EVIDENCE FOR EVOLUTION

WHAT IS EVOLUTIONARY THEORY?

Why are there so many kinds of organisms? Why do animals, plants, fungi, protists and bacteria look the way they do? Why do they behave the way they do? Why do some otherwise very different organisms have similar morphologies or behaviors? Conversely, why do otherwise very similar organisms have remarkably different characteristics? These are some of the major questions of biology. They explore the match between organisms and their environments, as well as how and why populations change over time. ***Evolutionary theory explains the diversity of life***. It does not explain the *origin* of life, but the *diversity* of life.

The **conceptual framework of evolutionary theory is made up of three interrelated parts**:

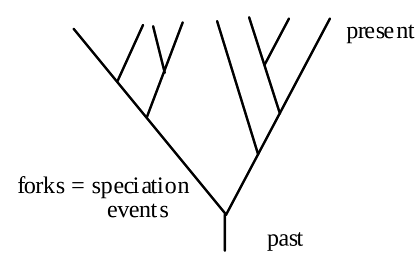

Figure 1: Shared Ancestry

1) **Organisms have a shared history—shared ancestry**
   - ? All species come from other species, with a history of common descent with genetic modification. This is Darwin's "descent with modification" (although this idea was not new to Darwin; it was well established by the 1830's). This idea can be visualized as a branching tree of life (Figure 1).
     - o In general, this is what is meant when the term evolution is used.
2) **The causes (or mechanisms) of evolution**
   - ? What causes evolutionary change?
   - ? These are known to be natural selection, genetic drift, and gene flow acting on genetic variation (produced by mutation) within a population.
3) **The specific pathways evolution has taken**
   - ? What has been the history of life?

MODERN EVOLUTIONARY BIOLOGY

There are two aspects of evolution today. First, ***evolution is the organizing principle for all of biology***. Just as you are descended from your parents, and your grandparents before them, and so on, all living organisms today are descended from organisms that lived in the past. Understanding how and why these ancestor-descendent lineages have changed through time helps us appreciate the diversity of life we see today. Genetics, anatomy, physiology, neurology, morphology, and behavior—all of these aspects of living organisms have evolved through time. The study of the evolutionary processes that produced these traits provides the comprehensive framework for understanding them. Without evolutionary theory as a guiding framework, biology is just a collection of facts. As Theodosius Dobzhansky said in his 1973 paper in American Biology Teacher (titled "Nothing in biology makes sense except in the light of evolution"):

> "Seen in the light of evolution, biology is perhaps, intellectually the most satisfying and inspiring science. Without that light, it becomes a pile of sundry facts—some of them interesting or curious but making no meaningful picture as a whole."

Second, ***evolution is also a dynamic field of research*** (evolutionary biology). In general, evolutionary biologists have two overarching goals:

1) to understand, in detail, the ***causes of evolution*** (the field of microevolution), and
2) to discover the ***history of life on earth***—how, specifically, are taxa related to each other (the field of macroevolution).

These two aspects of modern evolutionary biology correspond to the three parts of evolutionary theory. *That all organisms have a shared ancestry (have evolved) is the organizing principle in biology.* This idea is considered established (very well-confirmed) and is no longer the subject of scientific debate or inquiry. *The second and third parts of evolutionary theory (causes and pathways) are the focus of the modern science of evolutionary biology.* Why is the first part of evolutionary theory (shared ancestry) not a focus of current scientific investigation? Why is it considered factual (very well-confirmed)? Simply because the amount of evidence amassed in the past century and a half for a shared ancestry of all organisms is so overwhelming that it is no longer considered an issue. In addition, no evidence disputing this idea has ever been found.

EVIDENCE FOR EVOLUTION (SHARED ANCESTRY)

Darwin collected an abundance of evidence for common descent. After Darwin published his ideas, the scientific community accepted the idea of evolution (shared ancestry) relatively quickly, although it was decades before they were convinced of his proposed mechanism of evolution, natural selection (mostly because he did not have a plausible explanation for inheritance).

Just because scientists no longer debate the issue of shared ancestry, does not mean that it is not worth understanding **why** it is no longer debated. In other words, it is worthwhile to convince yourself (and your students) of the fact of shared ancestry by investigating the evidence.

Note that evidence for a historical idea like shared ancestry is historical in nature. Scientists use a method of induction, called the method of hypothesis, which is also called the ***inference to the best explanation***. In this method, one assumes a hypothesis for the sake of investigation, and then asks what would follow if the hypothesis were true. In other words, one makes a prediction from the hypothesis. This prediction, which can be a prediction of a future event, but also can be a *retrodiction of past phenomena*, is then tested against the empirical world. This is done for several competing hypotheses, and the hypothesis that is best able to explain the observed pattern of data, gathered either through experimentation or through historical means (e.g. fossils, patterns among current species, etc.), is accepted as the best explanation.

