Pre-Darwinian thinking, the voyage of the Beagle, and the Origin of Species

How did life originate? What is responsible for the spectacular diversity that we see now? These are questions that have occupied numerous people for all of recorded history. Indeed, many independent mythological traditions have stories that discuss origins, and some of those are rather creative. For example, in Norse mythology the world was created out of the body of a frost giant!

Some early attempts at scientific or philosophical discussion of life were apparent in Greece. For example, Thales (the earliest of the identified Greek philosophers) argued that everything stemmed ultimately from water. He therefore had a somewhat vague idea that descent with modification was possible, since things had to diversify from a common origin. Aristotle suggested that in every thing is a desire to move from lower to higher forms, and ultimately to the divine. Anaximander might have come closest to our modern conception: he proposed that humans originated from other animals, based on the observation that babies need care for such a long time that if the first humans had started like that, they would not have survived.

Against this, however, is the observation that in nature, over human-scale observation times, very little seems to change about life as we can see it with our unaided eyes. Sure, the offspring of an individual animal aren't identical to it, but puppies grow up to be dogs, not cats. Even animals that have very short generational times appear not to change substantially: one fruit fly is as good as another.

In the Western world at least, this observation combined with the Christian concept of perfected special creation to lead people to believe that all living things on Earth have existed in basically their same forms since they were created. As a result, throughout Europe in the Dark Ages and Middle Ages, there was essentially no thought about net development of species over time. Of course, in Islamic nations of the time (which were far more culturally and intellectually advanced), there were some discussions of the effect of environment on survivability and similar concepts that echo current evolutionary theory. However, Europe largely did not share in these ideas.

During the Renaissance and Enlightenment, it became more acceptable to break out of these modes of thought. For example, in 1750, Pierre Louis Maupertuis discussed how small changes between generations could accumulate into large changes given enough time, and even suggested that new species might arise. Incidentally, Maupertuis also made a major contribution to physics called the "principle of least action", which is an indication of how broad he was as an intellectual! Other people (e.g., James Burnett) agreed with this and even suggested that humans had descended from primates. Yet another thinker along these lines was Erasmus Darwin, Charles' grandfather.

Another major development occurred in the early 1800s via geology and paleontology. Georges Cuvier showed that mammoths were distinct from elephants and had gone extinct, which proved that extinction was indeed possible and thus opened the door for different organisms in the past than currently. Even more importantly, Cuvier, Charles Lyell, and others used their research and writings to demonstrate that the Earth has to be tremendously old. Lyell in particular was influential because he advocated the principle of *uniformitarianism*, i.e., that the Earth has changed its properties gradually rather than by the catastrophic events that were previously assumed to have produced mountains, facilitated extinctions, and so on. Ironically enough, both Cuvier and Lyell personally believed in the immutability of species and Lyell in particular was opposed to evolution, but the case he set out for an old Earth was ultimately one of the motivations for Darwin.

If change does happen, though, what could be the mechanism? Jean-Baptiste Lamarck proposed in 1809 that transmutation of species could be produced by individuals adapting to their environments *during their lifetimes*. For example, he believed that giraffes acquired long necks because they would stretch their necks to reach high leaves. Having done this, their progeny would start out with longer necks. This is *not* what we now think happened. In fact, when the Soviet geneticist Trofim Lysenko tried to apply these principles to farming (since he argued they were consistent with Marxist principles), he brought in multiple substandard harvests and set Soviet genetics back a generation. Other people during the next few decades proposed different ideas, some very close to what Darwin would suggest, but most did not recognize the true importance of their concepts and none provided observational evidence.

The stage was set for the entrance of Charles Darwin.

The voyage of the Beagle

Charles Darwin was born on February 12, 1809 in England, exactly the same day that Abraham Lincoln was born in Kentucky. His father was a medical doctor, and in his early years it appeared that Charles would follow in his footsteps. However, his time as an apprentice doctor in 1825 led to revulsion at the brutality of surgery (remember, they had no anasthesia at that time!). He then became interested in natural history and geology, but his father was disappointed with what he saw as a lack of direction and therefore enrolled Charles in a bachelor of arts program at Christ's College, Cambridge, to study for the clergy. After he finished his studies, he spent some time surveying rock strata in Wales. Then, in the fall of 1831, at the age of 22, he received a letter that was to change his life.

