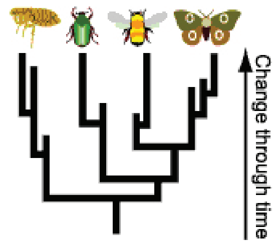
II. Key concepts and questions

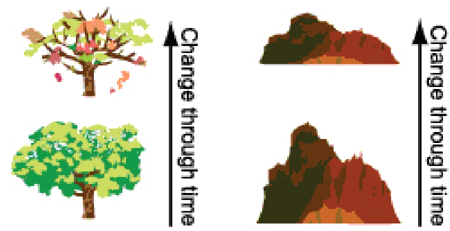
Here are some quick answers to key questions that visitors may ask regarding **Life Changes**.

❖ What is the theory of evolution?

Biological evolution, simply put, is descent with modification. This definition encompasses small-scale evolution (changes in *gene frequency* in a population from one generation to the next) and large-scale evolution (the descent of different lineages—like kiwis and penguins—from a *common ancestor* over many generations). Biological evolution is not simply a matter of change over time. Lots of things change over time: trees lose their leaves, mountain ranges rise and erode, but they aren't examples of biological evolution because they don't involve descent through genetic inheritance.



Evolutionary change based on descent through genetic inheritance.



Non-evolutionary change over time. Leaves on a tree change color and fall. A mountain range erodes.

The central ideas of evolutionary theory are that life has a history—it has changed over time—and that different species share common ancestors, just as you and your cousins share a common grandmother. Through the process of descent with modification, the common ancestor of life on Earth gave rise to the fantastic diversity that we see documented in the fossil record and around us today. Evolution means that we're all distant cousins: humans and oak trees, hummingbirds and whales.

gene frequency—proportion of gene versions in a population that are of a particular type.

common ancestor—an ancestral lineage that two or more descendent lineages have in common.

Evolution is a scientific theory—but in science, the word theory means much more than a guess or a hunch. **Scientific theories are broad explanations for a wide range of phenomena, and in order to be accepted by the scientific community (as evolution is), they must be supported by many lines of evidence**, help us understand a wide range of observations, and make predictions in new situations. Evolution is the very best scientific explanation for the diversity and history of life, and there is no controversy in the scientific community over its acceptance.

- To learn more about nature of science and how evolution fits into this framework, see http://evolution.berkeley.edu/evolibrary/article/nature_01.

Exhibit examples: Small-scale evolutionary change is represented in several ways in the exhibit. Dinosaurs with feathers do better than dinosaurs without feathers. They leave behind more offspring—which happen to inherit their parents' feathers. As this process continues over many generations, feathered dinosaurs become more and more frequent in the population. Similarly, the discovery box Who survives shows how small-scale evolution can occur in a population of moths. Large-scale evolutionary change is emphasized by other aspects of the exhibit: the evolution of birds from dinosaurs, the evolution of the suite of unique characters that make kiwis kiwis, and the diversification of honeycreepers from a common ancestor in the Honeycreeper Puzzle.

❖ How does evolution happen?

Natural selection is one of the key mechanisms of evolution (though there are others). **Natural selection is responsible for the close fit between organisms (e.g., a drought-tolerant cactus) and their environments (e.g., the Sonoran desert).** Natural selection involves four ingredients (VIST) and results in adaptation (A):

> **V** = **Variation**: All life forms vary genetically within a population.
> **I** = **Inheritance**: Genetic traits are inherited from parents and are passed on to offspring.
> **S** = **Selection**: Organisms with favorable traits are more likely to survive and pass on their genes.
> **T** = **Time**: Over time, this results in . . .
> **A** = **Adaptation**: A trait that increases the survival and reproduction of its bearers.

