Lesson 8: Evolution

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Learning objective for lesson 8: Students will understand the basic theory of evolution and understand how to interpret a phylogenetic tree

Learning objective 8.1 – Describe the principles underlying the theory of natural selection.

Evolution is the great unifying theory of all modern biology. The theory of evolution was first conceived by the British naturalist **Charles Darwin**. Darwin's theory explains how new species come into existence, how organisms become adapted to their environments, and why specific groups of organisms share specific traits. It also correctly postulated that all life on Earth is related and shares a single common origin. Despite its importance and tremendous explanatory power, evolution is a simple concept and is based on four basic principles of life.

First, many of the traits of an organism (everything from how it looks to how it behaves) are heritable. **Heritable** means that the trait is part of an organism's genetic code and, therefore, either will be, or (depending on the type of reproduction) has a chance to be, copied to the organism's offspring. Heritability is the reason that sons and daughters tend to resemble their parents. A trait must be heritable in order for that trait to evolve.

Second, sometimes organisms have heritable traits that are new, not copied from the organism's parent(s). One source for new heritable traits is random genetic mutation. In order for selection to occur on any given trait, there must be **variation** in that trait in a population.

Third, an organism's traits affect how successfully that organism is able to reproduce. Often, a trait's effect is indirect – that is, it improves or hinders an organism's ability to survive, which, in turn, affects how many reproductive opportunities the organism has. One variation of the trait must provide an **advantage (or, differential success)** over the other variations in order for evolution to occur.

Fourth, natural environments have limited resources, and **competition** for these resources permits only some organisms to successfully reproduce before they die. Some of the versions of a given trait must be 'selected out' of a population in order for evolution to occur, and this must occur because of competition for limited resources.

The theory of evolution combines these four basic principles of life together: the **differential success** of certain **variations** of a **heritable** trait, because of **competition** for limited resources, leads to the change over time (evolution) of that trait in a population. If an organism is born with a new trait *(say, for example, a woodpecker has a genetic mutation that makes the keratin covering of its beak a little stronger)* and this new trait improves the organism's ability to successfully survive and reproduce *(the harder-beaked woodpecker is better able to obtain nutritious food, which improves the quality of the woodpecker's mating plumage, allows it to lay healthier eggs, and makes the woodpecker better able to feed its young)*, then that organism is more likely to outcompete other similar organisms *(the harder-beaked woodpecker consumes more food and attracts more mates while other woodpeckers starve and are mate-less)*. The beneficial trait will likely be inherited by the organism's more abundant offspring *(many clutches of harder-beaked woodpeckers hatch)*. Over time and generations, the beneficial trait is likely to become widespread *(harder-beaked woodpeckers thrive, while softer-beaked woodpeckers may eventually become extinct)*. At the same time that one beneficial trait is becoming widespread, so too may many other beneficial traits become the norm *(for example, sharper woodpecker claws that can better hold onto tree bark, more sensitive woodpecker ears that can better detect boring insects, broader wings that can better maneuver through forests, or an additional mutation that helps to make the beaks even harder)*. Eventually, when many new traits become widespread, the organisms that have these accumulated new traits *(the super-hard-beaked, sharp-clawed, sensitive-eared, broad-winged woodpeckers)* are so different from their ancestors *(the soft-beaked, dull-clawed, insensitive-eared, narrow-winged woodpeckers)* that they constitute a new species.

The evolution of a new species does not necessarily require the extinction of its ancestor. For instance, a new species might simply branch off from an ancestral species if only a single population of the ancestral species was exposed to new environmental conditions that favored new traits. While the population in the new environment would acquire new traits better adapted to that environment and evolve into a different species, the ancestral species might continue to exist in its ancestral environment.

