BIOLOGICAL EVOLUTION

It is easy to see that some creatures are more like other creatures and construct a "tree" based on these similarities and differences (e.g. try humans, chimpanzees, wolves, cheetahs, worms, fruit flies, spiders, …). This is just the kind of categorization that can be constructed for any kinds of things—a car is more like a tank than a house, etc. The question that biology tries to answer is: How did these similarities and differences arise?

How do we know that "evolution" occurred at all?
All we really (think we) know is that all living species did not come into existence at the same time, and the order of their appearance. Also, that organisms which appear later seem more "complex" both physically and cognitively. Example: earliest rocks containing fossil evidence for single-celled organisms, insects, vertebrates, … The **only** assumption made in this is that ages of artifacts can be reliably determined by ***radioactive dating*** (which we'll discuss shortly). So that life "developed" or "evolved" in some way during the history of the Earth is not part of any "theory," it is more-or-less as simple as being able to tell by inspection that a book from 1922 is older than a book just published. The fact that the record of fossil evidence is incomplete and has gaps has *nothing* to do with this conclusion

"Evolution", as the term is usually used, means that these various appearances of "newer" species, and the categorization of the "tree of life" are linked by "inheritance." Darwin had no idea what this genealogical inheritance could be (Mendelian genetics came later, and knowledge of DNA later still), he only postulated that there must be some such mechanism by which traits can be passed down through generations of organisms.

Darwin added that the steps are linked by *gradual changes* under the operation of *natural selection.* However it is a mistake to think that modern evolutionary biology assumes either of these (although that natural selection plays some role is accepted almost universally, but with many who think that other things [which we will list: e.g. especially processes at the genome level, like "lateral transfer," gene duplication, …] play just as important a role. It is this shift from the evolutionary views of a few decades ago (which persist in the popular literature and even in university courses) to the current state of affairs, focused on evolution at the genome level and allowing for many important processes, some of which are surely yet to be discovered, that I would like you to appreciate. This will allow us to think more clearly about how the development of life on other planets might have taken place. For a good brief presentation of the older picture of evolution and its history, read pp. 56-58 in your book, and then read p. 59 on "Evolution at the molecular level."

The first thing to appreciate is the strong evidence that all life shares a number of fundamental properties indicating that life developed from some original life form:

Evidence for a common ancestor:

1. Universality of genetic code.
2. Same 20 amino acids in all species.
3. Identical "handedness" of biological molecules.
4. Energy carriers (e.g. ATP) and enzymes with identical functions in diverse organisms.

This is why evolutionists often write about a “last common ancestor” (LCA). But note that this “LCA” is supposed to already be complex, like a bacterium, not the first life on Earth, which would probably have been much more rudimentary.

Getting the ages of rocks containing fossils or chemical evidence for life.

How can we get the order and dates at which various crucial evolutionary developments occurred? Relative ages of rocks containing fossil evidence comes from *sedimentary strata*, as explained in detail on pp. 80-84 of your book. For absolute ages there are two methods:

1. Absolute dating using radioactivity—used for fossils or impressions in rocks. Although these methods give accurate ages for the rocks, the problem for the earliest life forms (say 2 to 4 Gyr ago) is that it’s difficult to establish that the rocks have traces of *biological* processes, i.e. evidence for life in them. But there are fewer and fewer problems for times less than about 2 Gyr ago.

Your textbook gives a detailed explanation of radioactive dating on pp. 85-90. It is important to realize that this method is not especially “scientific” (you don’t have to understand “radioactivity” to use it!) and is no more mysterious than watching a clock or an hourglass.

2. Relative dating by differences in DNA sequences—this is based on using the number of accumulated mutations as a clock, and can be used in DNA, RNA, and amino acids. The results generally agree. However this method does not give accurate absolute ages because we don’t really know how the rate of mutation has varied. Instead it gives the *lineage*, or the relative point in the “tree of life” at which two organisms with different DNA probably *diverged*. These relative ages can be put on an absolute scale if we know the rate at which mutations accumulate, and that this rate has been constant—that is a problem, but only introduces some uncertainty in the absolute ages, not in the order, and the ages inferred agree with ages from radioactive dating when comparison is possible.

