COUNTERING COMMON MISCONCEPTIONS OF EVOLUTION IN THE PALEONTOLOGY CLASSROOM

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ABSTRACT.—Students will come to class with misconceptions about evolution and about the nature of science itself. Erroneous views that create obstacles to teaching evolution include: 1) that the fossil record does not support evolutionary continuity between different taxonomic groups; 2) that the expected temporal pattern of evolution is linear and ladder-like; and 3) that evolutionary hypotheses are not subject to scientific testing. These views negatively impact the understanding of evolutionary science, particularly paleontology, in a number of ways. It is important that these misconceptions be recognized and explicitly countered. If student's false ideas are left unaddressed, new knowledge presented in the classroom will likely simply be superimposed on, or integrated with them. Effective teaching thus requires that we not only impart new knowledge, but seek to correct previously held false ideas. This essay presents several teaching strategies that can address misconceptions about evolution. These include: 1) teaching important concepts in their historical context; 2) having students construct and interpret cladograms; and 3) showing that, when interpreted as evolutionary trees, cladograms make testable predictions of the fossil record.

INTRODUCTION

MISUNDERSTANDINGS AND fallacious understandings of the nature and limitations of science are widespread in our culture. They underlie much of the popular resistance to the conclusions of modern science, particularly the historical sciences. Although the popular ignorance of the conclusions of modern science has been widely recognized, the false understandings of the nature and practice of science are more fundamental, and present a greater obstacle to scientific literacy.

It is being increasingly recognized that students' prior conceptions (or misconceptions) about science have a major effect on subsequent learning. Students, even those who have taken extensive secondary and college-level science courses, commonly will retain these prior misconceptions and will construct novel errant personal views from the newly learned content. This tendency was illustrated in a documentary film produced by researchers from the Harvard-Smithsonian Center for Astrophysics who interviewed both Harvard graduates as well as secondary students (Schneps and Sadler, 1988). The important role of preconceptions has been documented subsequently in several studies. In particular, Alters and Nelson (2002) summarized a number of studies that examine misconceptions concerning evolution held by undergraduate students. An important conclusion of these studies is that new scientific concepts cannot be learned if the prior erroneous views held by students are not explicitly addressed and corrected. Instruction should be conducted with a clear awareness of the various false views that students bring to the class.

In addition to prior learning, teaching of the process of scientific inquiry is complicated by the students' level of cognitive development (Verhey, 2005). Nelson (1999) evaluated learning in college students according to the model of cognitive growth proposed by Perry (1970). Most students enter college with a dualist worldview of black/white and right/wrong, and the inherent uncertainty of science can be confusing and frustrating to those seeking certainty. The acceptance of uncertainty leads to the cognitive mode of multiplicity. At this stage, students either may rely on authority to resolve conflict, or consider all positions as equally valid. According to Nelson (1999), most college students do not move be-

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yond the multiplicity level of thinking. However, critical thinking involves the next levels of cognitive growth, termed "contextual relativism" and "commitment." In the first, students begin to form their own considered opinions, but are unwilling to defend them, and in the second, students both form and defend their own opinions. Moving students beyond dualism and multiplicity is a significant educational challenge.

Overcoming the above conceptual and cognitive barriers is a necessary objective for the teaching of any scientific discipline. There are no simple pedagogical solutions, but there are approaches that can help move students from their prior misconceptions toward a more accurate understanding. In the teaching of paleontology and evolution, one particularly helpful approach is to present important concepts in their historical context (Jensen and Finley, 1995). This approach shows students how these concepts were historically constructed. Instruction recapitulates the conceptual challenges and new discoveries that resulted in the formulation of a new explanatory model. In doing so, students are exposed to how conflicts between theories of the natural world are resolved in the absence of certainty. The roles of observation of the natural world, theory construction, and prediction are made more tangible. Students are presented with a basis for confidence in scientific conclusions that is not rooted in a false dualism, or an appeal to authority. They are given historical answers to the question, "Why do scientists accept this particular view of the natural world and not another?" History provides an exposure to the real nature of science, not a cookbook process.