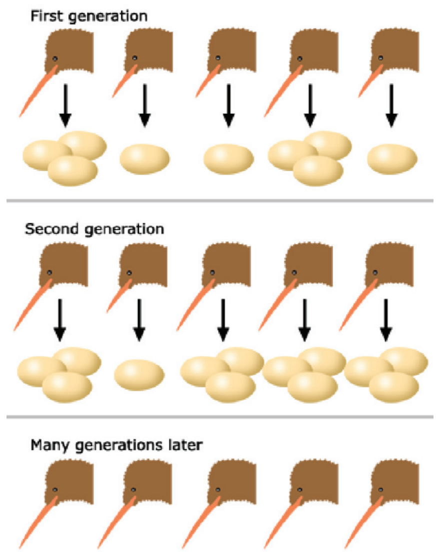
To see how it works, imagine a population of ground-dwelling birds:

1. There is variation. Some birds have short beaks and some birds have longer, pointier beaks

2. There is selection. The longer-beaked birds can catch more bugs, get more nourishment, and produce more offspring than short-beaked birds.

3. There is inheritance. Beak length has a genetic basis, so the offspring of long-beaked birds also have long beaks.

4. Over time, the more advantageous trait, long beaks, which allows the birds to have more offspring, becomes more common in the population. If this process continues, eventually, all individuals in the population will be long-beaked.



If you have variation, selection, and inheritance, you will have evolution by natural selection as an outcome. Over short periods of time, this process increases the frequency of favorable gene versions in a population. **Over long periods of time, these small changes can accumulate, resulting in the evolution of new complex adaptations and new species.**

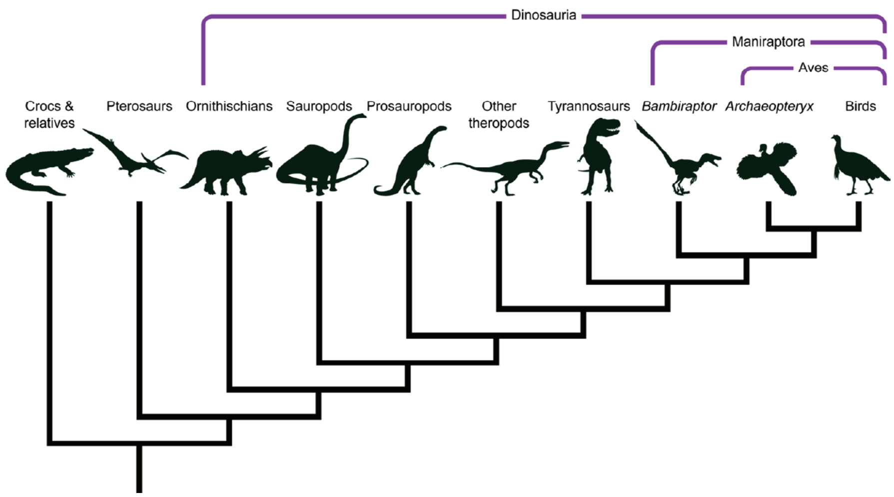
- To learn more about natural selection and other mechanisms of evolution, see http://evolution.berkeley.edu/evolibrary/article/evo_14.

> **Exhibit examples:** Natural selection is represented in several ways in the exhibit: the spread of feathers in the dinosaur population, the evolution of kiwi adaptations suited to ground-dwelling, the evolution of the moth population in *Who survives*, the evolution of honeycreeper traits suited to their environments, and the evolution of bird beaks specialized for different foods. The components of VISTA are emphasized by different discovery boxes and different aspects of the exhibit.

❖ What does it mean to say that dinosaurs and birds are related?

The process of evolution produces a branching pattern of relationships between species. As lineages evolve and split and modifications are inherited, their evolutionary paths diverge. This means that different species share common ancestors. So when we say that dinosaurs and birds are related, we mean that they share common evolutionary ancestors—just as you and your cousins share common ancestors (e.g., your grandparents). In fact, **birds evolved from dinosaurs**. The first organisms we'd call birds evolved more than 150 million years ago from a group of dinosaurs known as the Maniraptorans.