Thus, evolution uses only basic principles of the natural world to explain how one species can give rise to others. It is often mistakenly said that the evolution of new species is a random processes. Just the opposite is true. While new traits may be introduced by random mutations, the determination of which traits are successfully passed on to later generations is not random. Instead, it is based on a specific criterion: how well each trait improves an organism's reproductive success. Of course, most random mutations are more likely to diminish than they to improve an organism's success. The competitive selective process by which detrimental traits are competitively discarded and advantageous traits are retained is called **natural selection.**

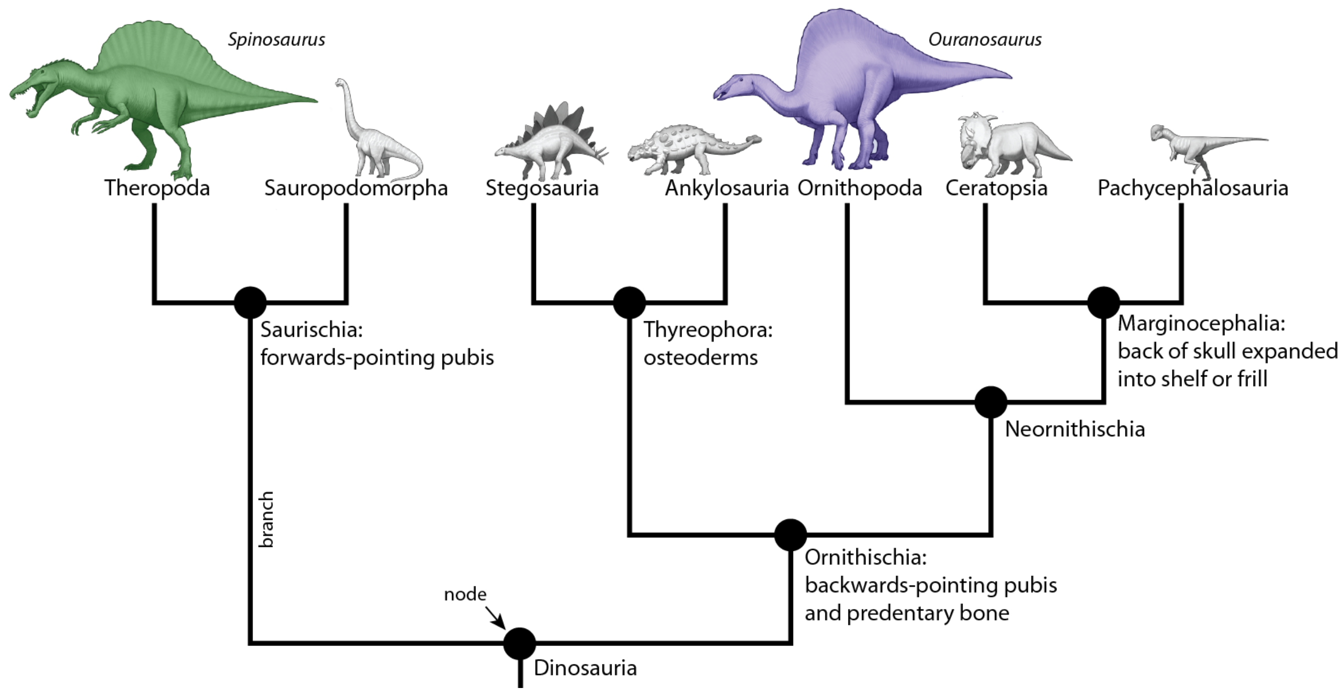
Learning objective 8.2 – Show how shared derived characters can be used to establish relationships between dinosaur groups.

Evolution provides a framework that modern taxonomy uses to categorize organisms. Organisms are grouped together based on their most recent **shared common ancestors**. For instance, all hadrosaurs, ceratopsians, ankylosaurs, and stegosaurs share a more recent common ancestor with each other than they do with sauropods, prosauropods, and theropods. Thus, hadrosaurs, pachycephalosaurs, ceratopsians, ankylosaurs, and stegosaurs are grouped together, and we call this group the Ornithischia. These ornithischians and the saurischians share a more recent ancestor with each other than they do with all other amniotes, and we call this group Dinosauria. In other words, all dinosaurs are classified together in a group because all dinosaurs evolved from a single species of amniote tetrapod. Within the dinosaurs, all ornithischians are classified together because they evolved from a single particular species of dinosaur, while saurischians are classified together in a different group because they evolved from another particular species of dinosaur.