Helping students to understand the nature of science (NOS) is a fundamental part of science education. The effective teaching of evolutionary science, in particular, seems to be tied to students' and teachers' understanding of the nature of science. For example, studies of both college students and science teachers have shown a clear relationship between the lack of understanding of the nature of science and low acceptance of the theory of evolution (Bishop and Anderson, 1990; Rutledge and Warden, 2000). Furthermore, middle- and high-school teachers have not been adequately prepared to teach the NOS. Too often, the NOS is left to be inferred indirectly through the students' science classroom experience and reading, rather than being the explicit topic of instruction. This is especially the case when science is taught as a package of received factual knowledge to be learned, and the emphasis is placed on the results of laboratory assignments rather than on the process of inquiry itself.

The teaching of the NOS must be made explicit, and teaching strategies must be developed with understanding the NOS as their primary goal. As emphasized by Cough and Olson (2004, p. 51), "Teachers must play an active role in posing questions at strategic points to explicitly draw students' attention to NOS ideas. Just as students rarely develop accurate science ideas from activities alone, accurate NOS ideas will not be learned simply by doing activities or reading/watching historical and contemporary accounts of science in action." Students do not acquire an understanding of science as a process and a way of knowing through traditional science instruction. Teaching of the nature of science must be explicit, reflective, and taught within an applied context (Scharmann et al., 2005). These concerns must be addressed at the college and university level, as well as at the secondary level. The nature of science needs to be a conscious focus of science instruction; it will not be learned passively or absorbed merely through the learning of science facts.

RECOGNIZING EVOLUTIONARY PATTERNS

The fundamental evolutionary concept is that all living things on Earth are connected by an unbroken series of ancestor-descendent relationships to a common origin in the distant past. The consequence of this evolutionary history is that the history of life can be illustrated by the image of a branching tree or bush. This simple, easily grasped, but powerful, image provides an effective way to counter many common misconceptions about evolution and the fossil record that students bring with them to the classroom. Encouraging "tree thinking" among students should therefore be a critical educational objective (Gregory, 2008). Because of its ability to concisely communicate the essence of evolutionary change, the tree model also has been the focus of persistent and broad-based attacks by those rejecting evolutionary explanations for the history of life. These range from attacking evolutionary continuity at some level, to claiming that an anastomosing trunk (resulting from lateral gene transfer) invalidates the tree of life (Hofman and Weber, 2003).

Perceiving the tree of life is a matter of pattern recognition. Furthermore, these patterns can be recognized without reference to any specific evolutionary mechanisms. Debates over the relative significance of natural selection, for example, do not change the historical patterns of life's diversity observed in the fossil record. The vast body of paleontological evidence supporting common descent is in the historical, geographic, and anatomical patterns that are present. It is these patterns that we should emphasize when presenting our science.

The presentation of evolution in the college and university classroom needs to focus on macroevolutionary concepts because they provide the evidential underpinning of common descent. Kevin Padian sees the teaching of macroevolution, which he defines as "... the patterns and processes of evolution above the level of population change and differentiation," as critical to improving the science literacy of our students (Padian, 2010, p. 207). Macroevolution concerns the splitting of lineages that generates the branches of the tree of life, patterns of speciation and extinction, the construction of genealogies (phylogenetics), and the rise of new evolutionary innovations in the history of life. To understand the explanatory power of evolution, students need to understand the ways in which these historical patterns are reconstructed. Without this understanding, students simply may incorporate concepts learned from biology or geology courses into already held, but false, views of evolution and Earth history. College and university courses in paleontology and historical geology (especially those directed toward non-majors) provide an important opportunity to communicate the evidence for macroevolution.

Although pattern recognition is central to the science, much of the popular presentation of paleontology emphasizes particular discoveries at the expense of the observed historical patterns. The public face of the science is almost always in the particulars. The emphasis on particulars (e.g., specific fossil discoveries or specimens), can can hide from public view the historical patterns that make those particulars important in the first place. Furthermore, how specific discoveries are presented to the student actually may reinforce false views of the history of life.