Since students are used to thinking about hypothesis testing only in the form of an experiment, it is worth taking the time to instruct them on historical types of hypothesis testing, which includes examining patterns and the clues left behind[1]. Both hypotheses: 1) species are static and unchanging, and 2) species are related through common descent, make clear predictions about patterns of data. ***Examining the predictions of these two ideas against the available evidence has led scientists to infer that common descent is the correct hypothesis***.

[1] This is the very same method that criminal detectives use when investigating a crime. This can be a very effective analogy to use with students, since they intuitively understand how a detective uses clues found at the scene to piece together what happened, even if they weren't there to see it happen.

There are several basic lines of evidence for evolution. The reason that scientists view this evidence as so convincing (besides the sheer vast quantity of it) is that *each of these lines of evidence is **predicted** by evolutionary theory*. In addition, *these lines of evidence are **independent** of each other*. One line of evidence does not depend on another. That they all corroborate with the same biological explanation (shared ancestry) is extremely convincing.

Biogeography

Biogeography is the study of how species are distributed spatially across the landscape (geographically). ***How species are distributed provides evidence for evolution***. The distribution of many species does not make sense, unless they shared a common ancestor. For example, if species were static (unchanging), then you would expect to find the same species in areas with similar environmental conditions around the world. Evolutionary theory, however, predicts that modern species should be found close to where their ancestors were, regardless of the environmental conditions. This is the major type of evidence that convinced Darwin.

Darwin collected many animal and plant specimens, as well as fossils during his voyage on the Beagle. It turned out that the South American fauna were quite different from the European fauna that Darwin was used to. It also turned out that the fossils he found in South America were very similar to the living animals he had collected. Why should a unique set of animals be found in the same place as what appeared to be related fossils? The best explanation for this pattern is that the extant South American species had descended from the now extinct fossil species.

A particularly clear example of how the current distribution of species provides evidence for shared ancestry can be seen on islands. *Evolutionary theory predicts that islands that have similar environments, but are in different parts of the world, will <u>not</u> be populated with the same species*. Instead, these islands should be populated with plant and animal species that are closely related to the species on the nearest mainland, even if the environment there is very different from the island. This is what is seen throughout the world. For example, the Galapagos Islands off of the coast of Ecuador, South America, are volcanic and barren. These islands are not populated with species from other volcanic islands around the world; instead, they are populated with species that are related to those found in the nearby lush tropics of South America.

This pattern is predicted by evolutionary theory: newly formed geographically isolated islands are populated (by migration events) with plants and animals from the nearest mainland. These populations then adapt to the new environments on the islands, and reproductive isolation (i.e. speciation) eventually results. Subsequent migration from island to island within the archipelago leads to further adaptive changes and to additional speciation events. This pattern of migration to new habitats, adaptive evolution in response to novel environments, divergence from the ancestral population, and ultimately the formation of distinct species, is especially apparent on islands. For this reason, island chains like the Galapagos provide us with convincing evidence for shared ancestry. *That different species on these islands have a shared history is the best explanation for their geographic pattern of distribution.*

Fossil record

Another line of evidence for shared ancestry includes various aspects of the fossil record. Since rocks are laid down sequentially, with older rocks laid down before, and thus below, younger rocks, the chronological sequence of organisms can be inferred from where the fossils are found. ***The chronological order of the major groups seen in the fossil record shows a succession of species that is predicted by evolutionary theory***. For example, prokaryotes, according to numerous independent lines of evidence, are thought to be the oldest group of organisms. Thus, evolutionary theory predicts that fossil prokaryotes should appear before (and therefore below) eukaryotes. This is what the fossil record shows: prokaryotes are found in older rocks than are eukaryotes. Likewise, fish appear before amphibians, which appear before reptiles, which appear before mammals; all as predicted by evolutionary theory.

Also as predicted, ***the fossil record shows transitions (links) between groups, which are evidence that these groups have a shared history***. For example, mammals are thought to have evolved from a reptilian ancestor, and this transition is thoroughly documented with a series of fossil skulls (reptiles ✍ mammal-like reptiles ✍ reptile-like mammals ✍ mammals). There are also examples of transitions/links between fossils and modern species (two exceptionally well-documented cases include horses and humans). Likewise, the newly discovered whale fossil with hind limbs is a link between modern whales and their hypothesized terrestrial ancestor.

Similarity

Evolutionary theory predicts that, if all organisms have a shared ancestry, then all living things should have certain characteristics in common. The genetic code (genes and how their protein products are coded) is universal—all plants, animals, fungi, bacteria and protists have the same genetic code. There is no chemical reason for the specific code that we have (i.e. the genetic code is not chemically constrained to be the way it is). Another code would have worked as well. Nor is this the only way that information can be transferred from one generation to the next. The genetic code that all organisms now have, just so happened to be the one that the ancestor of all living things had. The fact that all organisms share this code reflects this historical legacy and provides evidence that all living taxa shared a common ancestor at one point in time.