This method is also described on pp. 116-117 of your textbook.

Example: Assuming that the first sequence is the oldest, what is the order in which they probably arose?

TTGGACC
TGACGCT
TGGGACA
TTGACCC
TTGAACC

Radioactive Dating: ^{14}C as an example

Each radioactive atom has its own ***half-life.*** If we know the amount present in some sample, *and* can estimate the original amount, then we can calculate how long it's been decaying, which gives it's age.

Example: **Carbon-14 dating:**

Production:

cosmic rays in earth's atmosphere -------> neutrons -------> combine with ^{14}N ------> ^{14}C

Decay: ^{14}C -----> ^{13}C with half-life = 5730 years

In earth's atmosphere, the balance between production and decay gives an *equilibrium* ^{14}C abundance, which is well-known, and constant.

But $^{14}C + 2\ O \rightarrow {}^{14}CO_2$, which gets mixed with normal $^{12}CO_2$.

All plants take in CO_2 , and animals feed on plants, so **all <u>living</u> creatures have the equilibrium ratio of $^{14}CO_2$ to $^{12}CO_2$.**

When an organism is alive, you get 15.3 decays per minute for each gram of carbon in it. After 5730 years, only 1/2 of ^{14}C left, get 7.6 decays per minute for each gram of carbon. After 2 X 5730 = 11,460 years, only get 3.8 decays per minute.

------->**So by measuring the number of decays per minute in a gram of a fossil (using a Geiger counter, say), you get the time since it died, i.e. its age.**

Must shield the counter and allow for external radiation (U, Th, cosmic rays,...).

Can only use ^{14}C dating for ages less than about 30,000 yr (about 5 half-lives), or number of decays will be too small to separate from background noise.

Can check ^{14}C ages against known historical ages up to around 5000 yr. ago. Can check with other methods (e.g. geomagnetic dating, tree rings, ...) up to about 30,000 yr. ago. Maximum deviation is less than about 10 percent. (See M. Stuiver, 1978 *Nature*, vol. 274, May 25, p.271.)

But for *older* fossils, must use radioactive atoms with much longer half-lives: e.g. potassium-40 ---> argon-40 (1200 Myr); rubidium-87 ----> strontium-87 (5000 Myr); uranium-238 ---> lead-206 (4500 Myr). (See Table 4.1 on p. 89 for a more complete list—you don't have to memorize them.)

Fission tracks (=scars left in specimen by ejected particles) are used to get amount that has *already* decayed. Then get *present* amount by putting the specimen in reactor, inducing fission, count *new* tracks. Adding them give *original* amount. Knowing this, and amount that has already decayed, gives **age** of sample. (Actually, a more accurate method is now available that doesn't rely on counting tracks; e.g. mass spectroscopy for present amount.)

Simple example: If half of ^{238}U in a sample had decayed, its age must be 4500 Myr.

Also can check with newer methods like thermoluminescence and electron spin resonance (ESR--limited to about 0.5Myr: used recently to date material from what appears to be a fireplace). They agree. **It is extremely difficult to find any fundamental flaw in this method!** (e.g. maybe the half-lives of the elements have changed drastically over time, or ... None of these arguments work.)

How can we establish the biological origin of very old fossils?

A fossilized skeleton or an impression of a wing (say) is pretty easy to interpret as biological, but as we go to older and older strata there has been more decay, and organisms that had fewer "hard parts" that could be preserved. So this is a big problem for fossils older than about 1,000 Myr.

1. ***Stromatolites***--layered masses of limestone or chert formed by metabolic activities of bacteria. These are layered "biofilms." Present-day stromatolites are often associated with *aerobic* photosynthetic (i.e. photosynthesis that releases oxygen) cyanobacteria. Thousands of old stromatolites are known back to about 2.0 to 2.3 Gyr ago, but then they become rare. Only a few dozen are known from the Archean period and of these only four or five are older than 3.2 Gyr ago (e.g. in Western Australia and South Africa). This is usually taken as consistent with other evidence that the atmospheric oxygen content only got large around 2.0 to 2.5 Gyr ago. The older stromatolites are usually taken as evidence that there was "phototactic" bacterial life (life that moves in reaction to sunlight, not necessarily photosynthetic) around 3.2-3.5 Gyr ago.