By studying species' inherited characteristics and other historical evidence, **we can reconstruct evolutionary relationships and represent them on a "family tree,"** called a phylogeny. This is a phylogeny showing how birds are related to other dinosaurs:



You can see that the relationship between birds and dinosaurs is close. In fact, because of how biologists classify organisms, technically, **birds *are* dinosaurs**. That's because biologists classify organisms based on their evolutionary histories. They only gives names to branches of the tree of life—groupings called *clades*. Since birds evolved *from* dinosaurs, there's just no way to clip a single branch from the tree above that includes *Triceratops* and *T. rex*, but excludes birds. That means that birds are on the dinosaur branch (i.e., in the dinosaur clade)—and hence, *are* a type of dinosaur. This is cool because it means that dinosaurs are not extinct! In fact, there might be dinosaurs nesting in your tree at this very moment. Scientists call dinosaurs that are not birds "non-avian dinosaurs"—and they are extinct.

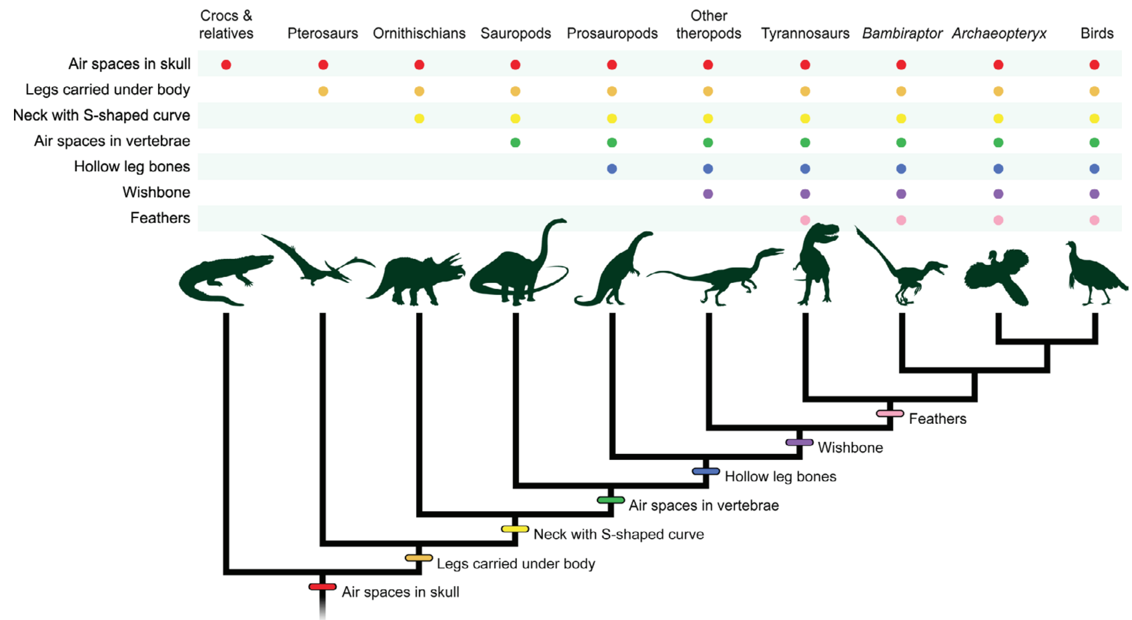
> *clade*—grouping that include an ancestor and all the organisms (whether living or extinct) descended from that ancestor.

- To learn more about family trees in evolution, see our factsheet on the tree of life (p. 44) and http://evolution.berkeley.edu/evolibrary/article/phylogenetics_01.

> **Exhibit examples:** The evolution of birds from dinosaurs is explained in Charlie's and Kiwi's story. Some of the evidence supporting this relationship is also shown in the display highlighting structures that dinosaurs, *Archaeopteryx*, and modern birds all share.

❖ How did dinosaurs evolve into birds?

Dinosaurs evolved into birds in little steps over millions of years. The features that we recognize as key characteristics of modern birds—feathers, the wishbone, hollow leg bones, an s-shaped neck, etc.—did not evolve all at once. This phylogeny shows where in the evolutionary history of birds and other dinosaurs different features evolved. The lineage in which the feature first evolved is marked with a dash. That lineage passed the trait on to its descendents.



From the phylogeny, you can see that not all of the traits necessary for flight evolved at once—for example, birds' ancestors evolved a lighter skeleton through hollow vertebrae and leg bones long before they evolved feathers. **This means that the traits useful for flying must have first evolved in some other context (e.g., under natural selection for some other function) and were later co-opted for flight.** Natural selection is an excellent thief, taking features that evolved in one context and using them for new functions.