How can we figure out which dinosaurs share a more recent common ancestor, and, therefore, should be grouped together? This is done by studying characters. A **character** is any heritable trait that can be described and labeled. A **shared derived character** is a character that is present in two or more groups and their common ancestor, but is not present in any more distantly related groups. A shared derived character is also called a **synapomorphy**. For instance, all species of ornithischians have a special bone in the lower jaw that forms a beak, called the predentary, and no other dinosaurs have this special beak bone. Thus, the character of the predentary was passed on to all ornithischians from their ancient shared ancestor and is a synapomorphy that testifies to this shared ancestry and can be used to define the group.

Learning objective 8.3 – Distinguish between similarities resulting from convergent evolution or shared derived characters.

Identifying shared derived characters and using them to identify evolutionary related groups sounds easy, but often it is not. One of the biggest challenges to determining evolutionary relationships is the common phenomenon of convergent evolution. Let's take a look at two dinosaurs, *Spinosaurus* and *Ouranosaurus*. *Spinosaurus* is a theropod with a long snout, sharp teeth, clawed fingers, and long processes on the vertebrae of the back that form a sail. *Ouranosaurus* is an iguanodont with a beak and grinding teeth, hoofed toes, and long processes on the vertebrae of the back that form a sail. *Spinosaurus* has the saurischian hip arrangement where the pubis points forwards, and *Ouranosaurus* has the ornithischian hip arrangement where the pubis points backwards. *Spinosaurus* and *Ouranosaurus* both have a sail, but we do not consider the sail to be synapomorphy, or shared derived character, between *Spinosaurus* and *Ouranosaurus*. *Spinosaurus* has many of the synapomorphies of saurischians and theropods, and *Ouranosaurus* has many of the synapomorphies of ornithischians and ornithopods. Therefore, the most likely evolutionary scenario is that the sail in *Spinosaurus* evolved independently of the sail in *Ouranosaurus*. A sail evolved twice in Dinosauria: once in the lineage leading to *Spinosaurus*, and once in the lineage leading to *Ouranosaurus*. The evolution of similar traits in two different lineages is termed **convergent evolution**.



The dinosaur family tree, showing convergent evolution of the sail in the theropod *Spinosaurus* and the iguanodont ornithopod *Ouranosaurus*. Diagram by V. Arbour, with dinosaur illustrations by J. Ang.

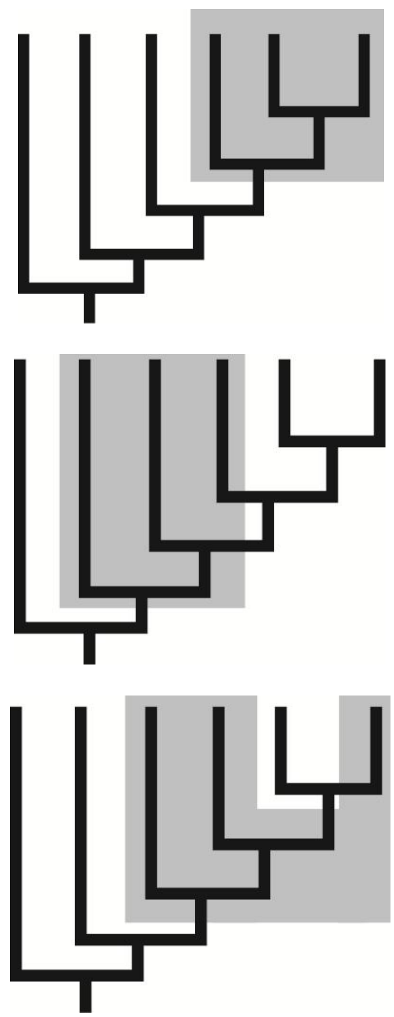
Usually, convergent evolution results when two lineages must adapt to similar environments and to similar modes of life. We aren't really sure what the function of the sail was in *Spinosaurus* and *Ouranosaurus*, but we have talked about many examples of convergent evolution in the lesson on feeding adaptations. For example, *Spinosaurus* has a long snout with conical teeth, similar to the jaw structure seen in some crocodilians and other piscivorous animals. The need to adapt to feeding on aquatic prey is probably responsible for the similarity in the tooth and jaw structures of the two groups. Another excellent example of convergent evolution is the evolution of wings in flying vertebrates. Birds, pterosaurs, and bats all evolved wings from the forelimbs, but did so in different ways. Pterosaurs have a wing made of a membrane supported by just one long finger. Bats (which are mammals) have a wing made of a membrane supported by several fingers. And birds have a wing made of feathers, and have fused the hand bones into a single unit.