However the scarcity of the Archean stromatolites has led some people to suggest that these stromatolites could be due to nonbiological, phyical, geological processes rather than stromatolite-building microbes. Note one of these ancient stromatolites is actually the site of the disputed "fossil cyanobacteria" that were for many years taken to imply that photosynthetic life may have arisen very quickly.

→ So your text is correct that the oldest stromatolites are 3.5 Gyr old. What is in question is whether this is evidence for oxygen-producing photosynthesis that long ago, and even whether they are biological in origin.

2. ***Relative amounts of ^{12}C and ^{13}C*** (extra neutron).

We have discussed this method before, in trying to establish the time at which the earliest life appeared on Earth. Green plants take in CO_2, selectively concentrate ^{12}C instead of ^{13}C in the carbohydrates they produce. Other life forms use these carbohydrates. So biological carbon compounds have less ^{13}C relative to ^{12}C than do carbon compounds not associated with life.

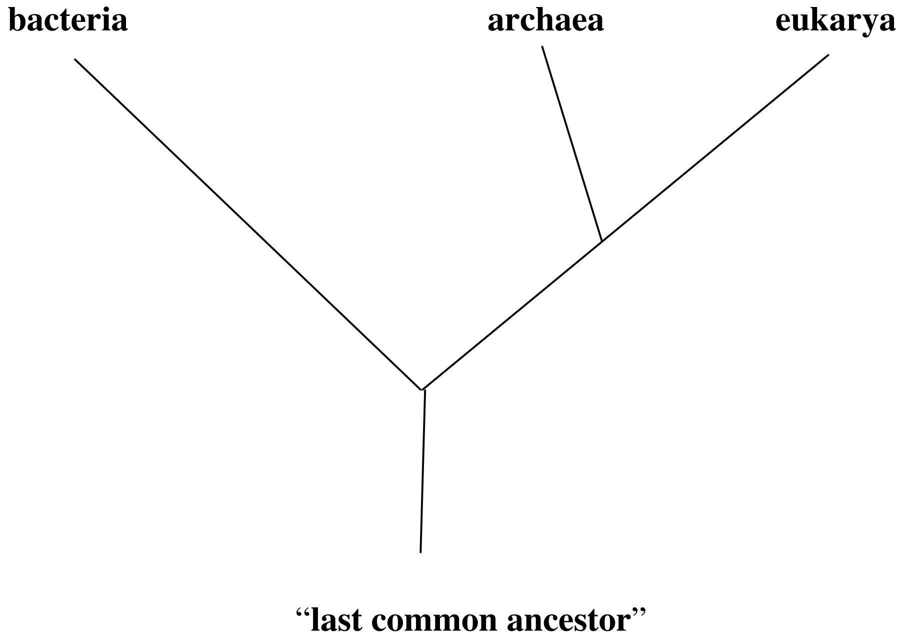
Problem: There are non-biological ways to affect this ratio.

[Note: As you may recall, this was one of the lines of evidence for the claim that the Mars meteorite was the site of (extraterrestrial) biological activity, and is part of the argument concerning evidence of terrestrial life 3.2-3.5 Gyr ago.]

3. Identification of biological hydrocarbons from absorption *spectrum*. Biological hydrocarbons leave a unique signature ("spectral lines") in the spectrum.

Notice also that so far, although this has sounded very "scientific", and it mostly takes place in some laboratory, it's really just been the use of technological instruments to observe and measure things (half-lives of radioactive atoms, isotope concentration in plants, spectrometers to look for spectral signatures of different compounds...) There is nearly no "science," in the sense that includes either theories or explanations, involved. The only thing “scientific” about the establishment of ages and of biological signatures is that they are subject to independent verification.