Exhibit examples: The display highlighting structures that dinosaurs, *Archaeopteryx*, and modern birds all share includes the small meat-eating dinosaur *Bambiraptor*. This dinosaur had feathers but could not fly, demonstrating that feathers must have evolved in some context other than that of flight.

The most obvious trait necessary for flight is wings. How did they evolve? Like other complex adaptations, wings must have evolved in small steps, becoming larger and more wing-like over the course of many thousands of generations. In the early part of this evolutionary transition, wings wouldn't have been any good at flying but must have served *some* adaptive function. There are many *hypotheses* about why wings might have offered a survival and reproductive advantage in their early stages:

- They may have been useful in capturing small prey.
- They may have helped with leaping into the air.
- They may have helped with running up steep slopes.
- They may have been used to attract the attention of potential mates.
- They may have been used for gliding.

Scientists are still gathering evidence to try to figure out which of these explanations is most likely to be correct.

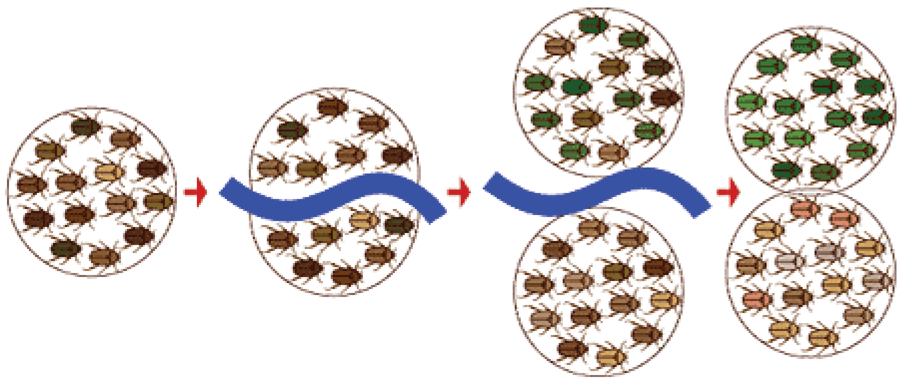
hypothesis—a proposed explanation for a fairly narrow set of phenomena, usually based on prior experience, scientific background knowledge, preliminary observations, and logic. A hypothesis must be testable with evidence from the natural world. If an explanation can't be tested with experimental results, observation, or some other means, then it is not a scientific hypothesis.

Along the same lines, feathers evolved in small steps. Based on fossil evidence, we think that the first feathers were simple affairs—little more than fuzz. But through many generations of random mutation and natural selection, they evolved into more elaborate structures. Scientists are still investigating the genetic changes that could have helped form early feathers and are making progress in this area. Feathers evolved in dinosaurs long before any of them had evolved the ability to fly or even wings—so in their early stages, feathers must have been useful for some other function. Insulation and thermoregulation are good hypotheses for the original function of feathers, but this question is still being actively investigated.

- To learn more about the evolution of complex innovations, see http://evolution.berkeley.edu/evolibrary/article/evo_53 and http://evolution.berkeley.edu/evolibrary/article/side_0/complexnovelties_01.
- To learn more about the early evolution of feathers, see our factsheets on *Bambiraptor* and feathered dinosaurs (pp. 42–43).

❖ How did we end up with so many different kinds of birds today?

Two hundred million years ago, birds did not yet exist. Today, they are the most diverse terrestrial vertebrates, with around 10,000 known *species*. How did this happen? Through speciation. The ancestral bird branch—the dinosaur lineage that scientists consider to be the first bird—split, or speciated, into two separate lineages. These descendent lineages split again and again, and those descendents diversified further. Many of the major splits in the bird clade occurred during the Cretaceous alongside non-Avian dinosaurs like *T. rex*. Despite many extinctions along the way, birds eventually diversified into the wide array of bird species on Earth today.