The most obvious misconception about the fossil record is the belief that it fails to support the historical continuity of life over time. Many people have been convinced that the fossil record disproves the view that all life is part of a single genealogy. The online and print media are filled with creationist claims that there are no clear transitions between major groups, or "kinds," of living things (what those kinds are varies from species to phyla). Fossil transitions either are dismissed as fraudulent, or defined away. This rejection of transitions essentially is a return to typological views of species that held sway until the mid-1800s. Life is viewed as fundamentally discontinuous, and organisms are seen as only exhibiting variation around some ideal type. There is no transmutation of species—indeed, there cannot be. Each created type is too functionally integrated to change in any substantial way. New structures or functions cannot evolve from existing ones.

Students' perception of how organisms are classified can either reinforce or help to counter the discontinuous view of life. It is therefore essential that teachers give attention to how classification is taught. How we teach classification can serve to obscure evolutionary patterns in the history of life, or it can function to illuminate them. Emphasis on placing new fossil specimens into existing higher taxa may distract from the actual patterns in the fossil record. Higher taxa give the impression of discontinuity. Is it a bird? Is it a whale? Is it a mammal? However, the very existence of these questions indicates the intergrading character of biological diversity.

Presenting the historical development of classification schemes is an effective way to both address the shortcomings of naive views likely held by students, and to provide the logical and practical basis of current taxonomic procedures. Excellent discussions of the history and philosophy of various theories of classification can be found in Schoch (1986), Eldredge and Cracraft (1980), and Hull (1988). It is important for the student to recognize that the grouping of organisms in a classification scheme does much more than describe nature—it also interprets it.

The Linnean system, which is likely the only classification system most students will know, was originally based on a typological concept of species. All individuals were compared to an ideal archetype that defined the species, and all observed variation was understood as variation from that type. Typology thus excluded transitions by definition. The Linnean system also first introduced a hierarchical nomenclature, with species grouped into genera, genera into families, families into orders, etc. Although a hierarchy of names captures some important aspects of observed biological diversity, "this system leads to the impression that species in different categories differ from one another in proportion to differences in taxonomic rank" (Carroll, 1988, p. 578). For example, two species placed within two different classes are likely to be perceived as being much more different from each other than two species placed into different orders within the same class. This is not always the case. A related misconception is that overall physical similarity reflects relatedness (Gregory, 2008). Linnaeus grouped organisms by physical similarity, but degree of similarity is sometimes a poor guide to actual evolutionary relatedness. Crocodiles, for example, are much more closely related to birds than to lizards, despite their overall appearance.

Despite the perception of discontinuity, higher taxa are distinct and easily recognizable groups only when we ignore the time dimension of the history of life. When the fossil record is included, the boundaries between higher taxa frequently become blurred during the branching of lineages associated with the appearance of new higher taxa. When looking backward through time using the fossil record, it is found that representatives of different higher-level taxa become more "primitive" (that is, have fewer derived characters), and appear more like the primitive members of other closely related taxa (Miller, 2003). They converge in appearance toward their common ancestors further back in time. Using the dinosaurs as an example, the ornithopod ornithischian dinosaurs (hadrosaurids, iguanodontids, and hypsilophodontids) and the armored thyreophorans (ankylosaurids, stegosaurids, and scelidosaurids) both converge back in time toward the earliest appearing ornithischian dinosaurs, such as the heterodontosaurids. Although stegosaurs and hadrosaurs are very distinct and easily recognized dinosaurs, the earliest representatives of the taxonomic groups to which they belong are quite similar.