The most basic result of method 2 above is that the “tree of life” basically has three (not two as was thought about 15-20 years ago) basic **domains**:



Bacteria and archaea are prokaryotic (no nuclear membrane, no cytoskeleton, no organelles like mitochondria,…). Eukaryotes range from single-celled to large organisms (like mammals), but all have the complex cell structures in common. The transition from prokaryotic to eukaryotic life was surely one of the milestones in evolutionary history. We’ll discuss how it might have occurred later.

[A much more detailed evolutionary tree is shown in Fig. 5.4, p.117, of your text.]

That the archaea are linked more closely with eukaryotes is still a matter of some debate, and is based on detailed comparisons involving DNA base compositions, membrane characteristics, etc. However the case connecting them more closely with eukarya has only grown stronger.

There is also evidence (too much detail to go into here, and disputed by some) that the “deepest branching” of all the organisms was a thermophile or hyperthermophile. This is important because it suggests that life might have arisen where it was hot (on an early Earth that hadn’t cooled much yet, around hydrothermal vents?). However many think that it gives no constraint on the origin of life, only that all life at one point had to adapt to some high temperatures. We have seen arguments that the early Earth was *cold*!

Some terminology

[This should seem like a review, since we have covered this before.]

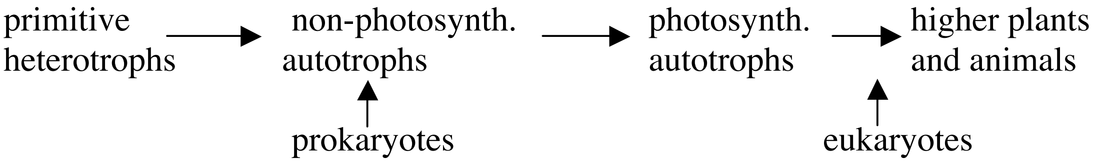
A. Types of cells

1. **Eukaryote** cells--cell nucleus + smaller bodies (mitochondria, chloroplasts, Golgi apparatus,…) + cytoskeleton. Appeared about 1500 Myr ago (Beck Springs Dolomite). Most present-day life (except bacteria and blue-green algae) are eukaryotic. Probably due to symbiosis between prokaryotes; good evidence for this for mitochondria.
2. **Prokaryote** cells--no chromosome-bearing nucleus; less complex structure, relatively small. Respiration and photosynthesis occur via cell wall. Prokaryotic organisms are in the domains bacteria and archaea.

B. Types of food gathering proto-organisms

1. **Autotrophs**--use CO_2 and water with energy from light (green plants, some bacteria) or chemical reactions (some bacteria). Appeared around 3200 Myr ago.
2. **Heterotrophs**--use organic compounds for construction. Probably came first.

Likely evolutionary sequence:



An organism that some think is a crucial clue to the prokaryote-eukaryote transition is called "Giardia." Most people think eukaryotes arose because of ***symbiosis*** of different prokaryotes; this is supported by several lines of evidence, e.g. the mitochondria have a slightly different genetic code than does the rest of a cell. This is just one example of the importance of symbiosis as an evolutionary "force." (There are many others—"natural selection" is a vast simplification.)

Current classification of most primitive life divides them up into three classes or "domains": bacteria, archaea, and eukaryotes, as outlined above and discussed in your text.

See text (p. 117) for good illustration of "tree of life" constructed according to molecular relative dating methods. (Mostly ribosomal RNA.)

Milestones in Evolutionary History

It will be very useful to have a rough idea of the times involved in the various topics that we'll be discussing. Most important thing to consider: how improbable, or "chancy," were these events? This is the crucial question of whether or not evolutionary development is "**convergent**." That is the fundamental question involved in the search for extraterrestrial life and especially intelligence.

Millions of Years Ago: What Happened (in most cases dates are approximate). Compare with nice chart on p. 84 of your text.