Exactly how does speciation or lineage-splitting occur? Scientists think that **geographic isolation is a common way for the process of speciation to begin**: rivers change course, mountains rise, continents drift, organisms migrate, and what was once a continuous population is divided into two or more smaller populations. This barrier prevents two parts of a population from mating with one another. While they are isolated, the two parts of the population evolve genetic differences from one another—often because the habitats they each occupy are different and natural selection favors different traits in the two groups. **Eventually, after many generations, the two groups have evolved so many differences that, even if they are reunited, they would not or could not successfully mate with one another.** These need not be huge genetic differences. A small change in the timing, location, or rituals of mating could be enough. But still, some difference is necessary. At this point, speciation has occurred.

Speciation may be facilitated if there are many unfilled niches available—perhaps because a *mass extinction* has left them open or because a lineage has evolved a key innovation that allows it to take advantage of resources and space that other organisms cannot. It is easy to imagine that flight was a key innovation that facilitated the diversification of birds. Scientists are currently studying this time in birds' evolutionary history to try to learn more about how and why they diversified.

species—members of populations that actually or potentially interbreed. In this sense, a species is the largest gene pool possible under natural conditions

mass extinction—event in which many different lineages go extinct around the same time. Mass extinctions involved higher rates of extinction than the usual rate of background extinction that is going on all the time.

- To learn more about speciation and macroevolution, see http://evolution.berkeley.edu/evolibrary/article/evo_40 and http://evolution.berkeley.edu/evolibrary/article/evo_47.

Exhibit examples: Speciation is responsible for the diversity of birds and other dinosaurs showcased in the exhibit. It is particularly salient to the diversity of closely related birds seen in the honeycreeper puzzle.

❖ How do scientists study evolution? How do we know that evolution has occurred?

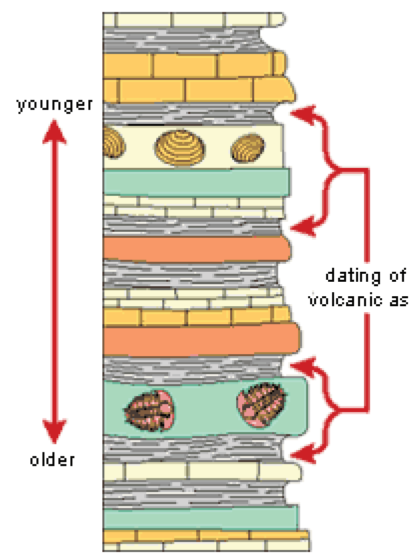
We can't directly observe the past, but we can gather evidence available today in order to figure out what happened in the past—much as crime scene investigators collect evidence to try to figure out how and why a particular crime was committed. **Overwhelming evidence supports the idea that life has existed for billions of years and has changed over time.** Scientists continue to argue about details of evolution, but the question of whether life has evolved was answered in the affirmative at least two centuries ago. Here are a few of the lines of evidence that have convinced us of this fact:

- **The fossil record**. The fossil record provides snapshots of the past that, when assembled, illustrate a panorama of evolutionary change over the past four billion years. For example, paleontologists have found many examples of fossil organisms that show the intermediate states between an ancestral form and that of its descendants.

- **Homologies**. Evolutionary theory predicts that related organisms will share similarities that are inherited by different lineages from their common ancestor. Similar characteristics due to relatedness are known as homologies. Homologies can be revealed by comparing the anatomies of different living things, looking at cellular similarities and differences, studying embryological development, and studying *vestigial structures* within individual organisms. We observe homologies across the tree of life.

> *vestigial structure*—a feature that an organism inherited from its ancestor but that is now less elaborate and functional than in the ancestor. Usually, vestigial structures are formed when a lineage experiences a different set of selective pressures than its ancestors, and selection to maintain the elaboration and function of the feature ends or is greatly reduced.

- **Dating techniques**. The ages of the Earth and its inhabitants have been determined through two complementary lines of evidence: relative dating and radiometric dating. Relative dating places fossils in a temporal sequence by noting their positions in layers of rocks. Radiometric dating relies on the decay of radioactive elements, such as uranium, potassium, rubidium, and carbon. Very old rocks must be radiometrically dated using volcanic material. By dating volcanic ash layers both above and below a fossil-bearing layer, as shown in the diagram, you can determine "older than X, but younger than Y" dates for fossils. Sedimentary rocks less than 50,000 years old can be dated using their radioactive carbon content.



