number of branches leading to extinct organisms, which we cannot sequence.

For purposes of discussion, I start at the root of the tree, the last universal common ancestor (LUCA). There are three major branches (Figure 2). The first branching from the trunk is Bacteria. (The public and scientists over 40 tend to use bacteria to mean microbe. This use needs to be avoided like the plague that is caused by a type of Bacteria.) Bacteria also include Escherichia coli (E. coli) in our guts and Streptococcus in our throats, as well as numerous free-living forms. The second branching is between Eukarya and Archaea. We belong to Eukarya. Plants, other animals, and Fungi are our close relatives on the tree. Single celled Giardia is a more distant relative, a bane to back-backers. The Archaea are small single cell organisms. The name reflects the hypothesis that they retain ancestral features of early life. They are quite common on the Earth but escaped detection until scientists discovered forms that live in extreme environments. They are a significant part of the oceanic biomass.

Biologists can do better in constructing the family tree by taking account of the function of genes. Take for example a gene that codes for an important protein in primates. We have copies of the gene and the protein in many primates including lemurs and ourselves. Every change between the ancestral gene and the current one coded for a functional protein. A lot of mutations in any branch did not all occur in one generation. With these restrictions on evolution, it is possible to reconstruct and genetically engineer several tens of million year old genes and their proteins. Linguists do the same thing to reconstruct the Indo-European language. They can deduce the speaker's lifestyle. For example, our words "ewe" and "wolf" trace back to the original language. The speakers raised sheep in a wolf-infected region.

In analogy with languages, borrowings do occur. Genes jump from one "species" to another. The process is a major part of genetic engineering. It is frequent among microbes in nature. It creates a problem in constructing the tree of life. Did the gene that we are sequencing jump in from another line? Again the analogy to "word borrowing" is useful. For example, there are no deserts in England or eastern North America. The British encountered deserts in Arabia. Their desert words like wadi (dry streambed) come from Arabic. The Americans reached the desert in the southwest. "Arroyo" comes from Mexican and Microsoft Word recognizes it as American English. Back to the genome, burrowed genes come into the genome as groups and stay linked. They also tend to do tasks that the organism did not already do well. The west coast settler did not need to borrow Mexican words for public body parts that were already in English.

Gene transfer can be turned into a signal on the timing of various branches of the tree. Back to languages, careful examination of regional varieties of English would show that groups of Mexican words came into western English after 1830. With regard to life, the chloroplasts in plant cells are the descendents of cyanobacteria that plant microbial ancestors once trapped with their cells. By examining the chloroplast genome and the genomes of its free-living relatives, we could tell where within the branching of the tree the chloroplasts moved into the ancestor of plant cells. We can correlate branching events in two limbs by seeing which Eukarya lack chloroplasts as a primary feature.

What was LUCA like? It was obviously a highly complex organism. The genetic code was already in place. Several gene families predate it. Biologists construct the family trees of these genes to times predating LUCA. In addition, genes transferred from extinct lineages probably exist within LUCA and its living descendents. Biologists have suggested some examples.

Where did LUCA live? Probably in the dark. Photosynthesis evolved much later well up into the tree, though billions of years ago. It got its "food" from chemical disequilibria as occur now around hydrothermal vents. LUCA's resistance to arsenic indicates that it (or its ancestor) hung out around hydrothermal systems. The universal need for elements, like nickel and cobalt, indicates that it lived within rocks erupted from very hot volcanoes that were common on the young planet.

Did it live in hot water? Maybe. Both the Bacteria's and Archaea's last common ancestors were high temperature organisms. It is less clear whether Eukarya had a thermophile ancestor. This observation and more sophisticated molecular biology provide hints that LUCA had ancestors that evolved at temperate conditions and may have itself inhabited temperature environments.

Early biology and present vanity. What does this portend for planetary habitability? First we can throw out traditional ecology dependent on primary photosynthetic producers. The early ecology likely did not depend on sunlight and in fact may have found it lethal. (There are just-discovered organisms that use photo-electricity from zinc sulfide crystals. This mineral, sphalerite, was likely on the early Earth and is a candidate pre-biotic environment.) Dark oceans in ice-covered planets like Europa and ground water a kilometer down in Mars are habitable provided that the planet is geologically active enough for hot springs and volcanism to maintain disequilibria, like those LUCA lived around. There is no outer limit to the habitable zone for microbes, provided the planet is large enough to maintain liquid water and some geological activity. It is a matter of logistics that it is hard for us to get at the subsurface of a frozen world. Fortunately, life-charged water may erupt to the surface.