Learning objective 8.4 – Use a family tree to show the relationships between groups of dinosaurs.

Suppose that in the previous example you had no particular reason to suspect that the similarities between *Spinosaurus* and *Ouranosaurus* were the result of convergent evolution. How could you figure out that *Ouranosaurus* was an ornithopod dinosaur and not a theropod? The answer is obvious. Although *Ouranosaurus* has a sail like *Spinosaurus*, it shares many more traits in common with iguanodonts (such as grinding teeth and a beak), and ornithischians (a backwards-pointing pubis, a predentary bone, and more). It is simpler to assume that the one character in common between *Ouranosaurus* and *Spinosaurus* (the sail) is the result of convergent evolution, than it would be to assume that the huge number of similarities between *Ouranosaurus* and iguanodonts are all the result of convergence. The idea that "all other things being equal, the simplest answer is usually the right one" is called **parsimony**. Parsimony is also referred to as **Occam's razor**.

Figuring out the relationships between only a few kinds of distantly related organisms is usually not too hard, as we can rely on our own ability to judge which of a handful of alternative relationships is the most parsimonious. To determine the evolutionary relationships between large numbers of species, many of which may be closely related, and to take into consideration a large number of characters, paleontologists use computer programs. These programs analyze a list of characters that is first compiled by the researcher. This list is called a character matrix. Based on the character matrix, the computer program applies the principle of parsimony to arrange the organisms in a sequence of relationships that requires the fewest instances of convergent evolution. The resulting arrangements look like diagrams of a "family tree" and are called **phylogenetic trees**.

Phylogenetic trees are composed of **nodes and branches**. A node is where two branches diverge, and shows the point at which two linages shared a common ancestor. After a node, the pattern of subsequent branches and nodes shows how the descendants of that common ancestor continued to diverge from each other. A group of species that share a common node is called a **clade**. Clades can be very small (even as small as two species), or very large – there are no size limits. A clade must contain the ancestor of a group and all of its descendants. A group that does not include all of the descendants of a common ancestor is therefore not a clade.



Only one of these phylogenetic trees shows a clade highlighted in grey – the top tree. The middle and bottom trees do not include all of the branches from the earliest node. Diagrams by V. Arbour.

In previous biology courses you may have been taught a system of classification that we call the Linnean Hierarchy, which classifies organisms as belonging to a Kingdom, Phylum, Class, Order, Family, Genus, and Species. While the Linnean hierarchy works pretty well, especially considering it was formed long before our current ideas about natural selection and evolution had solidified, the original classifications do not always work well with our current understandings of the evolutionary relationships of organisms. For example, Mammalia (mammals), Aves (birds), Pisces (fish), and Amphibia (amphibians, lizards, snakes, crocodiles, and turtles, but also sharks, rays, and some fish!) were all classified at the equivalent rank of Class. But we can trace all four-limbed animals (the tetrapods, including mammals, reptiles, birds, and amphibians) back to a fish ancestor – Class Mammalia, Aves, and Amphibia are all a subset of Class Pisces (now called Osteichthyes). One of the best examples of this problem is what to do with the birds…

Learning objective 8.5 – Evaluate the evidence for a dinosaurian origin of birds.