- **Geography**. The distribution of living things on the globe provides information about the history of life and of the Earth. This evidence is consistent not just with the evolution of life, but also with the movement of continental plates around the world.

- **Observations of modern organisms.** There are many ways we can look at present-day organisms, as well as recent history, to better understand what has occurred through deep time: (1) Artificial selection in agriculture or laboratories provides a model for natural selection. (2) Looking at interactions of organisms in ecosystems helps us to understand how populations adapt over time. (3) Experiments demonstrate selection and adaptive advantage. (4) And finally, we can observe evidence of evolution in the way that the diversity of life is arrayed. Evolutionary theory leads us to expect that living things should be arrayed in nested hierarchies of groups within groups, delineated by the characteristics they inherited from their ancestors. This is indeed what we observe in the living world and is strong evidence supporting evolutionary theory.

The following lines of evidence have been particularly important in helping scientists figure out that birds evolved from dinosaurs and how this occurred:

- Studies of fossil birds and dinosaurs
- Anatomical studies of birds, dinosaurs, and other organisms
- Genetic studies of modern birds
- Observations of modern bird behavior
- Studies of bird movement
- Knowledge of aerodynamics

Exhibit examples: The exhibit includes information on several lines of evidence relevant to evolutionary theory: the fossil *Archaeopteryx*, the homologies shared by *Bambiraptor*, *Archaeopteryx*, and modern birds, and the homologies between bird and bat wings (in the *We can fly* discovery box).

❖ Why is evolution so important?

Evolution is of practical importance. **Because biological systems evolve, solutions to biological problems that don't take evolution into account are likely to fail**. Here are just a few ways that evolution helps us solve practical problems:

- **In medicine**. Because both disease-causing organisms and their victims evolve, understanding evolution can make a big difference in how we treat disease. For example, bacteria and viruses reproduce rapidly and so evolve rapidly. These short generation times mean that natural selection acts quickly. In each pathogen generation, new *mutations* and gene combinations are generated that then pass through the selective filter of our drugs and immune response. Over the course of many pathogen generations (a small fraction of a single human lifetime), they adapt to our defenses, evolving right out from under our antibiotic and antiviral drugs. By understanding these pathogens as evolving entities, scientists are developing new drugs to treat them and providing doctors and patients with guidelines for extending the useful life of our existing drugs.
- **In agriculture**. Crops, livestock, pests, and crop diseases evolve—so in the field of agriculture, just as in medical science, evolution matters. For example, understanding the evolutionary history of domestic crops and other organisms helps scientists identify valuable stores of genetic variation. Corn viruses can seriously damage crops unless resistant varieties are grown. So where do we get resistant varieties? Many are genetically engineered using genes found in closely related plant species. In this case, an evolutionary perspective—one that considers the history of corn—can point scientists searching for these genes towards the closest living relative of modern corn, teosinte. Using genes from the teosinte species *Zea diploperennis*, scientists have developed several virus-resistant domestic corn varieties.
- **In conservation**. Understanding evolution can also help us protect Earth's dwindling biodiversity. For example, determining the population size at which a species becomes threatened is important for our conservation efforts. Without evolutionary theory, one might imagine that a fairly small population—just enough to breed—would be sufficient to repopulate a species. However, according to evolutionary theory, very small populations face two dangers—*inbreeding depression* and low *genetic variation*—that might keep them from recovering, despite our best efforts to preserve them. Taking evolution into account allows us to plan our conservation efforts more realistically.

mutation—a change in a DNA sequence, usually occurring because of errors in DNA copying or repair. Mutation is the ultimate source of genetic variation.

inbreeding depression—decreased health and reproductive capacity experienced by the offspring produced through the mating of close relatives.

genetic variation—loosely, a measure of the genetic differences within populations or species. For example, a population with many different versions of a particular gene may be said to have a lot of genetic variation for that gene. Genetic variation is essential for natural selection to operate since natural selection can only increase or decrease frequency of gene versions already in the population.