The letter was from Reverend John Henslow, a Cambridge professor of botany who had been very influential during Darwin's student days. It said that 26 year old Captain Robert FitzRoy, who was to lead the planned two-year voyage of the HMS Beagle to South America and elsewhere, had requested a gentleman's companion during the voyage so that FitzRoy wouldn't go crazy (as did the previous captain, who committed suicide!). After some twists and turns (Darwin's father thought it was a waste of time; FitzRoy himself almost rejected Darwin because Darwin's nose supposedly indicated a lack of resolve!), Darwin, FitzRoy, and crew set off on December 27, 1831.

The voyage itself lasted five years instead of two. At the beginning, FitzRoy gave Darwin a present of Charles Lyell's "Principles of Geology", which made the case for uniformitarianism and influenced Darwin greatly. Throughout the voyage, Darwin became gradually more convinced of the evidence for a large age of the Earth. More importantly for our purposes, he saw numerous small variations in different species, which put in his mind that these might have diverged from a common ancestor. Ironically enough, what was to become the most famous example of this (the many closely related species of finches on the Galapagos Islands) was a case where (1) Darwin misidentified a number of the birds, and (2) he didn't keep track of which specimen came from where. Luckily other people on the expedition kept better notes, and since Darwin sent all his samples back to England along the way specialists were able to examine them.

The voyage was long enough that Darwin had multiple important changes to his view of life and the history of Earth:

- Darwin began fairly convinced by William Paley's argument for special creation of each and every species. The classic Paley argument is that if one encountered a watch, one would know immediately that it had been designed by an intelligent entity because of its intricacy. Life is even more intricate, so the conclusion seemed obvious.
- However, during Darwin's travels he saw many closely-related species. For example, Darwin's finches are 13 different species that have different sizes, beak lengths, etc. but are otherwise very close indeed. He began to wonder: why would individual special creation be requred for each of these, when he knew from first-hand experience that artificial breeding could produce radical changes in a relatively short time? Consider, for example, how diverse dogs are (Darwin actually used pigeons for his example, but geez). Chihuahuas are rather different from Great Danes, but they come from a common ancestor. Could nature have done the same thing over longer timescales? Darwin also saw many extinct forms that were close to living species.
- Another input to his views was that he saw many geological formations and occurances (including an earthquake) that were in accord with Lyell's uniformitarianism. This was important because it implied that the Earth has been around for a long time, thus allowing life to develop much more than it would otherwise.

When Darwin returned to England, he found himself a scientific celebrity because

Henslow had allowed key naturalists access to the specimens Darwin had sent back as well as to his letters on geology. One of those naturalists was Richard Owen, who identified many of the fossils Darwin had found but was later to become one of his bitterest enemies. For the moment, though, Darwin was the toast of scientific England.

The Origin of Species

We now skip forward about twenty years. The subject of transmutation of species was one that met with significant emotion, because to some it suggested that somehow the initial creation was incomplete. Other people proposed ideas to try to bridge the gap, e.g., Lyell suggested a "law of succession" in which mammals would be replaced by similar mammals (still specially created) on each continent. However, those who proposed actual transmutation (e.g., the anonymous author of the November 1844 publication "Vestiges of the Natural History of Creation") were met with a storm of protest. Darwin had been sensing such problems for a while, and indeed in 1837 had begun keeping a secret notebook in which he put his own speculations. His concern kept him from publication, because he wanted to amass more and more evidence and answer all the objections he could conceive.

However, on June 18, 1858, he received a paper from Alfred Russel Wallace that described natural selection in a form very similar to Darwin's. Darwin had had correspondence with Wallace before and knew that Wallace was thinking about the introduction of species, but was stunned by how closely Wallace anticipated many of Darwin's own idea. Darwin then suggested to Wallace that their papers be presented jointly at a conference, and they were, but neither was able to attend in person. The presentations sank without a ripple, with the only review being that of a certain Professor Haughton of Dublin: "all that was new in them was false, and what was true was old."

Darwin then worked hard at a book on his findings, and on November 22, 1859 he published "The Origin of Species" (actually an abbreviation for its long title). It is a long book, with many detailed arguments, but the thesis is set out in the introduction:

"As many more individuals of each species are born than can possibly survive; and as, consequently, there is a frequently recurring struggle for existence, it follows that any being, if it vary however slightly in any manner profitable to itself, under the complex and sometimes varying conditions of life, will have a better chance of surviving, and thus be naturally selected. From the strong principle of inheritance, any selected variety will tend to propagate its new and modified form."