Phylogenetic systematics is the most widely accepted method in use today for assigning species to taxonomic groups. Unlike the Linnaean system, which was based on pre-evolutionary views of biodiversity, it focuses only on reconstructing the order in which new anatomical features were added in an evolving line of descent. It was developed based on the conviction that biological classification (using Linnaean names or not) should directly and unambiguously reflect the relative degree of evolutionary relatedness among species (i.e., the branching patterns of the tree of life). Phylogenetics also rigorously demands that taxonomic names apply to all descendants of a single common ancestor (a clade). Closely related taxonomic groups that do not share the same common ancestor are called sister-groups. An early-appearing species of one taxonomic group may closely resemble an early-appearing member of its sister group. Only a few anatomical characters may decide its placement in one group or another. As a result, placing more-primitive species into their correct monophyletic groups can be very difficult. A case in point is the current debate over the proper phylogenetic position of *Archaeopteryx*. Although it has long been viewed as the earliest known “bird,” or avialan, new fossil specimens and new analyses have suggested that *Archaeopteryx* may be a primitive deinonychosaur, a sister group to the birds within the maniraptoran dinosaurs (Xu et al., 2011).

Further complicating the assignment of fossil organisms to higher taxa is that the anatomical characteristics that are used to define higher taxonomic groups did not appear simultaneously, but were added over time. This has resulted in the distinction between so-called "crown groups" and "stem groups" in the scientific literature (Budd, 2001). A crown group is composed of all the living organisms assigned to a taxon, plus all the extinct organisms that were descended from the common ancestor of those living organisms. The stem group is composed of extinct organisms that are more closely related to one crown group than to another, but that do not possess all of the distinguishing characters of the crown group. Such distinctions are important in that they make clear the intergrading nature of anatomical diversity, and emphasize the time dimension of the tree of life.

In emphasizing the patterns of diversification over time, the transitional character of many fossil organisms needs to be illuminated. However, even the presentation of transitional forms in the fossil record can reinforce, or even create, false views of evolutionary change. An example of how the presentation of new discoveries can reinforce a false view of evolution is the casual use of the term “missing link.” The phrase “missing link” emphasizes particulars, not patterns. It implies that the validity of an evolutionary interpretation hinges on the discovery of a particular unique specimen. Missing links are perceived as critical breaks in the continuity of life, and their absence as evidence against evolution.

The media, and scientists themselves, are often responsible for helping to perpetuate the false views that surround the popular reference to missing links. The famous "Archaeoraptor" debacle of 1999 is a good illustration of the hazards associated with this language. When the announcement of "Archaeoraptor" was first made in the popular magazine *National Geographic*, the headlined quotation stated: "It's a missing link between terrestrial dinosaurs and birds that could actually fly" (Sloan, 1999). When the specimen was discovered to be a faked composite, subsequent articles in the popular press continued to use the "missing link" phrase. An article in *National Geographic News* reported, "The Archaeoraptor fossil was introduced in 1999 and hailed as the missing evolutionary link between carnivorous dinosaurs and modern birds" (Mayell, 2002). Similarly, a BBC News article began, "Forensic analysis of a forged fossil once hailed as a "missing link" between birds and dinosaurs has shed light on its murky origins" (Briggs, 2001). As might be expected, the uncovering of the faked specimen was quickly used by creationist organizations as evidence against evolution (Austin, 2000). By setting up a single specimen as a crucial evolutionary link, all of the fossil evidence for evolutionary patterns is lost to the public. A similar failure of the science media was exposed more recently during the hyped announcement in 2009 of the discovery of *Darwinius masilae*, an early primate, as "evolution's missing link" between early primates and humans (Zimmer, 2010).

The phrase "missing link" also tends to reinforce another common incorrect view of evolution—that evolution is linear and ladder-like. The ladder-like view of evolution, referred to as "orthogenesis," finds expression in the false view that ancestors are replaced by their descendants and cannot be coextensive with them. Combined with a Linnean view of classification, a linear understanding of evolution typically undergirds creationist and neo-creationist critiques of the fossil evidence for evolution (Padian and Angielczyk, 1999).