When the theory of evolution was first proposed by Charles Darwin in the 1800's, many scientists were skeptical and wanted to see more evidence supporting evolution in the fossil record. These skeptics reasoned that, if indeed new species evolved from ancient species and if all life shared a common evolutionary history, then fossils should exist of major "missing links" – that is, organisms that show an evolutionary connection between two major groups of organisms by displaying some traits that are characteristic of one group and some traits that are characteristic of the other group.

Thomas Henry Huxley was a close colleague of Charles Darwin and one of the earliest advocates for the theory of evolution. Huxley was also the first scientist to recognize that birds evolved from dinosaurs, and he cited the newly discovered specimens of ***Archaeopteryx*** as fossils of a "missing link" between dinosaurs and birds. Specimens of *Archaeopteryx* had been found exquisitely preserved in fossil lake deposits. These specimens clearly show that *Archaeopteryx* has long wing-feathers and tail feathers just like a bird, but they also show that *Archaeopteryx* had teeth, clawed fingers, and a long series of tail vertebrae just like a dinosaur. With the help of *Archaeopteryx*, Thomas Henry Huxley showed that transitional forms do exist in the fossil record, just as the theory of evolution predicted, and also showed that birds are a branch of the dinosaur family tree.

Of course, not everyone was convinced by Huxley's arguments. It took many years before the theory of evolution was fully accepted by the entire field of biological science and even longer for the theory of a dinosaur origin of birds to be fully accepted. Since Huxley's time, paleontologists have come to recognize an increasing number of characters that birds and other theropod dinosaurs share. One of the most significant shared characters was discovered in a specimen of the little dinosaur ***Sinosauropteryx***. *Sinosauropteryx* was the first non-avian (non-bird) dinosaur to be discovered with feathers. The feathers of *Sinosauropteryx* had a simple structure compared to the feathers of modern birds and were used for insulation, not for flight, but they were feathers just the same. Many other small theropod specimens have since been found with feathers, some with complex flight feathers. Recently, feathers have also been found on specimens of

***Sinosauropteryx* life restoration by Matt Martyniuk, used under the CC-BY-SA license.**

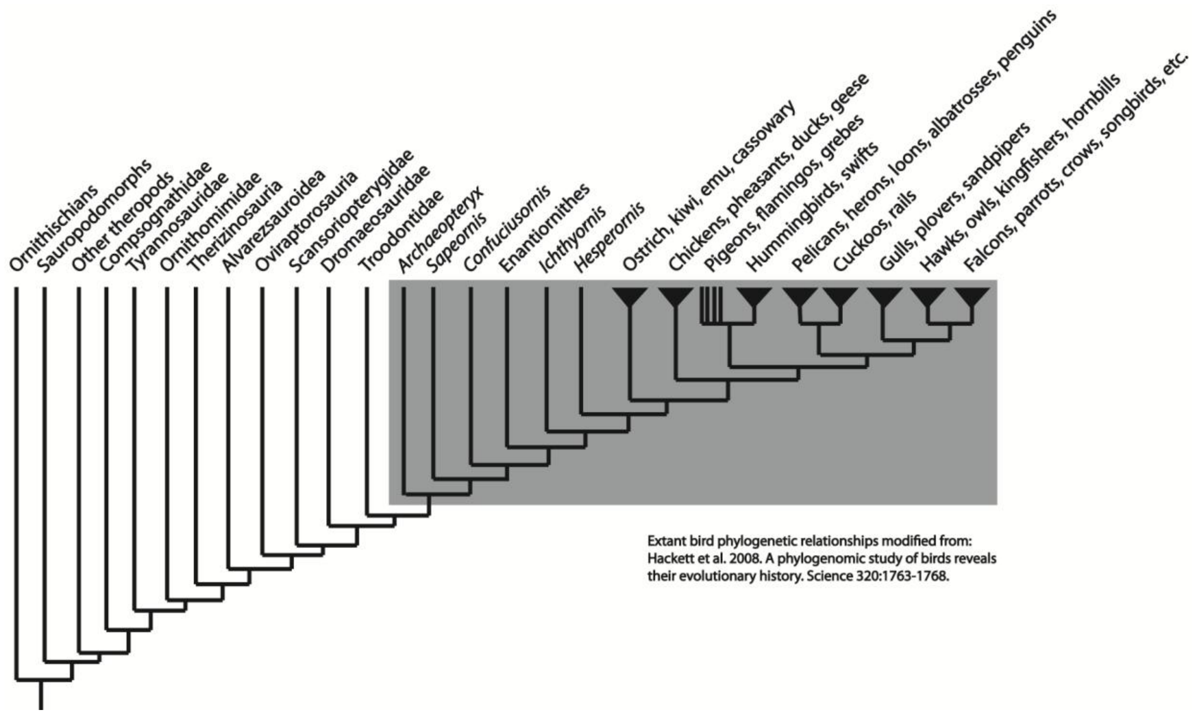
the large tyrannosauroid ***Yutyrannus***, showing that some large dinosaurs had them as well.