His conclusion is poetic enough to include as well:

"There is grandeur in this view of life, with its several powers, having been originally breathed into a few forms or into one; and that, whilst this planet has gone cycling on according to the fixed law of gravity, from so simple a beginning endless forms most beautiful and most wonderful have been, and are being, evolved."

Reaction to the Origin

Reaction by the public and the scientific community was swift. All 1,170 copies of the first printing were purchased on the very first day, and a new run of 3,000 copies were quickly bought out after their release on January 7, 1860. This was rather a surprising reaction, but it indicated the thirst for understanding of life's development.

Although the Origin did not explicitly discuss human evolution, the implications were clear and immediately divided the scientific establishment. Owen, Lyell, Darwin's old mentor Haslow, and many others took theological exception to the "men from monkeys" implication, as did the Church of England. However, liberal theologians and many of the younger scientists saw this as a beautiful way for one or a few initial forms to diversify. Indeed, there is some (disputed) evidence that Darwin himself looked at this mechanism as the way God did things, as opposed to a substitute for a creator.

Conflicts have never ceased since, but the most famous of the confrontations of the early days was that between Samuel Wilberforce (the Bishop of Oxford) and Thomas Huxley, a biologist who was to become known as "Darwin's bulldog". At a debate at Oxford in 1860, "Soapy Sam" (known as such for his rhetorical slipperyness) finished a sarcastic condemnation of Darwin by asking Huxley if he was descended from monkeys on his grandfather's side or his grandmother's. According to legend, Huxley muttered: "The Lord has delivered him into my hands" and replied that he "would rather be descended from an ape than from a cultivated man who used his gifts of culture and eloquence in the service of prejudice and falsehood". This probably didn't really happen, but it stands as an important tale of the importance of basing scientific arguments on evidence, right up there with Galileo supposedly whispering "and yet it still moves" after being forced by the Catholic Church to renounce Copernicanism.

Darwin went on to produce six editions of the book. He also wrote "The Descent of Man" to discuss human evolution, as well as more specialized books on orchids and worms. He was buried in Westminster Abbey near Isaac Newton, properly honored as one of the greatest scientists in history.

Subsequent development of evolution

Given that biology is by far the largest of the sciences in terms of number of participants, and that evolutionary biology is its most important synthesizing component, we can hardly give a fair summary beyond a few highlights.

One critical issue left unresolved by Darwin was the actual mechanism of heredity. This was demonstrated first by the Austrian monk Gregor Mendel, who did a famous series of experiments on pea plants that established patterns of heritability. He is therefore considered by many to be the father of genetics. His work, although published in 1866, languished in obscurity until 1900. At that point, two people (Hugo de Vries and Carl Correns) discovered the patterns of heredity independently of each other and of Mendel. Being good scientists, both searched the literature, both found Mendel's 1866 publication, and both credited Mendel with the discovery. All in all, that's a pretty unlikely series of events! Nonetheless, Mendel now had credit for his discoveries.

For a few decades, though, Mendel's work was considered to conflict with Darwin's idea of gradual small changes because genetic changes can be abrupt (e.g., eye color can change radically from one generation to the next). All this was, however, resolved in what is now called the "modern evolutionary synthesis". Basically, genes regulate the individual, and genes are what change from generation to generation.

Now the pace of molecular and evolutionary biology is truly fantastic. The full genome (i.e., sequence of molecular rungs in the ladder of DNA) has been sequenced for humans as well as for a rapidly growing list of other animals, plants, bacteria, and archea. This has in fact become so common that DNA analysis is regularly used to evaluate guilt in crimes as well as parenthood.

In summary, although the current view of evolution is vastly more sophisticated than Darwin could ever have imagined, the basic principles have been tested over and over again for more than 150 years and the theory has passed every single time with flying colors. We will discuss some of the evidence for evolution in the next lecture, but first we will discuss some of the misunderstandings that are unfortunately common about evolutionary ideas.

Common misconceptions about evolution, and how it really works

The *fact* of evolution is straightforward: forms of life change over time, via descent with modification.

