Evidence for evolution from fossils

For a much more detailed discussion of evidence for evolution, see http://www.talkorigins.org/faqs/comdesc/

Our second lecture on evidence for evolution will concentrate on fossils. In general, gradual transitions can be seen along many lines, but not all. In addition, the evidence does depend on us being able to assign dates to the fossils. We will therefore begin our discussion by talking about ways to determine the age of fossils, then by exploring some of the conditions needed for fossilization.

Dating fossils

The fundamental problem we face is that for life on Earth, the fossils that trace it are vastly older than humanity. Therefore, we don't have the luxury of looking at historical writings to establish age. This is important, because evolutionary expectations are that there should be a fairly clear sequence of changes with time. How can we go about figuring out ages?

The most reliable method turns out to be a technique known as radiometric dating. It relies on the decays of atomic nuclei, so let's discuss that for a bit.

Some atomic nuclei are completely stable in isolation as far as we know. If you let a carbon-12 nucleus alone, it will apparently sit there unaltered until the end of time. In contrast, other nuclei change spontaneously with time. For example, carbon-14 (with six protons and eight neutrons) reaches a lower energy state via the decay

$$^{14}_{6}\mathrm{C} \rightarrow ^{14}_{7}\mathrm{N} + e^- + \bar{\nu}_e \ . \tag{1}$$

That is, carbon-14 decays into nitrogen-14, an electron, and an electron antineutrino. Laboratory experiments demonstrate that it is not possible to predict when any given nucleus will decay. In addition, the probability of decay in the next time interval dt is *completely independent* of how long the nucleus has lasted up to that point, be it an attosecond or a billion years. What this means is that the probability that a nucleus will decay at a time between t and $t + dt$ after its formation is

$$P(t)dt = e^{-t/t_0}dt \tag{2}$$

where t_0 depends on the particular nucleus. This is often phrased in terms of the *half-life* $t_{1/2}$, which is the time by which half the nuclei would have decayed: $t_{1/2} = \ln(2)t_0 \approx 0.7t_0$. Because nuclei are very compact compared to the distance between atoms, external effects have negligible impact on the spontaneous decay rates.

A point worth stressing here is that the nature of this process allows half-lives to be measured even if they are extremely long compared to a laboratory timescale. For example, suppose that you have 10^{20} atoms of uranium-238. After one hour, you determine that there have been approximately 1.8 million decays. From the equation $P(t) = e^{-t/t_0}$ you know that in a time $t \ll t_0$ a fraction $\approx t/t_0$ of the nuclei will decay. Therefore, in this case $t_0 \approx 6.43 \times 10^9$ yr and $t_{1/2} \approx 4.46 \times 10^9$ yr.

This is all very well, but how does it help us determine ages? The simplest case would be one in which we know the initial amount of the radioactive substance. For later purposes, we will call the initial amount P, which will stand for "parent nucleus." Similarly, D will be the initial amount of "daughter nucleus." For example, ${}^{14}_{6}\mathrm{C}$ is a parent nucleus, and ${}^{14}_{7}\mathrm{N}$ is a daughter nucleus. Suppose that P_t is the amount of the parent nucleus at time t. The time is then simply

$$t = t_0 \ln(P/P_t) \ . \tag{3}$$

Fine, except that we *don't* know the initial quantity of the parent nucleus. Luckily there is a circumstance in which we can know something almost as valuable: the *ratio* of the initial quantity of a radioactive *isotope* of a nucleus to a nonradioactive isotope of the same element. I'm talking, of course, about radiocarbon dating, which since its discovery in 1949 by Willard Libby and colleagues has been the workhorse for dates within historical times. We'll discuss this in a little detail (although it is restricted to timescales within about 50,000 years). For longer timescales, different nuclei can be used, but (with a couple of twists) it's the same process.

Carbon, with six protons, has a very common stable isotope (carbon-12), an uncommon stable isotope (carbon-13), and a moderately common unstable isotope (carbon-14). Neutrons in cosmic rays entering the Earth's atmosphere can interact with nitrogen to form this isotope:

$$n +^{14}_{7} \mathrm{N} \rightarrow^{14}_{6} \mathrm{C} + p \ . \tag{4}$$

The cosmic rays do most of their work at high altitudes, 9–15 km, but the carbon gets taken up in carbon dioxide and spreads around all altitudes and latitudes. Plants acquire it during photosynthesis, and animals acquire it by eating plants. The net result is that for living things there is an approximately constant ratio

$$n_{{}^{14}_{6}\mathrm{C}}/n_{{}^{12}_{6}\mathrm{C}} \approx 10^{-12} \ . \tag{5}$$

After the animal or plant dies, however, there is no additional intake of ${}^{14}_{6}\mathrm{C}$, so the ratio decreases steadily on the carbon-14 half-life $t_{1/2} = 5730$ years. As a result, measurement of the isotopic ratio (most sensitively using mass spectrometry) tells us the age of a given sample. In practice, ages beyond about 10 half-lives are inaccurate because there are so few carbon-14 nuclei left. However, within historical times this method is outstanding, and as I indicated before one can use other isotopes for longer times.