Birds are the only clade of dinosaurs alive today. Birds can be classified as theropod dinosaurs, because they evolved from theropod dinosaurs. But where we draw the line between non-avian theropod dinosaurs and 'birds' is more complicated than you might think. So many fossils of bird-like dinosaurs and dinosaur-like birds have been found, that the line between dinosaur and bird is blurry. Let's finish this lesson by discussing some different definitions for 'bird'.

What is a bird? Many palaeontologists use Aves to refer to the crown group of birds, which includes all living birds as well as extinct taxa like the dodo and moa. Another clade name, Avialae, is generally equivalent to 'flying dinosaurs', which includes extinct species that looked very similar to modern birds, including *Archaeopteryx*. However, 'birds' can be defined in several ways:

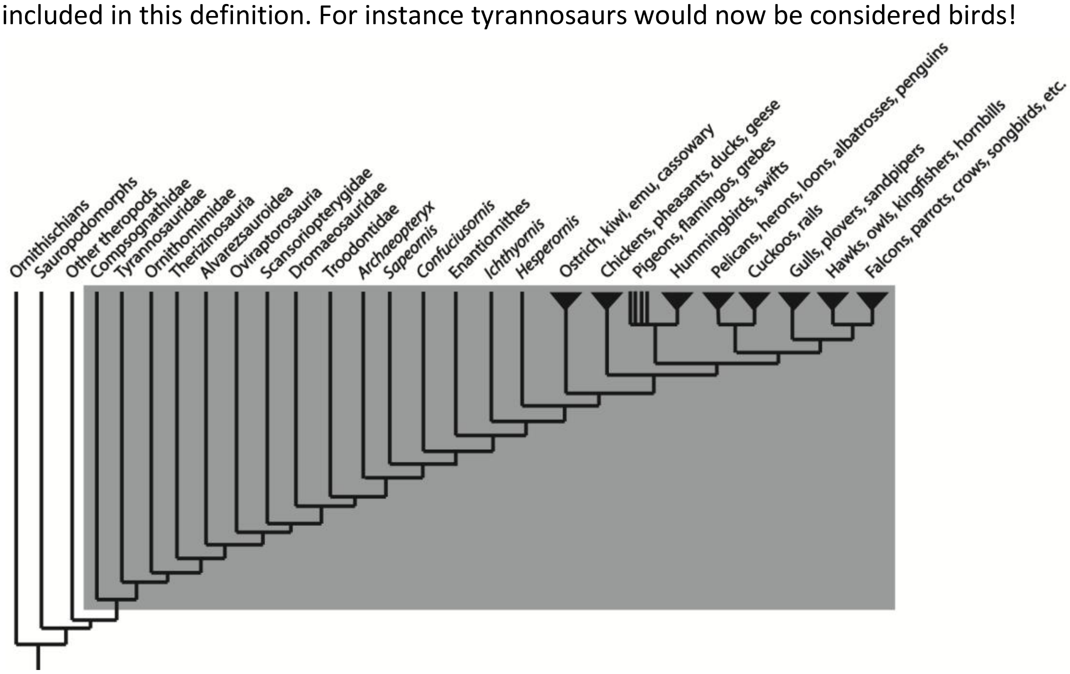
"The Ascent of Bird" by Matt Martyniuk, used with permission. From left to right: the tyrannosaur *Dilong*, the possible ornithomimid *Nqwebasaurus*, the alvarezsaur *Haplocheirus*, the maniraptoran *Yixianosaurus*, the dromaeosaur *Xiaotingia*, *Archaeopteryx*, *Confuciusornis*, the enantiornthine *Bohaiornis*, the ornithurine *Apsaravis*, and *Ichthyornis*. Where would you draw the line between birds and non-avian dinosaurs?