There is no "ladder" of life on the Earth, like in bad K-12 science books. All organisms have had equal time to evolve from LUCA. Vent Archaea, for example, are quite fit for their environment. The ladder idea applied to humans led to scourge of “scientific” racism in the 1800s and 1900s. Modern genetics show that human populations differ systematically only in a few genes, including those that code for the obvious physical traits.

We are quite fit ourselves. This is to be expected of a common wide-ranging organism. Yet we are not even the most successful organism by many measures. There are a lot more worms than people on your yard after a hard rain. Our body structure is more complex than microbes and I am writing now. But our chemistry is quite similar to microbes. We are really microbes (at the start of our lives) that have evolved to be multicellular.

We call our close relatives “primates” and call animals and plants “higher organisms.” The former is vanity and the latter is, at best, a useful fiction. Modern biologists avoid the word “primitive” especially with extant organisms. It is best to use "conservative" to imply that the organism has retained ancestral traits. They do not belittle traits, like the external fertilization of eggs by sperm. These traits aptly serve many organisms. They do not go looking for some gross misadaptation in extinct species, like the popular meaning of dinosaur. After all, extinct organisms had successfully evolved for billions of years.

There are real evolutionary contrivances. To boot, the first organisms to occupy a niche were likely to be inept at it, like the first land animals, including fish-amphibians. They had no competition at first. It may be productive to call the first adaptations for land life “primitive” but not the organisms as a whole.

Life's origins

My children (at ages 6 and 7) were, as often, fighting in the car. To stop the fight, I asked them, which came first the chicken or the egg? They stopped to think for a while. Finally some quiet! But it did not last. In a crescendo, Zacky insisted that eggs hatch into chickens and Jacob insisted that chickens lay eggs. Through the din, I realized that the question, as phrased, relates only to Creationism. There is no problem in evolution for an ancestor of chickens to evolve the ability to lay eggs. There is a more fundamental problem of how life started in the first place. Darwin avoided the problem beyond stating it might have happened in a small pond.

Looking back. We can start with LUCA and try to work back. LUCA, like modern microbes, is too complex to be a first common ancestor. No one would repeat Pasteur's spontaneous generation experiments now except as a demonstration. The most telling issue is that its DNA needed proteins to replicate, but the proteins needed the DNA to form. We are back about 4 billion years to chicken and egg.

We can go back to RNA. The RNA in the ribosome may be the vestige of an earlier genetic material. There are numerous RNA-bearing molecules in the cell (called RNA-cofactors) including vitamin B-12 that probably date from the RNA world. Importantly, RNA can act as its own catalyst in replication. It also has a 4-base system that codes for proteins. Perhaps RNA-based organisms evolved the ability to produce proteins and then DNA to aid their replication. The DNA proved to be a better genetic material. (It is more stable.) It eventually evolved into that information function, relegating the RNA to the ribosome and the cofactors.

This RNA world has been the subject of much speculation by biologists. There may be vestiges of the original RNA molecular organisms in repeated sequences in ribosomes. So far, no one has a model for working RNA organisms and none have yet been found in the wild. In any case, modern RNA is too complex to be the first living thing. Biologists have ideas for simpler self-replicating systems.

There is a wide choice of other bases and compounds similar to RNA and DNA, but the vestiges of them are not evident in living organisms. Overall RNA seems to be a good material that might be generated abiotically. Its "backbone" sugar, ribose, has 5 carbons. It forms spontaneously in alkaline water that occurs naturally within serpentinite, a rock consisting of hydrous magnesium and iron silicates and hydroxides discussed in Chapters 4 and 8. The trace element boron stabilizes ribose from decomposing into tar.

The lack of “smoking-gun” evidence in extant organisms occurs because evolution tends to wipe out some of its tracks. Some of the early evolutionary lines may have retained pre-RNA and RNA heredity. The DNA life out-competed these organisms, eventually driving them to extinction. We have no fossil record from this early time on the Earth. As we will see in the Chapter 11, disasters may have helped cull these conservative lineages.