But what did paleontologists do before radiocarbon dating? They had another method available to them that gives good *relative* dates, but not such good *absolute* dates. This is the method of *stratigraphy*. Basically, one can look all around the world and see similar layers of rock in similar orders. Occasionally one sees other things as well: for example, around 66 million years ago, one finds a layer of iridium all over the Earth that is thought to have been deposited when the dino-killer asteroid hit. By comparing these layers, one gets a relative ordering of when the rocks were layed down.

Even if we can get the ages of fossils, though, what should we expect? For example, if nearly every animal is fossilized, then we would anticipate a clean, continuous record of life on Earth (and we'd have one heck of a lot of fossils!). To explore this, we need a little understanding for the conditions for fossilization.

Conditions for fossilization

In fact, it turns out to be extremely rare for life to become fossilized. In most cases, the animal/plant/bacterium/archean simply decays away. Even bones weather into dust pretty rapidly if they are exposed.

In most cases, it is necessary for the individual to be covered up with sediment as rapidly as possible (e.g., in a river bed). There are occasions, though, when conditions that prevent decay (dessication, low temperatures, or oxygen-free environments such as peat bogs) can preserve a fossil in pretty good shape for a while. Even in these circumstances, though, it is much easier to fossilize something with hard parts (e.g., bones or exoskeleton) than something that is purely soft (e.g., bacteria). These requirements tell us that fossilization is actually quite rare, and biased to boot: finding things that have skeletons is much easier than finding leaves, jellyfish, or whatever.

In detail, there are many different ways in which fossils can be formed. For example, empty spaces in an organism can fill with groundwater that then leaves behind minerals. This can lead to fossils with lots of fine detail. Something like a leaf can be compressed, which can change the leaf chemically. Sometimes trails or footprints are even fossilized. However, the takeaway message here is that fossilization is a lucky event that happens much more to some organisms than to others. The fossil record therefore needs to be examined with understanding of incompleteness and bias.

Fossils tell the story of life on Earth

The story told by fossils is a remarkably consistent one. Before about 550 million years ago, almost all organisms on Earth were single-celled. Some evidence of life can be traced back to about 3.8 billion years ago, but it tends to be indirect (e.g., based on chemical evidence rather than fossils).

About 550 million years ago, however, there was a burst of diversification of life. Now, when we say "burst", what we really mean is that over some tens of millions of years most of the basic body plans now used by life emerged, so "burst" may sound like we're overdoing it. However, when you compare it with the three billion years of single-celled life that preceded it, that's pretty fast! The most famous deposit of fossils around this time is in the Burgess Shale, a region in the Canadian Rockies. This stage in life's history is known as the Cambrian explosion, based on the geological era of the rocks in the Burgess Shale and elsewhere. From that point on, fossils of large animals and plants become more common, telling the story of the development of sea creatures first, then plants on land followed by insects, then early amphibians, reptiles and mammals, and birds. Anatomically modern humans appeared around a hundred thousand years ago.

Stated dryly like that, it is difficult to conceive of the vast stretches of time that are involved. We will therefore use a standard analogy. Suppose that we compress the entire 4.6 billion year history of the Earth into a single day, starting at midnight. The first life, which we assume to be 3.8 billion years ago, appeared at 4:10 AM. This may well have been basically as soon as it could have, given that the Earth was being pounded by large planetesimals prior to that. Then, however, there was a very long stretch in which, no doubt, the single-celled life was changing in many important biochemical ways. From our standpoint, however, nothing much occurred until the appearance of the first multicellular life, about 800 million years ago. That would put it at 7:50 PM(!!), most of the way through the day! The Cambrian explosion occurred at 9:08 PM. About 230 million years ago (10:48 PM), the dinosaurs appeared, and about 66 million years ago (11:39 PM), they checked out when a large asteroid hit. Anatomically modern humans appeared around 100,000 years ago (11:59:58), and all of our recorded history of about 6,000 years fits in the last 0.1 seconds!!!

Phrased this way, we really seem like an afterthought in life. Therefore, we can ask whether the fossil record accords with the expectations of evolution. Indeed it does: simple things appear first, for example, and you never get fossils of complex modern animals in rocks that are, say, a billion years old. For lineages with many fossils (e.g., our own ancestors), there are very well recorded transitions between types. In the late 1800s and through the first half of the 1900s, there was an interesting puzzle that kept cropping up, which is that very similar fossils were found very far apart on the globe. For example, fossils were quite similar in South America and Africa, or in Antarctica (of all places!) and Australia. To make a long and pretty interesting story short, it turns out that continents move around a lot in hundreds of millions of years, and indeed those pairs were part of one continent in the good old days. The theory of plate tectonics, which explains such movements, also explains the distribution of earthquakes and volcanos, and is the organizing theory of geology.