<u>Definition 1: *Archaeopteryx* and all of its descendants</u>.
<u>Problem</u>: New phylogenetic analyses sometimes show that *Archaeopteryx* is more closely related to the dromaeosaurid theropods than to modern birds.

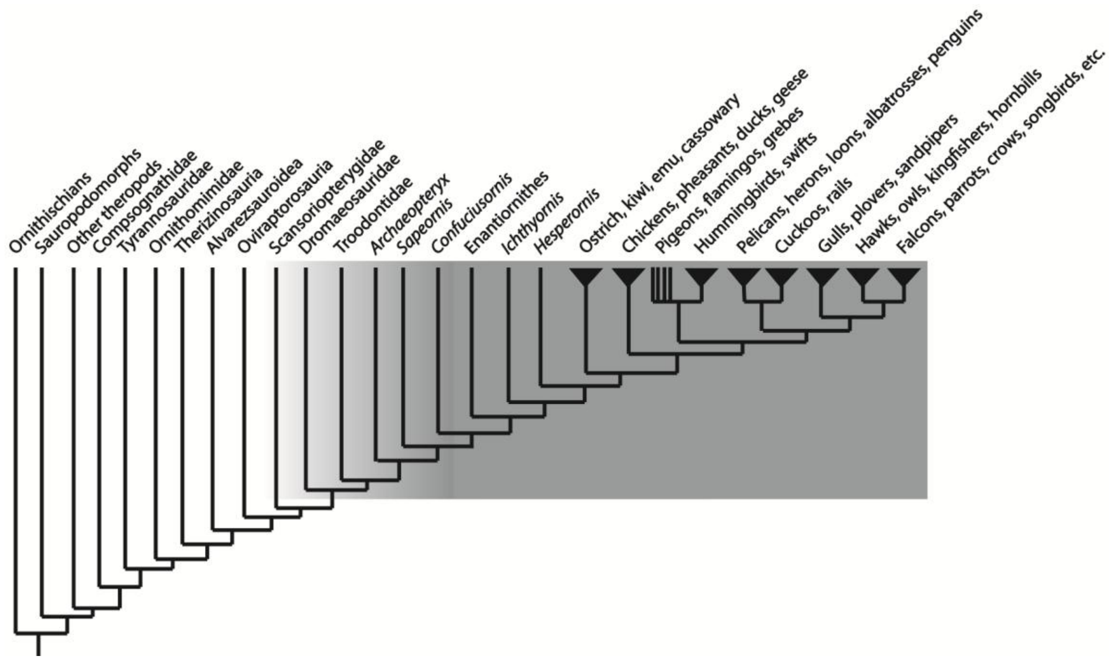


Diagrams by V. Arbour.