The linear view of evolution harkens back to ideas of progress and the "Great Chain of Being" that predated evolutionary perspectives, and influenced early expressions of evolutionary thought, such as those of Lamarck. Organisms advance up the ladder of progress from simple to complex. The tree or bush metaphor provides a counter to these false perceptions. There is no necessary trend toward complexity or progress -- only diversification and adaptation to changing environments. Organisms at the end points of branches are equally derived, whether primates or bacteria.

Suggesting that certain fossil specimens or species are ancestors to others is also problematic. Such language suggests that our evolutionary models hinge on the serendipitous discovery of that unique direct ancestor. But no particular species or specimen can ever be identified as an actual ancestor. For this reason, phylogenetic systematics avoids using known species as representatives of ancestors, and instead, defines branching points based on the appearance of unique derived anatomical characters. We search for historical patterns in the characters of extinct organisms. Searching for ancestors or missing links is not the goal of paleontology. Rather, we seek to unfold the pattern of relationships among known living and extinct organisms. The concepts of stem groups and sister groups are much more appropriate than ancestors or missing links when reconstructing the history of life.

The term "transitional fossil" is also fraught with misunderstanding. Transitional fossils often are expected to be intermediate between species at the ends of the branches of the tree of life. This common misconception was recognized by Darwin himself. In the Origin of Species, Darwin states:

> "I have found it difficult, when looking at any two species, to avoid picturing to myself forms directly intermediate between them. But this is a wholly false view; we should always look for forms intermediate between each species and a common but unknown progenitor; and the progenitor will generally have differed in some respects from all its modified descendants" (Darwin, 1859, p. 280).

As an example of this confusion, transitional forms are not to be sought between equally derived living whales and their closest living relatives, the hippos. We do not search for "whippos." Rather, the transitions are to be sought between whales and their common ancestors with the hippos. These transitions will lack many of the characters that distinguish their derived descendants. Transitional forms are found by moving down the tree of life into the past, not by trying to jump from limb to limb (Miller, 2003).

The expectation of common descent is convergence in the anatomy of closely related branches as we move back in time toward their branching points. When looking backward through time using the fossil record, we see such historical patterns extending deep into the past toward the trunk of the tree of life. By drawing attention to these patterns and their predictive power, we can provide a more robust understanding of the scientific community's confidence in evolutionary theory.

TESTING EVOLUTIONARY HYPOTHESES

The particularization of science that typically results from its popularization impacts not only the perception of the content of science, but also the public understanding of the nature of science itself. Paleontology often is presented as a series of serendipitous discoveries rather than a systematic study based on predictive theory. No wonder that it is often perceived more like stamp collecting than as a rigorous and testable investigation of the past.

This emphasis on particulars is made worse by the popular view of science as a process of accumulating facts (Bauer, 1992). As discussed earlier, this emphasis on facts is a reflection of a dualistic level of reasoning. A statement is considered either true or false, right or wrong. For too many people in our society, science is simply the discovery of unchanging truths that are then simply added to the list to be memorized in the encyclopedia of scientific knowledge. Theories are viewed as merely unsubstantiated guesses rather than as the unifying concepts that give our observations coherence and meaning. As a result, many people are unable to distinguish valid scientific conclusions from pseudoscience. The dynamic nature of science with the continual revision of theoretical constructs becomes evidence of the fleeting validity of scientific “truth” and a basis for its rejection. Theories within the historical sciences, in particular, are seen as being inherently untestable and driven by a materialistic philosophical agenda (Miller, 2005).

Science is not the mastery of a body of unchanging scientific facts, but rather a way of inquiring about our physical environment. It provides a way of understanding, explaining, and integrating our observations of the natural world. While observations form the foundation of scientific description, serious theoretical inquiry is the essence of science. Nothing could be more deadly to science than to divorce it from the unifying theories that make our observations intelligible. Theories are attempts to provide explanations for the patterns and regularities that have been recognized in the natural world. They also provide the predictions that suggest new observations and drive new discovery.