14,000 Big Bang—origin of our (part of the) universe

4,600 Origin of planets and Sun (only took about 10 mill. yr. [10 Myr])

4,400 Earth cools enough for water to condense (recall: evidence from zircons), even in the presence of (probably) sterilizing impacts during the "era of heavy bombardment."

3,500: Earliest evidence for life (or at least "last common ancestor" LCA) – some think thermophiles (?), but everyone agrees LCA was some form of bacteria (Notice importance and adaptability of bacterial life.)

Recall that this date is extremely uncertain—evidence now rests on indirect methods like carbon isotopes: the case for bacterial fossils has been considerably weakened. Could be 3,800, could be 3,200.

[When did DNA repair pathways develop? Must have been very early or life would have been mutated out of existence. These repair enzyme processes are very complex so if they arose early, it suggests that the gene-protein system was well-developed very early.]

3,500 and later: "Lateral" or "horizontal" transfer of genetic material may have dominated evolutionary process among bacteria (J. Ford Doolitle and many others). This would mean that there is no single "root" to the evolutionary "tree of life."

3,000 (?) Anaerobic photosynthetic bacteria—biochemicals in environment ran out, some microbes evolved this process to convert sunlight to ATP energy (can think of this as "origin of behavior"). It is "anaerobic" because instead of using H_2O, it used other molecules, especially H_2S, to get the hydrogen that is reacted with CO_2 to make glucose/ATP energy. So no oxygen is released.

2,500 Cyanobacteria and other bacteria probably injected some oxygen into atmosphere (because they release oxygen as they use H_2O and CO_2 to make glucose), but most of it was used up by oxidation reactions in minerals, so atmospheric oxygen levels stay small (~1%).

2,000 → "oxygen holocaust." In one version, the H supply became exhausted, some bacteria developed a way to get H from H_2O, releasing O_2. The more accepted version is that the earth's crust finally got saturated with the oxygen from photosynthesis, so the oxygen started flooding the atmosphere. Those that adapted (including cyanobacteria) gave us aerobic respiration and metabolism.

2,000 (?) Eukaryotic cells arise (more complex cells—cell nucleus, organelles, cytoskeleton,…) . Probably symbiosis with mitochondria and chloroplasts. (e.g. mitochondria have DNA sequences more like bacteria [prokaryotes] than eukaryotes). Many consequences, such as whip-like spirochete microtubules, which were originally used for movement, and increase in the length of genomes (so can code for more complex organism).

1,000 Meiotic sex (egg and sperm). Diploid cell (errors in mitosis and refusing? Or bacterial cannibalism?) --->origin of "parents" Half of genetic material left to offspring.

Is meiosis advantageous? Most, but not all, think it is, because it is a way to increase genetic diversity, which is believed to be the main driver of evolutionary development. It also allows for an escape from "mutational meltdowns" caused by the accumulation of deleterious (disadvantageous) mutations—some think that very complex life would not be possible without meiosis (or at least "recombination").
→ Was it a very improbable accident?

600 "Cambrian explosion"--Multicellular organisms. Nearly all "body plans" (phyla) appear to arise about 545 Myr ago! First skeletons & easily recognizable fossils. Cambrian-Precambrian boundary; cell specialization -----> large multicellular plants and animals. Occurred very rapidly, perhaps within 10 Myr (still somewhat disputed). Unexplained major transition—text gives several possible "explanations". "Snowball Earth episode" is viable, but even that is *very* uncertain.

1996: Wray et al. Oct.25 Science, use DNA sequence dating in seven genes in living animals to find how long ago their ancestors split apart. They claim the transition wasn't so sudden, with branching of invertebrate phyla occurring about 1200Myr ago, but invertebrates diverging from chordates (the phylum to which vertebrates belong) about 1000Myr ago. But paleontologists dispute this, since no fossils are found older than about 565 Myr. Maybe the earlier creatures left no fossils—too "squishy." But the DNA dating method has only been calibrated back to 500Myr, so maybe a problem there. This older age actually supports estimates obtained in 1982 by Bruce Runnegar using blood protein as a molecular clock. So although most scientists think there was a rapid increase in complexity of life at the Precambrian-Cambrian boundary, not all agree how rapid it was.