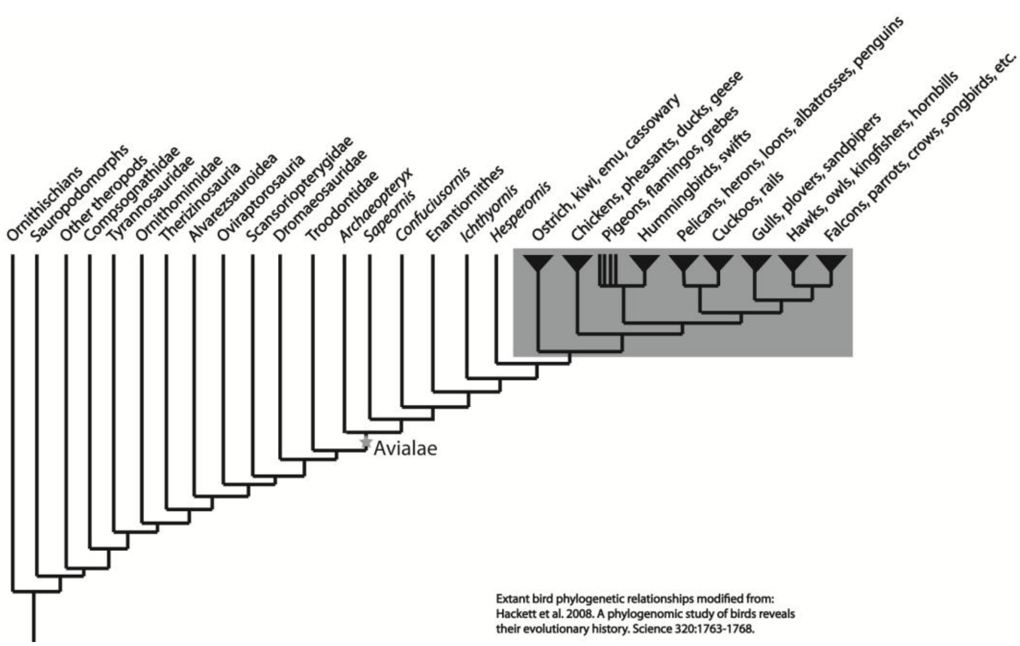
<u>Definition 2: Feathered dinosaurs</u>.
<u>Problem</u>: As more and more feathered dinosaur fossils, like *Yutyrannus*, are found, more dinosaur are included in this definition. For instance tyrannosaurs would now be considered birds!



Definition 3: Flying dinosaurs.
Problem: It is difficult to determine exactly which dinosaurs were capable of flying (as opposed to simply gliding).



Definition 4: Crown dinosaurs. This a somewhat technical term that means the last common ancestor of all extant birds and its descendants.
Problem: This definition fails to recognise many feathered and flying dinosaurs that are more closely related to modern birds than to *Archaeopteryx* as birds. However, this is the definition favoured by many palaeontologists. We then use the name Avialae for the clade containing *Archaeopteryx* and all of its descendants.



Supplementary Materials.

Evolution:
How evolution works [video]

University of California, Berkeley - Evolution 101 [website; contains some material that we don't cover in Dino101, like genetic drift, but you should still have a look through the whole site.]

Tetrapod Zoology – Species recognition vs. Sexual selection in dinosaurs. [Blog post]

PhD TV – Dogs vs. Hyenas (another example of convergent evolution in the fossil record, but not dinosaurs) [video]

OneZoom Tree of Life Explorer: Although it currently only includes living species, and therefore there are no dinosaurs on the tree, this is a really excellent tool for visualizing the branching nature of evolution! Try zooming in on the very tip of the bird branch!

Birds are Dinosaurs:
TED-Ed - How did feathers evolve? [video]

Dinosaur Tracking - Did all dinosaurs have feathers? [Blog post]

Dinosaur Tracking - Feathery ostrich mimics enfluffle the dinosaur family tree. [Blog post]

Optional: PBS – The Four-Winged Dinosaur [video; long, but very good!]