There are two patterns of similarity in traits among species. The first type is an **analogous similarity,** which is when a *trait in two different species is similar and they have the same function*. The other type of similarity is **homologous similarity,** which is when *two traits are similar, regardless of the function of the trait*. In this case, two traits are similar even when it is not functionally necessary for them to be similar. The best explanation for this pattern of homologous similarity is that the traits are similar because of a common history of the two species. In other words, two species have the same trait because the common ancestor of the two species had the trait. For example, all vertebrate embryos look very similar during the earlier stages of development, including having gill pouches and tails. Thus, a reptilian embryo, a bird embryo and a human embryo look very similar, even though they develop into very different adult organisms (Figure 2)[2]. The best explanation for this similarity in embryos is a shared history of vertebrates—all vertebrates share a common ancestor that had a tailed embryo with gill pouches.

[2] Figure from Kerry Foresman

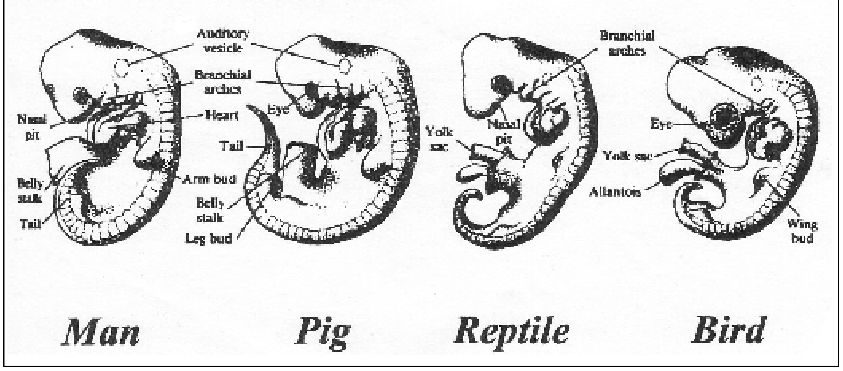

Figure 2: Homologous Similarity Among Vertebrate Embryos

Evolutionary theory predicts that different species will evolve different forms of shared (homologous) traits. As lineages of organisms expand their ranges to new environments, they adapt to function in those new environments. The similar traits that different populations inherited from their common ancestors may be modified and diverge from each other (due to different environments). Thus, a shared (homologous) trait may diverge in form among related taxa. For example, all vertebrates have forelimbs made up of exactly the same bony elements. However, these elements have been greatly modified in different species for different functions. If organisms have evolved, then comparative studies of the morphology of these organisms should reveal evidence of shared ancestry. The fact that bird wings and mammal limbs (for example) share the same basic structure and bony elements provides convincing evidence that these animals share a common ancestor. Thus, homology provides evidence for shared ancestry—it provides glimpses into the shared ancestry of organisms today, and how they have diverged from their ancestors in the past.

Along the same lines, **vestigial organs** are structures that are currently of little use to the organism (i.e. they have no known current function). *They are the historical remnants of structures that did have a function in earlier ancestors, and provide evidence for shared ancestry*. Whales, for example, do not have hind limbs, but some whales have the vestiges of a pelvis and leg bones. The best explanation is that these pelvic and leg bone vestiges are homologous to all vertebrate pelvises and leg bones. This means that the ancestors of whales had complete structures, and that they have been greatly reduced in whale evolution.

Evolutionary theory also predicts that different organisms will independently evolve similar solutions to the same functional problem (analogy). For example, the wings of bats, birds, and insects all serve the same basic function (flight) and are similar in appearance. They are not similar because of shared ancestry (the common ancestor of bats, birds and insects did not have wings), but because they serve the same function. In another example, plants in the cactus family are only found in the New World. However, they are very similar in appearance to plants in the euphorb family, which are only found in the Old World. These two plant families are not closely related, yet they have very similar traits (e.g. thorny spines and highly reduced leaves). They do not share a common history; instead they share a common environment (hot, dry desert), to which they each have independently adapted similar traits. Another term for this is *convergence* or *convergent evolution*. The existence of similar characteristics in taxonomically different taxa with similar environments can be evidence for adaptive evolution (i.e. evolution by natural selection), if the similar characteristics function in similar ways to the shared environmental conditions.

Imperfect Adaptations/Contrivances

Evolutionary theory predicts that some traits will not be "perfectly" adapted. Natural selection (the only evolutionary mechanism to produce adaptations) does not "start from scratch" when a new functional challenge is presented. If it were able to start from scratch, we should expect to see nothing but perfection in adaptation. But since natural selection acts on the genetic variation that is currently available in a population, the "best" solution cannot always be found. Often, existing traits are modified ("contrived") to serve a new function. The giant panda's thumb, a modified wrist bone, is one famous example of a clumsy adaptation contrived from an existing trait.