In addition, there are endless specific predictions that evolution makes. For example, according to the story laid out by fossils, birds split off from the dinosaur line long after mammals had split from reptiles. Therefore, one does not expect any transitional fossils between mammals and birds.

In contrast, one *does* expect transitional forms between fish and amphibians, or between amphibians and reptiles. However, as we noted earlier, most organisms never fossilize and therefore there will always be gaps. This is something often pounced on by opponents of evolution, who like to point to existing gaps and announce that they are impossible to bridge. As we noted earlier, though, this is a dangerous policy, because future discoveries can fill those gaps. We now discuss some of those "missing links" and how they were filled.

The issue of missing links

In a given lineage, it is possible that the fossil record contains only one individual in a stretch of millions or tens of millions of years (this is more and more likely for progressively more ancient fossils). This inevitably leads to gaps in the fossil record. We will examine two such cases: the evolution of whales, and the transition between fish and amphibians. Both, as it happens, are gaps that have been filled in very recently.

Whales, of course, are mammals that live their entire lives at sea. Although they don't get their oxygen from the water as fish do, they are otherwise superbly adapted for aquatic living. They are streamlined for swimming, their air holes are on the tops of their heads, they echolocate, and so on.

At the same time, however, there are features of whales that seem to point to a terrestrial origin. For example, some species have vestigial pelvises, occasionally one sees greatly reduced and nonfunctional hind limbs, and so on. Based on these and other features, in 1883 Flower suggested that whales might have descended from extinct ungulates (hoofed animals, with current examples being horses, pigs, sheep, etc.). Later, the hypothesis sharpened: whale ancestors were thought to be part of a specific group called artiodactyls (pigs, camels, cattle, hippopotami, etc.). However, this seemed to pose a problem: how would one get from carnivorous cows (or whatever!) to whales? At that time, transitional species were unknown. Indeed, by the mid-1980s there were still no transitional fossils along this line, leading to various bits of name-calling from anti-evolutionists.

However, in the past 20 years, there have been excavations (largely in Pakistan) that have revealed a wonderfully mapped out set of intermediate organisms, from *Pakicetus* 53 million years ago (which has an ear structure found only in modern whales) to *Ambulocetus* 50 million years ago (an amphibious creature much better suited for swimming than Pakicetus, and it could swallow underwater), to *Rhodocetus* 47 million years ago (with some transitional bone structure, e.g., a large pelvis fused to vertebrae), to *Basilosaurus* 40 million years ago (60 feet long, with vestigial hind limbs), to *Squaladon* 33 million years ago (the first fossil with a melon-shaped forehead, typical of creatures that echolocate). Many other examples exist as well. Basically, in the last 20 years or so this lineage has gone from having no transitional forms to one with a huge abundance. In every case, the evidence is consistent with gradual changes. For instance, starting with *Pakicetus*, the nasal openings go from the front of the nose, to the middle, to the top of the skull. Pretty impressive!

Another famous recent example is the transition between fishes and four-legged animals (also called tetrapods). Enormous numbers of fossil fish, amphibians, and reptiles had already been discovered. However, there were various gaps in the limb structure and ear regions between fish of about 380 million years ago, and the first clear tetrapods of about 365 million years ago.

Knowing that evolutionary theory predicted that intermediate forms should be found in rocks of intermediate age, Neil Shubin of the University of Chicago and his colleagues decided to do excavations in rocks on Ellesmere Island, Canada, that were of the right age. The team worked for five years, and were at the end of their funding, when they finally saw a remarkable skull poking out of a cliff. This was named *Tiktaalik* after the Inuktitut language for a particular fish. Indeed, the group found several such fish, and these were precisely the intermediate forms that they had expected.

These are, of course, not the only such examples! Every year brings new discoveries of fossils that fit well into the evolutionary picture. Note, also, that paleontologists don't just dig randomly and hope to find something. Like Shubin and colleagues, they go to places that are expected based on evolutionary and geological theory to have the greatest likelihood of containing the fossils that interest them. No authentic fossil has been found to conflict with the basic principles of evolution, which is really saying something given the tens of thousands of fossils that have been discovered!

This is the reason that I have taken you through these four lectures. Evolution is such a simple mechanism that it seems that once life gets going anywhere in the universe, evolution will cause adaptation. How far it would go in any environment, we don't know. As a result, we will now go into classes that discuss questions that are important for life in many environments. (1) What exactly is life, and how did it arise? (2) What are the environments in which life on Earth can exist? (3) How fragile is life; could it be snuffed out by a cataclysmic event?