480: colonization of land by plants and fungi—evolved from algae in shallow ponds? Notice that there weren't any predators yet! Did land colonization have to wait until the oxygen went up in the atmosphere, giving UV protection by the ozone layer? Was there bacterial life on land long before this? What about subsurface life, which currently makes up a large fraction of the biosphere?

Notice the importance of land life for the viability of our search extraterrestrial life

~400: amphibians, insects.

2 Homo erectus
0.2 Homo sapiens
0.006 Sumerians (and some earlier) invent civilization, or at least abandon nomadic life.
0.002 Roman Empire "civilizes" Europe
0.0004 British Empire "civilizes" World
0.00004 DNA double helix discovered
0.000004 you enrolled at UT

CONVERGENCE IN EVOLUTION

Many groups of creatures seem to have "**converged**" by evolving independently, i.e. in parallel, to "exploit particular ecological niches" or "solve a 'problem'", or to acquire a certain advantageous physiological adaptation. [Notice the anthropomorphisms, with terms like "exploit" or "solve a problem."]

Whether or not this occurs ***generally*** in evolution, and for complex traits like intelligence, is the most important question for our problem of the possibility of extraterrestrial intelligence—it is the question of "convergent evolution." As we'll see, you can argue it either way, and biologists are indeed split on the question. What I want you to be able to do is NOT to form an opinion about it, but to be able to argue it either way.

Some examples (many shown in class):

a. **flight**--birds, bats, insects, pterodactyls
b. **torpedo shape** (to swim rapidly in coastal water to catch small fish)-- tuna (fish), dolphin (mammal), ichthyosaur (extinct reptile)
c. **sonar** (echolocation)--bats, porpoises, and 2 (?) species of birds. (And human infants? 1996 report.)
d. **placental pouches**--Australian marsupials and counterparts on other continents.
e. **devices for electrocuting prey**--eels, ...
f. **eyes in squids and vertebrates** (one reference says this type of eye occurs in 10 distant species)
g. **jet propulsion**--bivalves (clams, scallops), cephalopods (squid, octopus, cuttlefish), jellyfish, some insects (dragonflies swimming). [See S.Vogel, Discover, Aug.1994, p.71]
h. **whales and elephants**--similar life histories and social structures (including social females and roving males); see Weilgart, L. *et al.* 1996, Amer. Scientist, May-June, v.84, p.278.

[But notice that these *could* be due to viral transduction or some other form of "lateral transfer"...]

----->But how about a certain form of **intelligence** (e.g. dolphins) and **dexterity** (e.g.spiders)? Both are needed to make radio telescopes or starships. If these are useful adaptations, what are the chances that they would both arise, in the same species, somewhere else?

Examples of useful adaptations that only evolved once, or never

(i.e. examples that suggest how convergence should *not* be expected)

1. Woodpeckers--niche based on excavation of live wood.
Very useful: year-round food from sap and insects, great place to nest (protection). Very successful--over 200 species spread over most of world.

If convergence is the rule, then woodpecking should be widespread among birds, especially close relatives. But this turns out not to be the case: even on remote landmasses that woodpeckers never reached (e.g.Australia, New Guinea, New Zealand), nothing excavates live wood.

Likely reason: woodpecking requires *four* main types of adaptations (e.g. for drilling, perching vertically,...will go over them in class), most of which *have* evolved convergently in other animals. But *not* the whole package.

2. An unfilled niche: animals eat plants, but no higher animal has evolved a cellulose-digesting enzyme! (Cows and other animal herbivores rely on microbes in intestines.)

You can think of other, sometimes more whimsical examples; e.g. why no animals with wheels? [Useful to think about anthropomorphism here--why would wheels be useful?]

So *some* useful adaptations only evolved once, or not at all. And it's not so clear that our type of "intelligence" + dexterity are *useful* adaptations in the long term. (Remember "L" in the Drake equation!)

Can evolutionary biology, especially at the genome level, give us some hints to an answer? (Answer: only in vague terms. We will try to cover this next.)