Starting life from scratch. We can start with the conditions on the early Earth and try to work forward. It is easy to generate complex organic molecules, like amino acids, without life. Organic is royally awkward here but we are stuck with it. The term dates from when scientists believed a vital force is necessary for life. Laboratory chemists have “abiotically” produced organic compounds since the early 1800s. Chemistry and physics inside a cell are the same as outside but often more complicated.

The first serious attempt at replicating early Earth conditions came when a graduate student at the University of Chicago mixed water, ammonia, and methane and hydrogen in a flask. He sent electric sparks to simulate lightning on an early planet. His advisor, Harold Urey, was expecting negative results. To his surprise, Stanley Miller found complex compounds including amino acids.

Debate continues to the present day on whether these conditions represented the early Earth. The flask material was probably too reducing (has too little oxygen) for a long-lived planetary atmosphere. It could have occurred when there was a lot of iron metal around, like after an asteroid hit in Chapter 11. Subsequent work showed that other somewhat more oxygen-rich mixtures generate complex organic compounds and that the bases in the genetic code can form abiotically.

Meteorites with organic matter. Fortunately, we have natural examples where complex organic matter formed abiotically. A class of meteorites called carbonaceous chondrites frequently falls to the Earth. Geochemists eagerly analyze samples that have not been fouled by terrestrial organisms, like pissing dogs. As expected from their name, these meteorites contain complex carbon compounds including amino acids. They formed underground with water circulating through the asteroid-sized body (many kilometer-diameter) from which the meteorite formed. There was iron metal around. These are conditions expected on any clement body in the early solar system.

In addition, organic compounds occur in interstellar space, especially the star-forming regions of giant molecular clouds. These include simple amino acids. The work utilizes spectral lines at radio frequency from jumps between closely spaced energy states. See Chapter 6.

How far did this prebiotic chemistry get toward life? There are no cellular fossils in any carbonaceous chondrite meteorite yet studied. Life did not form in the hundreds of thousands to a few million years that these objects stayed clement with liquid water. However, we do not know the duration of clement conditions very well. Still there is a hint of autocatalysis, but it is not a smoking gun.

Amino acids have mirror image forms, left (L) and right (D, dextral from Latin). Terrestrial life uses the L forms. An abiotic process produces both forms equally and a biotic sample will eventually decay to equal amounts. The dry-cold space environment of meteorites is sufficient to preserve the L:D ratio for geological time. There is an excess over 50% of L in some samples where terrestrial contamination can be excluded. This would occur if autocatalysis produced an excess of the L forms or if it "ate" more of the D forms. We do not know which. On the Earth, it proved advantageous for life to use only the L forms. There are plenty of D forms around in degraded organic matter so this did not occur from lack of supply.

These observations provide a general way to quickly distinguish biological from nonbiological organic matter in pristine samples. Life evolves to use a limited number of complex compounds as building blocks like in a *Lego* set. These include DNA, its 4 bases, and the 20 standard amino acids. The abiotic meteorites contain a vast number of complex compounds with done particularly abundant. The difference becomes obvious with modern chemical analytic techniques. Degraded organic matter falls in between.

Biochemists seek to recognize vestiges of biological or abiotic origin in extremely degraded organic matter in the oldest rocks.

Bottom lines

Life on the Earth is typically well suited for its mode of existence. Natural selection over geological time produced this illusion of design. With a little thought you can see the effects of evolution. [see Do it Yourself with Acorns] Evolution also produced many contrivances that any conscious designer from scratch would promptly reject.

Evolution gives us, the sole conscious survivors on our planet, an illusion of miracle. With an aura of Darwin's time, consider the analogy of a shipwreck on the Dover coast. (Darwin never sailed again even to France once the *Beagle* reached port.) The survivors, once ashore, reflect eloquently on the miracle of their fate to the press. The drowned victims cannot partake in the interviews. The miracle of the accident does not impress the families of the victims, nor the owners of the ship and cargo. Survivor bias is well known to salesmen and hence to the wary. A new car salesman will point in the lot to used cars of his make that are still running after 12 years and not take the client to visit the junk yard. The majority players remaining around a roulette table at 4 A.M. may be ahead. Families of speculative hedge and mutual funds persist partly for this reason. The salesmen notes with pride that both of his company's funds doubled in the past year; never mind that the other 8 went belly up.

We can export to astrobiology that natural selection leads to a vast assortment of life forms if it can act for geological time. It also limits what we can export it detail.