The basic principle of the *theory* of evolution is also easy to state: **the characteristics of a population are most strongly influenced by the individuals who leave the most viable offspring**. This seems so uncontroversial as to be almost tautological, but there is a lot of confusion about what evolution means. Admittedly, most of the confusion is promoted by people who feel that evolution threatens their worldview in some way, but there can be honest misunderstanding as well. Most of this part of the class will therefore be a discussion of some common misconceptions, but first let's break evolution into a two-step process:

- Variation. Some variation is needed to produce changes that can lead to better adaptation. Mutation is an example: when a new organism is created, there are sometimes errors in transcription of DNA. Sex is another: both parents contribute part of the genome, and mixing of characteristics can produce surprising differences sometimes (e.g., very tall children from ordinary-height parents). At the single-celled level there are other less-familiar mechanisms, such as horizontal gene transfer, in which an organism gets part of its DNA or RNA from a separate organism (one mechanism for this is movement of the DNA by a bacterial virus, which suggests that viruses may have a profoundly important role in evolution). Another example is the incorporation of entire cells (which is thought by some to be the origin of the organelles in cells, e.g., mitochondria, which have their own separate DNA).
- Selection. Any time you have variation in a population, some individuals will produce more viable offspring than others. This isn't completely related to genetics, either: environment and luck play significant roles. However, if there are characteristics that make it easier to pass on genes, those characteristics will become more common in the population. Note that both "natural" selection (whether something survives to reproduce) and sexual selection (whether the individual can find a mate, in sexually reproducing organisms) play a role. Note also that except for the simplest characteristics there are tradeoffs: being able to run 40 miles per hour would obviously be advantageous to humans, but putting developmental energy into such fast running would take away from other abilities we would have, so the net result could be negative. Finally, note that there are many variations that have zero or negligible impact on reproductive success at the moment, but can later play key roles because of the genetic diversity they produce (this is called "neutral drift"). The importance of neutral drift is becoming more and more evident; variations need not all be beneficial to be propagated to the next direction.

The "Understanding Evolution" site at Berkeley (http://evolution.berkeley.edu/evolibrary/) summarizes the process as variation + differential reproduction + heredity = natural selection.

Now let's address some misconceptions.

Misconception 1: Evolution is incompatible with religion or leads to bad behavior.

This is the big one, and it is at the basis of a never-ending series of attempts to kick evolution out of classrooms or raise invalid doubts about it. Fundamentally it comes down to two concerns that are raised. If I accept that evolution has occurred, do I have to be an atheist? Also, if we agree that we are descended from other animals, does that mean we have no ethical guides and therefore can or should act animalistically?

Even for people who think that atheists are automatically awful, the first concern can be dismissed easily: there are endless biologists and other scientists who are religious and also accept the overwhelming evidence for evolution. One can also go the other way. For example, check out
http://www.theclergyletterproject.org/
This has links to a number of letters that have been signed by ministers, rabbis, etc. (12,945 Christian clergy at last count!). The statement supports science in general and evolution in particular; for example, part of the Christian clergy letter says "We believe that the theory of evolution is a foundational scientific truth, one that has stood up to rigorous scrutiny and upon which much of human knowledge and achievement rests." There are representatives of all denominations in this letter, including fairly fundamentalist ones such as Southern Baptists. Think about this when you see people claiming that you can't be a good Christian if you accept evolution!

The second concern is also dealt with straightforwardly. Evolution, like any scientific concept, is a description of what *is*. It is *not* a guide to what *should be*. In other words, it is most definitely not something that should be used as a guide to human behavior. To make this clearer, suppose we use an analogy. Gravity is something that definitely exists. As with evolution, we can distinguish the factual part (things fall) from theoretical models of gravity (Newton's laws are generalized by Einstein's general relativity, and in the future we hope to have a theory of quantum gravity). However, suppose that someone says to you "Since gravity makes things fall, I am required to push old ladies down flights of stairs." Would your reaction be to blame gravity and curse Isaac Newton? I hope not! Gravity is simply a fact of the universe, and evolution is as well. You need to draw your behavioral guides from some other source (for example, your upbringing, or observations of how people interact, or religion).

Some people have gone even further in trying to attack evolution, e.g., by alleging that the Holocaust came from Darwinian principles. Given that Hitler never mentioned Darwin in Mein Kampf (not once!), and that unfortunately anti-Semitism and even massacres were common many centuries before Darwin was born, this is also emphatically not a conclusion that can be drawn.

Misconception 2: Evolution has never been observed.