The history of our changing scientific understanding of the universe, with new theories replacing old, and previously accepted “facts” being overturned by new discoveries, can be puzzling to someone who has learned science as a body of facts. Furthermore, uncertainty and sharp disagreement within the scientific community are often seen as failures of science rather than expressions of its very strength. Science is a social activity that takes place within a community; it is not done by individuals in isolation. Ideas about the natural world are continually tested by that community by appeal to the available evidence. Scientific knowledge is mutable as new ideas are put forward and new evidence is obtained. Science is itself an evolutionary process (Hull, 1988).

There is a common public perception that evolutionary claims are inherently untestable. This view is part of a broader belief that the historical sciences, in general, deal with unrepeatable events and therefore are not amenable to experimental manipulation. Furthermore, because past events and processes are not directly observable, theories concerning the past are deemed inferior or less certain than studies of present processes. This view commonly finds expression in statements such as: "No one was there so we can never know what really happened." This view is false. The historical sciences are no less scientific or testable than the so-called "hard sciences" (Miller, 2002). In both cases, new observations can be tested against expectations based on previous experience and theoretical predictions. If the predictions deduced from a hypothesis are not supported by new observations, then that hypothesis is no longer useful, and ultimately will be modified or rejected. Scientific research proceeds by an almost continual process of hypothesis creation and testing.

Biological evolution, like all scientific disciplines is a theory-driven enterprise. Evolution (that is, descent from a common ancestor) makes specific predictions about the patterns of organic change that should characterize the history of life if current ideas are correct. These expectations are tested against each new observation or analysis.

TABLE *1*.—Data table used to introduce students to the construction of cladograms.

	Characters												
Taxon	A	B	C	D	E	F	G	H	I	J	K	L	M
1	1	0	1	0	0	0	0	0	0	1	0	0	0
2	0	0	1	1	0	0	0	0	0	1	0	0	0
3	0	1	1	1	0	0	0	0	1	1	0	0	0
4	0	0	1	0	1	0	1	1	0	0	1	0	1
5	0	0	1	0	1	0	0	1	0	0	1	0	0
6	0	0	1	0	1	1	0	0	0	0	1	0	0
7	0	0	1	0	1	1	0	0	0	0	1	1	0

Obtaining data from a newly analyzed fossil specimen, or newly described locality, is no different methodologically than obtaining data from a new experimental trial. Our knowledge of the history of life is advanced by deliberate search based on the predictive power of the concept of common descent.

The perception that evolution is inherently untestable is likely shared by many entering college students. It is therefore important that students be presented with real examples of how hypotheses of evolutionary relationships can generate predictions that are subject to testing. Because of the continued rapid pace of new fossil discovery, the fossil record can be used quite effectively to illustrate how particular evolutionary hypotheses have been supported by subsequent fossil discoveries. Cladograms are a particularly useful tool for this purpose.

Phylogenetic analysis not only reveals the branching patterns of the history of life as currently known, but also generates testable hypotheses (Carlson, 1999). Cladograms are hypotheses of evolutionary relationship that can be tested against the fossil record. Interpreted as phylogenies, they yield predictions of the relative order of appearance of different anatomical characters in the fossil record, and the relative order of divergence of different taxonomic groups (e.g., the nested order of branching points). Cladograms can also extend the predicted temporal ranges of fossil taxa, identifying so-called "ghost ranges" beyond where fossil representatives are currently known. Evolutionary hypotheses also result in expectations concerning the general character states of transitional forms between known sister taxa and their presumed common ancestors. It is

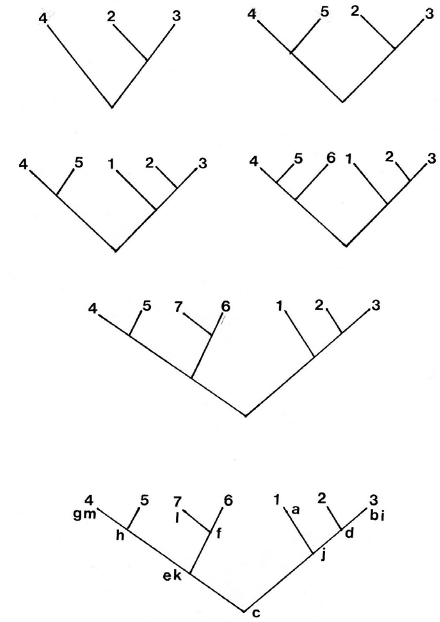

FIGURE *1*.—Construction of cladogram from data matrix. The final cladogram shows position of character states at branching points.

important to emphasize these predictive aspects of the model of common descent to properly present paleontology as a rigorous scientific discipline.