Terrestrial biota evolved for the conditions on the Earth. Early biochemical innovations have locked in because many things in the cell depend on them. We can at least export that the biological innovations that we see on the Earth are possible even if they are not optimal.

We can trace evolution back beyond the last common ancestor of extant life and probably back to an RNA world. An unknown genetic mechanism possibly RNA existed at first. We do not know when life became cellular. In fact, the building blocks of cell walls form abiotically and the wall material can self-assemble abiotically. Still the issue is merely finding out how a series of biological innovations and adaptive radiations occurred once we are into descent with modification.

Getting abiotically to complex organic molecules like amino acids and ribose is easy even in the laboratory. A poorly understood gap exists between this “Darwin soup” and descent with modification. We will never find this gap preserved in terrestrial rocks. What happened as autocatalysis moved toward life? Biologists just do not know at this stage and it makes some very religious people happy. Biologists are stymied, but by the lack of a rock record and by the lack of vestiges in extant organisms. Like Darwin, I argue from this ignorance that it is way premature to banish reason for mysticism. We still do not know whether the origin of life is hard or easy. We still face the weak anthropic principle that we need to be here to observe.

Notes

Perhaps ironically, antievolution tactics in K-12 education have themselves evolved under the selective pressures of public opinion and court decisions. In my youth in western Michigan, even high school texts had little discussion of evolution. This was necessary for sales in such Bible Belt regions. The topic did not arise at all in my 9th grade class. In 12th grade in 1963, the teacher carefully stated she had no opinion. To do otherwise would have bought on the wrath of numerous parents and school-board members. She had given Darwin a ringing endorsement. After that day, I regarded high school science teaching as an occupation of last resort that accommodated duplicity. I was driven to succeed to avoid this fate well into graduate school. Countless other students must students must have been deterred from high school science teaching by fear of Creationists.

The U.S. Supreme Court Decision in 1968 made it unconstitutional for governments to forbid teaching of evolution in a public school. One is still free to believe whatever one chooses on faith. Parents are free to send their children to private schools or to educate them at home. The U.S. courts allow the teaching about religion as history and social studies if it is done descriptively. Public schools are not required to hide the fact that many citizens object to evolution on religious grounds and that they are free to do so. Schools are free to teach about the intellectual climate at the time of Darwin and even that Darwin's early views followed Paley. However, Darwin and most of his scientific associates saw Paley's views wilt in the harsh lights of science, evidence and logic. Paley was willing to accept an old Earth if evidence became available. He lived before Playfair made old-earth geology accessible to the English public.

Young-Earth Creationists responded by promoting their work as a science and their views as a dichotomy with standard science. Their tenets, like the Flood and a 6000-year-old Earth, are specific, testable, and wanting. It was easy for scientists to establish that the dichotomy is false. Every culture has its own creation story. U.S. courts have consistently ruled in that way.

The Intelligent Design movement is a recent twist, a form of old-Earth Creationism. It is attractive to religious individuals who find young-Earth Creationism outmoded. I.D. includes Paley's watchmaker argument on complexity and Mivart's arguments on perfected organs. These Creationists appeal to dichotomy and fairness. That is, they state that schools should be required to teach "flaws" in evolution. They, however, do not offer positive results. Rather, they advocate a selective lack of imagination, which attributes gaps in scientific understanding to supernatural causes. U.S. courts have ruled that Intelligent Design is religion.

St. George Mivart published *On the Genesis of Species* (Appleton, New York, 1871) as a response to Darwin. Until this time, he had been a supporter of evolution by natural selection. The book validly brings up questions (like the seeming inutility of initial variations that lead to highly complex structures) that any successful theory for the origin of species must address. It had some positive effect in that Darwin and subsequent scientists have addressed his substantive points. Mivart accepted limited evolution and limited natural selection. He was (and remained after 1871) an excellent descriptive zoologist.

Some appeal to Devine Intervention was acceptable in 1871 science. For example, Wallace like Mivart was unwilling to attribute the origin of the human intellect to natural processes. To Darwin, difficulties with natural selection represented problems to be addressed by further work. Darwin readily acknowledged that use and disuse might have a direct effect, knew that the mechanisms of heredity and of the initial variations that lead to selection were poorly understood, and agreed with Mivart on almost all of the data.

