Overview

This lesson combines instruction on the nature of science with evidence for macroevolution. Students test hypotheses of common ancestry by using the traits of extant organism to make explicit predictions about evolutionary history, then checking their predictions against the fossil record.

Key Concepts

- Doing science involves testing explanations by comparing their predictions with empirical evidence.
- The theory of descent with modification from common ancestors predicts that when we group organisms by their shared traits they will form nested sets. We can use these nested sets to predict the order in which traits evolved and we can compare our predictions with the fossil record. When such tests are done the results are consistent with the theory of evolution.
- Once we have a specific hypothesis of evolutionary relationships, we can predict the past existence of transitional forms. Comparing these predictions against the fossil record offers an additional test of evolutionary theory.

Objectives

After completing the lesson, students should be able to:

- Classify a novel set of organisms according to the traits they share and recognize whether the resulting classification is characterized by nested sets.
- Use the nesting of shared traits, and the hypothesis of descent with modification from a common ancestor, to predict the order in which the traits evolved.
- Compare the predicted order versus the actual order in which traits appear in the fossil record and draw conclusions about whether the data from fossils are consistent with the theory of evolution.
- Explain what a transitional form is and describe how transitional fossils that were predicted before they were found have provided evidence for evolution.

Instructional Materials and Teaching Methods

We have taught the lesson using both a computer tutorial (available as the Evolutionary Evidence lab from SimBiotic Software) and a lecture/discussion format. For the latter we used a combination of pencil-and-paper exercises and projected images upon which the instructor could draw as the students talked.

Time

Taught by either method the lesson takes about 2 hours.

Procedure

1. Begin with a discussion of the nature of science. We like this summary from physicist Richard Feynman (Feynman and Sykes, 1994):

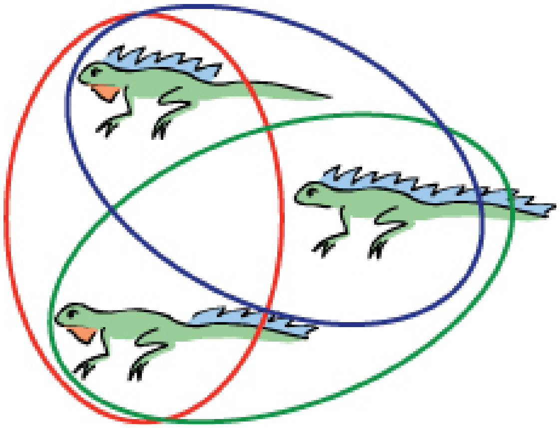
   > *"In general, we look for a new law by the following process. First, we guess...No! Don't laugh—it's really true. Then we compute the consequences of the guess to see if this law that we guessed is right—what it would imply. Then we compare those computation results to nature—or, we say, to experiment, or experience—we compare it directly with observation to see if it works. If it disagrees with experiment, it's wrong. In that simple statement is the key to science. It doesn't make any difference how beautiful the guess is, it doesn't make any difference how smart you are—who made the guess, or what his name is. It disagrees with experiment, it's wrong. That's all there is to it."*

   We find it useful to point out that we all use the method Feynman describes to test various explanations in our day-to-day lives. For example, "Why isn't the printer working? Perhaps it's not plugged in. If so, then…" Tell the students that in this lesson they will use the same method to test explanations of where Earth's organisms came from. An important caveat is that some students may think that hypotheses are the same as uninformed guesses. If you are concerned about this quote reinforcing a misconception, you may wish to point out that "guesses" in science are based on previous observation and research.

2. Before starting the guided exercises, have the students explore their own ideas about the relationships among organisms by giving them a set of extant species to classify. We use seven organisms, ranging from an amoeba to a bird. When using a lecture format, we give the students a paper card for each organism with a photo on the front and a list of salient traits on the back. An example appears below:

☑ Amniotic egg
☑ Backbone
☑ Bilateral symmetry
☑ Complex cells
☑ Feathers
☑ Four limbs
☑ Jaws

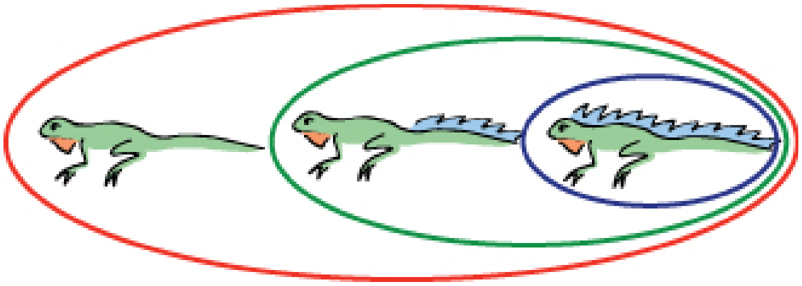
3. Ask the students to arrange the seven organisms in a way that represents their biological relationships to each other, to discuss their reasoning, and to draw a picture summarizing their classification scheme.
4. Now let the students design some organisms of their own. We start with a simple cartoon animal and a set of readily visible traits the students can add, as if dressing a paper doll. When teaching the lesson in lecture format, we start with a projected image, and then draw the traits by hand as the students call them out. Let the students design several organisms, bestowing at least two or three traits on each. The set of traits students can add should be small enough that each species they design has a unique combination of traits, but shares one or two traits with some of the other species.
5. After the students have designed all their organisms, have the students examine the pattern of trait sharing by circling all the animals that share each trait. Each trait should get a different color. The typical result is a Venn diagram with trait sets that overlap haphazardly, as in the example below:



This exercise demonstrates that a set of organisms need not share traits in any organized fashion.