As we'll see especially in the next lecture, this is entirely false! Most people who say such a thing are influenced by Misconception 1. To the degree that there could be honest misunderstanding, though, one possible source of confusion could be that many people don't have a good sense for the types of changes that they would expect, and thus by adding these incorrect expectations they think they see inconsistency with observations. For example, people may not understand how many generations it takes to produce significant evolutionary change. As a result, they think that in the past few thousand years one would have expected to see cats turn into dogs, or something of that magnitude.

In reality, the fossil record and even experiments in the laboratory with bacteria and viruses have demonstrated evolution beyond question. We'll cover this in great detail in the next class.

Misconception 3: Evolution is random.

Now we pass from concerns that are emotional to ones that are often the result of genuine confusion. It is often said that evolution is random, and this is true in the sense that there is no final goal in mind. It is also true that mutations, which drive some but not all of the variability on which evolution acts, are basically random (it is actually the case that some parts of the genome are copied with greater fidelity than others).

However, the critical aspect of evolution that allows it to be so effective is that there is much more to it than pure randomness! Natural selection, in fact, is the opposite of randomness: individuals that are better adapted to their environment have a better chance of leaving offspring. These offspring inherit many characteristics of their ancestors, so in fact there is a strong drive towards better and better adaptation. This natural selection works on the variations produced by mutation and other mechanisms to produce evolution.

An example may help make this clearer. Suppose that we have a bank vault that is protected by a combination lock that has 100 dials that go from 0 to 9. If we try to break into the vault by spinning the dials again and again, and if only the right combination has any effect at all, we would expect to spin the dials 10^{100} times to have a decent chance of breaking in. At once per second, we would only get through about 4×10^{17} combinations in the current age of the universe, so obviously we'd have no chance.

However, let us say that the lock has a flaw such that if any one of the numbers is the right one, the dial sticks right there. Then on the first set of spins we'd expect to get 10 right numbers. On the next set, we only have 90 to spin, and we'd expect to get 9 more right numbers. At one set of spins per second, we'd have it all right in less than a minute. This, in a simplified way, is the power of natural selection. Any time a change leads to an advantage (defined as always in terms of leaving more viable offspring), that change tends to be incorporated into the population. Over long times (and remember that we have billions of years to play with!), this can diversify into the remarkable richness of life we have on Earth.

Misconception 4: Evolution is about the ladder of progress

Quick quiz: which is more evolved, a human being, or a current-day E. coli bacterium? We are tempted to answer that it is the human, and at first glance this seems entirely reasonable. We have many cells that do many different things, and the cells themselves are fairly large and complicated, with nuclei and various organelles that carry out sophisticated biochemical tasks. In contrast, bacteria have but a single cell, which doesn't even have a nucleus! How can anyone doubt that we are more evolved?

This, however, is not the most productive way to look at things. It is true that the E. coli is surely much more similar to the organisms that existed 2 billion years ago than we are (for example, at that time there was no multicellular life). However, the perspective we need to adopt is that evolution is all about reproductive success. In practice, this means that there are effectively a large number of ecological niches, and every organism adapts over time to best fill those niches. Note also that the niches can change, sometimes radically. A familiar example is that during the roughly 150 million years that dinosaurs roamed, mammals were essentially rat-sized things that mainly hid. When the asteroid hit 66 million years ago and killed off the dinosaurs (except for those that evolved into birds), luckily for us some mammals survived, and within a few million years we had the largest land mammals ever, e.g., 20 foot tall sloths! The death of the dinosaurs and other changes had opened up a niche that was filled, eventually, by evolving mammals.

With this perspective, we can understand that every current species of life on earth is *equally* evolved in the sense of adapting to their various niches. There are, of course, some niches that change fairly slowly, which is why current-day sharks are basically the same as their ancestors of nearly 300 million years ago. Really rapid evolution can occur when the time between generations is small and the environment changes rapidly. For example, nylon, a completely artificial substance, was invented in 1935. By 1975, scientists discovered bacteria that could metabolize some byproducts of nylon manufacture (which, to drive the point home, had never before been seen on Earth). The three main enzymes used by the bacteria are completely novel. A more tragic example is seen in the development of diseases; for example, HIV has developed new biochemical pathways in the last few decades.

Misconception 5: Natural selection involves organisms "trying" to adapt or getting what they "need"

This is sometimes phrased in a different, way, such as "It would obviously be advantageous for humans to be able to run 40 mph [the speed of an ostrich, the fastest two-legged animal]. Since we can't, evolution has clearly not applied to humans."