Scientists avoid presenting one-sided arguments, like those of lawyers advocating a case. Mivart had crossed this unmarked line. To him, all difficulties with significant natural selection seemed insurmountable. He felt that a major scientific theory needed to include First Cause. Yet he offered no alternative acceptable to Darwin and his associates, who were unwilling to base their work on (to them untestable) Revelations about a Deity "utterly beyond our power to imagine" (Mivart, 1871, p. 254) at every turn. By 1874, Mivart was ostracized by Darwin's circle. Wallace in contrast acknowledged that his views on the human intellect were nonstandard and remained part of the circle.

Much of Mivart's motivation was to make evolution and science in general acceptable to the religious. This tread throughout Mivart's life proved tragic. He joined of the English Catholic Church in his youth. The Oxford movement reacted to the national limitation (parochial in the secular meaning of the word) of the Anglican Church by joining the Catholic (all encompassing in its secular meaning) Church. It advocated a liberal theology and active participation in education. Mivart became the only English Catholic scientist of note. He initially received Papal support for his work on theistic evolution.

However, many elements of the English Catholic Church and essentially all the Church on the Continent became increasingly medieval (Ultramontane) during Mivart's life. Mivart believed that both those born and those converted into Catholicism needed to accept their faith on an informed rational basis. Mivart recognized that faith based on ignorance maintained by forbidding education would lead a declining membership living in increasing squalor. Quoting Galileo, he maintained that banning scientifically testable hypothesis on the grounds of Dogma would expose the faith to ridicule, killing conversions and driving apostasy. Shortly before Mivart's death, the Church forced continental evolutionists to recant. The Catholic Church now accepts evolution with natural selection as likely valid science.

The Dreyfrus affair in France triggered Mivart's final break with the Church and his excommunication. Mivart as a Catholic was a voluntary minority in England. He expressed in print that the virulent anti-Semitism emanating from the French Church shocked him. More distressingly the Roman Curia openly welcomed this intolerance. (Alfred Dreyfus was a Jewish French army officer who was convicted twice of treason in show trials on fabricated evidence. Pressure by Émile Zola eventually led to his exoneration.) The Church demanded and Mivart refused to recant.

Gruber, Jacob W. (1960) *A Conscience in Conflict: The life of St. George Jackson Mivart*, Temple University Publications by Columbia University Press, New York, pp. 266. This is an excellent discussion of Mivart and his times.

Cellular life separates the tasks of storing genetic information with DNA and reading this information to make the organism out of proteins. An alternative lifestyle would have the reader (the ribosome on the Earth) read the genetic information and then duplicate it. A single stranded molecule like protein then could store the genetic information to make the reader, the cell, and more copies of itself. A partial analogy exists. Prions are small proteins that cause, for example, mad cow disease. These proteins carry the genetic information to make more copies of themselves at the expense of their host. Study of the evolution of prions is in its infancy. Still the tracks of natural selection are evident. Closely related different varieties of prions infect different host species.

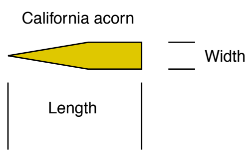
Scientists and the public use the term “natural” in various ways. Artificial selection and natural selection contrast manmade processes from all else. Similarly, a person may die from “natural causes.” Yet cat breeding and axe murders do not violate any of the laws of nature. That is, they are not “supernatural.” It might be better to make artificial selection a subclass of natural selection for this reason. The present terminology is in wide use; I stick with it with these qualms and caveats.

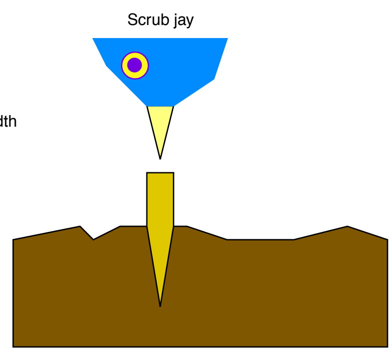
Exercises

Do it yourself evolution project with acorns

There is evidence for evolution in all biology. The objective here is to see the affects of evolution for yourself. This project is set up for California. If you live where squirrels plant acorns you can do that part of the study and use the photos for west-coast acorns. You will also see that ecology is complicated when viewed in any detail. In California, jays collect acorns and bury them point first by pounding on them with their beaks. The jay later finds and eats most of the acorns, but some get missed. This serves to plant the acorns often in fresh soil. Squirrels do the same thing in the eastern United States. The tree squirrel, *Sciurus carolinensis,* is not native to California. (Black and gray forms are this same species; I give Latin names so the curious can search the Web.) Most of the native oak trees predate their arrival. In any case, the introduction of squirrels is too recent for them to affect evolution of local oaks.