6. After having created a set of organisms independently, ask the students to evolve a set of organisms by descent with modification from a common ancestor. We start with the same simple animal as before and have the students add a trait or two. We then imagine that this animal's lineage splits into two. Each daughter lineage inherits the traits of their common ancestor, but also gains new traits of its own. Repeat until the students have evolved several animals. To avoid complications best left for more advanced lessons, we impose two rules that are sometimes violated in the real world: We allow each trait to evolve only once, and once a trait has evolved we do not allow it to be lost.

7. After the students have evolved all their animals, have the students examine the pattern of trait sharing by circling all the animals that share each trait. This time the result should be a Venn diagram with nested trait sets:



This exercise demonstrates that the theory of descent with modification from common ancestors makes a specific prediction about how shared traits will be organized.

8. Ask the students to consider a related question about the distribution of traits among the species they have just evolved. Some traits occur in many species, other traits in few. Why is this so? The students should realize that traits that evolve early in an evolutionary radiation will occur in many species, whereas traits that evolve late will be confined to a few species or to one.
9. Students should now be able to complete a basic exercise in reconstructing evolutionary history. Give them a set of cartoon organisms that evolved by descent with modification from a common ancestor following the rules outlines in Step 6. Have the students group the species by the traits they share. Ask them to pick a suite of traits with several layers of nesting, and to predict the order in which the traits in the suite evolved. In the example above, dewlaps evolved first and back crests last.
10. Give the students the true evolutionary history of the organisms and have them compare their predictions to the true history. A convenient way to do this is with a scatter plot showing, for each trait, the predicted versus actual rank order of appearance.

    An advantage of teaching this exercise with our computer tutorial is that each time the tutorial is run it generates a new example. Each student, or group of students, gets a different example. Students can practice reconstructing evolutionary history as much as they like.
11. An additional task the students should be able to complete at this point is to look at a set of cartoon organisms and determine, by analyzing the pattern of shared traits, whether the

species arose by special creation or by descent with modification from a common ancestor.

12. The students are now ready to use the seven real organisms they classified in Step 2 to test the theory of descent with modification from a common ancestor. We frame this test as an evaluation of the merits of two hypotheses on where Earth's organisms came from. The first is special creation, exemplified by a quotation from John Ray (1686): "...[O]ne species never springs from the seed of another" The second is evolution, exemplified by a quotation from Charles Darwin (1859): "...all the organic beings which have ever lived on this earth have descended from some one primordial form..."

    The first step in testing the two hypotheses is to examine the pattern of trait sharing among the seven organisms. The fact that real organisms share traits in nested sets—tetrapods, for example, nested within gnathostomes, gnathostomes nested within vertebrates—is, in itself, evidence of evolution. But the students can go further.

    The students can use the nesting of shared traits, and the theory of descent with modification from common ancestors, to predict the order in which the traits should appear in the fossil record. We can then let them check their prediction by showing them photos and dates of fossils representing the earliest known vertebrates, gnathostomes, tetrapods, and so on.

    We chose the set of organisms we use for this exercise such that the analysis is straightforward and the fossils are readily interpretable. We disclose this fact to the students and use it as an opportunity to discuss published papers reporting similar analyses for which the species included were not hand-picked. We show scatterplots, from Norell and Novacek (1992), showing predicted versus actual order of appearance for various vertebrate clades. Norell and Novacek performed two dozen analyses. Their predictions better matched the fossil record for some clades than others, but the overall result is strikingly consistent with the theory of evolution.

13. Close the lesson with a brief discussion of an additional kind of evidence for descent with modification: transitional fossils. We choose photogenic examples that dovetail with the extant species we use in Steps 2 and 12, such as *Tiktaalik rosae* (Shubin et al., 2006; Downs et al., 2008).

Literature Cited

Darwin C (1859) *On the Origin of Species by Means of Natural Selection*, First Edition. London: John Murray. (Quotation is from page 484.)

Downs JP, Daeschler EB (2008) The cranial endoskeleton of *Tiktaalik roseae*. Nature *455*, 925–929.

Feynman RP, Sykes C (1994) No Ordinary Genius: The Illustrated Richard Feynman. New York: W. W. Norton & Company. (Quotation is from page 143).

Norell MA, Novacek MJ (1992) The fossil record and evolution: Comparing cladistic and paleontologic evidence for vertebrate history. *Science 255,*1690-1693.

Ray J (1686) Historia Plantarum. London. (Quotation is from volume 1, page 40; translated by E. T. Silk, as reproduced in Beddall, BG (1957) Historical notes on avian classification. *Systematic Zoology 6*, 129-136.)

Shubin NH, Daeschler EB, Jenkins FA (2006) The pectoral fin of *Tiktaalik roseae* and the origin of the tetrapod limb. Nature *440*, 764–771.