Another example of an imperfect adaptation is the vertebrate eye (including our own). The design of the vertebrate retina is "inside-out." The retina is behind the nerves that form the optic nerve. Where the optic nerve leaves the eye, there is a hole, which results in a blind spot. There is no functional reason for our eyes to be this way; the best explanation is historical—a "better" retina was not available in the common ancestor of all vertebrates. In the eyes of some mollusks (squids and octopuses) the retina is in front of the optic nerve, and thus they have no blind spot. Their ancestors happened to have the structures that could be modified into functional eyes without the design compromise of a blind spot.

RESOURCE LIST

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LESSONS ABOUT THE EVIDENCE FOR EVOLUTION

General lessons on evidence:

Segue from a nature of science unit into a general lesson on evidence in science. A general activity on weighing evidence can be found at the ENSI site: "**The Flat Earth**." [[www.indiana.edu/~ensiweb/lessons/flaterth.html]] Also check out PBS' Evolution website for a lesson about evidence from students' own lives "**Leaving a Trail of Evidence**." [[www.pbs.org/wgbh/evolution/]]

An important point to emphasize throughout the school year is the idea that evolution is a unifying theme in biology. One way to do this is to ***continuously refer to evolution*** throughout your course. For example, when you are talking about cellular structure, mention "this cell has evolved this structure…" Constantly use the phrases, "…has evolved" "has adapted." Try *not* to refer to "develop" (unless of course you are teaching about development…), as in "this species has developed this trait."

Also check out the PBS evolution series, episode two ("**Great Transformations**") and the video "**Learning and Teaching Evolution,**" [[www.pbs.org/wgbh/evolution/educators/teachstuds/svideos.html]] which is a companion to the series that contains short, seven-minute segments for use in the classroom. Segment three of Learning and Teaching Evolution ("**How Do We Know Evolution Happens?**") as well as episode two "Great Transformations" both use whales as an example of using different lines of evidence to understand evolution.

Biogeography:

The UCMP website has a nice (but complex) activity on island biogeography in which the students use real data for real species: "**Island Biogeography and Evolution: Solving a Phylogenetic Puzzle Using Molecular Genetics**."

[[www.ucmp.berkeley.edu/fosrec/Filson.html]] The PBS' Teacher's Guide [[www.pbs.org/wgbh/evolution/educators/teachstuds/tguide.html]] also has a lesson on the effects of saltwater on seed germination that re-creates one of Darwin's experiments: "**Seeds at Sea**." Go to the online Teacher's Guide, click on "download PDF" under Unit 2: Who Was Charles Darwin?

Fossil record:

The UCMP website has a collection of activities on various aspects of the fossil record, called "Learning from the Fossil Record" [[www.ucmp.berkeley.edu/fosrec/Learning.html] "**Sequencing Time**" and "**What Came First**" are companion activities to understand the sequence in the fossil record. Other lessons include "**Determining the Age of Rocks and Fossils**" and "**Fossilization and Adaptation**," both of which explore just what a fossil is.

ENSI also has a lesson on whale transitional fossils: "**Becoming Whales**." [[www.indiana.edu/~ensiweb/lessons/whale.ev.html]]

Similarity:

Access Excellence has a comparative embryology activity in which students' breed Japanese Medaka fish: "**Comparative Embryology Using Japanese Medaka Fish**." [[www.accessexcellence.org/AE/AEPC/WWC/1995/medaka.html]] The students breed Japanese Medaka fish, collect eggs, and then watch the embryos throughout their development. Students then compare the fish embryos with pictures of embryos from chicken, humans, etc. If you do not have the equipment necessary for raising fish, you could order eggs (instead of adult fish) for a relatively cheap alternative.

PBS' Teacher's Guide [[www.pbs.org/wgbh/evolution/educators/teachstuds/tguide.html]] also has a lesson on vertebrate forelimbs: "**Winging It**." Go to the online Teacher's Guide, click on "download PDF" under Unit 3: What is the Evidence for Evolution?

Imperfect Adaptations/Contrivances:

The ENSI website has a read-and-discuss activity based on a couple of S.J. Gould's essays: "**Panda's Thumb**," [[www.indiana.edu/~ensiweb/lessons/contriv.html]] a lesson on contrivances: "**Blocks and Screws**," [[www.indiana.edu/~ensiweb/lessons/bl%26scr.html]] and a new lesson design efficiency: "**Why Don't Whales have Legs?**" [[www.indiana.edu/~ensiweb/lessons/wh.legs.html]]