Project: California acorns are bullet-shaped with pointed ends. This is an obvious adaptation for being planted by jays. Eastern acorns are round and evolved for being planted by squirrels. The top of California the acorn may be thicker to withstand pecking but this is harder to measure than shape. We will measure native and eastern acorns to see difference in acorn shape.





The ground squirrel (*Otospermophilus beecheyiis)* is native to California but does not plant acorns.

 Find an oak tree with acorns on it on or the ground. Try for one that looks like it grew in the wild rather than being planted by humans.

Now measure the length and width of 5 acorns. If you are working in a group, do not all use the same tree, if possible. Record the measurements

length width ratio(l/w)

compute the averages _____ ______ _________

Now repeat with an eastern oak. The pin oak (*Quercus palustris*) has been introduced widely. If you are east of the Rockies you will have native oaks.

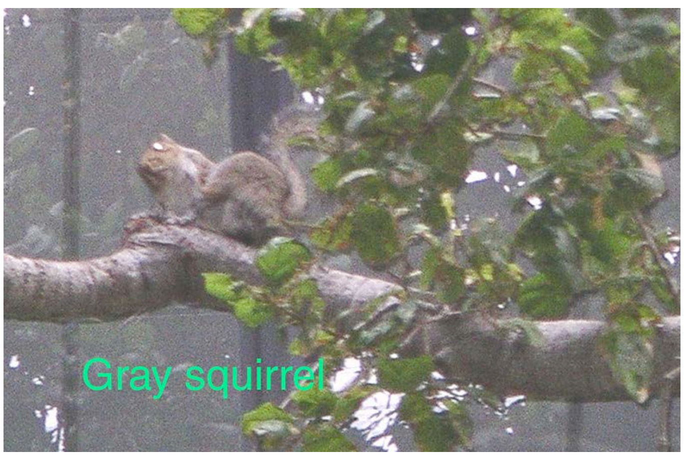
length width ratio(l/w)

compute averages _____ ______ _________

Do you see the expected differences between eastern and native oaks?

We now get into more complicated aspects of evolution and ecology. There are two common jays in the Bay Area of California. The scrub jay (*Aphelocoma californica*) lives at low elevations like around the campus. The Steller's jay (*Cyanocitta ctelleri*) lives up in the hills. The scrub jay is larger and has a larger beak than the Steller's jay.

One might expect that the acorns in the hills have evolved to be narrower than the acorns in the lowlands. There are three obvious complicating factors. (1) A larger acorn can grow a more vigorous seedling, so there is selective pressure for the acorn to be large when this helps. (2) There is a native tree squirrel (*Sciurus griseus*) at high elevations that also plants acorns. (3) The acorn woodpecker (*Melanerpes formicivorus*) eats acorns but does not plant them. It stores them in granaries in tree trucks and tree limbs. It can store only acorns that it can fly with. It makes holes of this size. It is of advantage for an acorn to be too big for woodpeckers. Measure woodpecker holes on the trees if available to check things out.



Did you see native acorns that were larger than this?

Acorn woodpecker with acorn in beak on granary tree.

For sports buffs

You can get an idea of the comparative easy that evolution leads to serviceable organisms and the difficulty of design from scratch by comparing basketball (a designed game) with evolved games including golf, hockey, tennis, baseball, soccer, and American football. Evolved sports existed as informal activities long before there were formal leagues. The players by agreement eliminated unworkable aspects and unworkable (or highly dangerous) sports died out.

What happens at the end of most close basketball games? What has been tried to improve the situation? Do you see a remedy?

You may want to look up other major rule changes in basketball since 1950. It now has some evolved aspects.

Can you think of another designed sport that has a major following? If so what changes have been made since it started and why? Can you think of recent changes in evolved sports?

If you are familiar with American football, soccer, and rugby (or other forms of football), you may be able to recognize signs of their evolution from a common ancestral sport. Do you see the equivalent of vestigial organs? That is, rules in one sport that now only play minor roles, but remain important in the related sports.