What is behind this misconception is that in some sense we want to think about organisms controlling their destiny. Indeed, in this idea we see echoes of Lamarck's concept that, e.g., giraffes stretch their necks to get at high leaves, so their offspring will have longer necks.

However, this isn't how evolution works. The variations produced by mutations are entirely random, meaning that if some of them make it easier to leave viable offspring that's great, but there is no direction or plan. Sexual selection can be directed by intelligent enough organisms (i.e., humans!), but there are enough complicated things going on in our genomes that there can be unintended negative consequences. For example, hemophilia is a very rare blood disease in which clotting is ineffective, so if you get a pinprick you are in danger of bleeding a lot. It happens in perhaps 1 in 5,000 males (and fewer females), but in the mid to late 1800s it was highly prevalent in the royal families of Europe due to many generations of inbreeding! Overall it's better to have a wide-ranging genetic population.

We can therefore say that evolution gropes blindly in innumerable directions at once, rather than seeing a goal. Some of those directions are advantageous, and thus naturally larger numbers in the population go that way.

Misconception 6: Some structures have been demonstrated to be too complex to have arisen one small step at a time.

Given that evolution proceeds one small step at a time, without foreknowledge of the goal, and that all the myriad steps have to be at worst neutral in selectability, how can one explain the origin of complex structures such as the eye? This is an argument that goes back to William Paley in 1802, but has been recently resurrected as a "new" argument by opponents of evolution.

Michael Behe, one of the more prominent members of the anti-evolution movement, has phrased this as an analogy. Consider a standard mousetrap: it has five essential components (a base, a hammer, a spring, a catch, and a metal bar to hold back the hammer). If any of these are removed, one has a non-functional mousetrap. Now, says Behe, consider any number of biological structures such as the eye, or more obscurely, the bacterial flagellum. These have many interleaved components and removing any of them prevents functionality.

Essentially, Behe and others like him are promoting a disguised version of the classic "God of the gaps" approach. What this essentially says is that if we don't *currently* understand how something happens, God must have done it and we should stop investigating. This is unproductive scientifically (why should we cease searching?), and dangerous theologically because if your religion relies on there being no other explanation for a phenomenon but then an explanation is obtained, your faith is weakened.

Indeed the complexity argument poses no problems to evolution, because the fundamental assumptions of people such as Behe are misguided in two important ways. The first is to note that although our eyes are very sophisticated, there are examples throughout the animal kingdom that range from simple light sensors to eyes that are arguably better than ours (e.g., octopus eyes, which don't have a blind spot on their retinas). Having a sensor that tells you if it is light or dark is better than having none; having one that tells you the direction of the light is better than one that can't; having one that can discriminate colors is better than having one that can't; and so on. For example, although my eyes are far from perfect, even without glasses I'll happily accept my out-of-focus vision in preference to complete blindness! The same thing is true with Behe's favorite example of flagella (these are the hairlike things that can propel bacteria and archea). Looking throughout the bacterial and archeal domains, one finds that many of the proteins that Behe thought critical are absent in a number of cases, and there are major differences between bacterial and archeal flagella that prove that there is more than one path that can be taken.

The second point is that Behe's approach has the implicit assumption that evolution was somehow "aiming" towards a given complex feature, in contradiction to our discussion about the previous misconception. What I mean by that is that he is effectively assuming that if the system can't function as its final goal, it's useless. This, however, is emphatically not the case, as has been demonstrated in endless laboratory and computer experiments. For example, consider the mousetrap. Maybe if we remove all but the spring and hammer we don't have a functioning mousetrap, but we could use it as a tie pin. For the bacterial flagellum, parts of the system are extremely similar to other aspects of the bacteria, and much simpler, which thus provide stepping-stones to more complicated structures.

Evolution is opportunistic, and works with what it can get. This is one reason why there are many *non-optimal* structures in nature. A classic example is the thumb of the giant panda. This is a clumsy structure that the panda uses to strip off bamboo. If one designed this from the start, one would use a much more efficient system. However, the panda's ancestors were carnivorous, and when the environment changed and they adapted to a new diet, they used the claws they have.

In summary, evolution is a profound and elegant mechanism, and in broad sweep it isn't that difficult to understand. Of course, to be scientific it has to confront data, and there may well be no theory that has done that more successfully, with more diversity, than evolution. In the next lecture we will discuss the fossil evidence and evidence from experiments and molecular genetics.