EXAMPLE LESSONS

To illustrate ways in which the above educational objectives can be pursued, I will briefly describe some lessons and assignments used in my introductory level, non-major, geology course, "The Age of Dinosaurs." This course has no prerequisites and includes mostly non-science majors. For many of the students, this course will be one of only a handful of college science classes they will ever take.

I begin the course with a historical survey of the development of modern conceptions of Earth and life history. Starting with Gesner's descriptions of "fossil objects" in the 1500s, this survey includes discussions of Steno, Hutton, Cuvier, and ends with Darwin. Much of this synopsis is based on Rudwick's (1985, 2005) excellent work in the history of paleontology. This historical overview describes how fossils were first recognized as the remains of living organisms, placed within the context of Earth history, and tied together into a

CONSTRUCTING A CLADOGRAM FROM A DATA TABLE

Every student will be given a presence/absence data table for a group of dinosaurs. Different students will have different groups of dinosaurs and different characters listed on their tables. The anatomical characters chosen for each data table are important for distinguishing between the different dinosaurs in that group. It is not important that you understand the meaning of the anatomical characters used.

Skeletal reconstructions for the dinosaurs listed on each table are included with the data table. After you have constructed the cladogram, the skeletal reconstruction can help you visually see how your cladogram has grouped your particular collection of dinosaurs.

On the due date, you should turn into me the final cladogram that you have constructed. The cladogram must show the names of the different dinosaurs at the end of the cladogram branches.

FIGURE *2*.—Copy of dinosaur cladogram assignments given to students in the non-major introductory class "Age of Dinosaurs."

diversifying evolutionary tree. Most importantly, the construction of these important concepts is placed against the backdrop of the critical questions and conflicts of the time. Geological and paleontological science is revealed, not as a steady, objective pursuit of facts, but as a continuing process of constructing explanatory models that make sense of the observations at hand. Students are not told the "right" answers, so much as shown why the scientific community came to hold the views that it does. In the process, students are likely to encounter some of their own prior misconceptions.

After the above historical background, I introduce the science of classification beginning with the Linnean system that is familiar to most students. This is followed by a discussion of the problems and limitations of the Linnean system, and the reasons for the recent switch to a phylogenetic approach. I emphasize to the students dur-

TABLE *2*.—Example of presence/absence data matrix for character states of a select group of dinosaurs used in student homework assignment. Characters A–M: A, Open acetabulum; B, Triradiate pelvis; C, Tail stiffened by interlocking vertebrae; D, Large opening in snout of skull; E, Wrist bone permitting folding of hands; F, Long arms and grasping hands; G, Furcula or wishbone; H, Flexible tails; I, Sickle-like claw on hind foot; J, Long flexible neck; K, Bony crest on skull; L, Long toothless snout; M, Massive skull w/ robust teeth; N, Short skull w/ toothless beak; O, Numerous small serrated teeth; P, Downward/backward pointing pubis.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Allosaurus	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Ceratosaurus	1	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0
Coelophysis	1	1	0	0	0	0	0	1	0	1	0	0	0	0	0	0
Eoraptor	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ornitholestes	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Oviraptor	1	1	1	1	1	1	1	0	0	0	0	0	0	1	0	0
Struthiomimus	1	1	1	1	1	1	0	0	0	0	0	1	0	0	0	0
Troodon	1	1	1	1	1	1	1	0	1	0	0	0	0	0	1	0
Tyrannosaurus	1	1	1	1	0	0	0	0	0	0	0	0	1	0	0	0
Velociraptor	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0	1

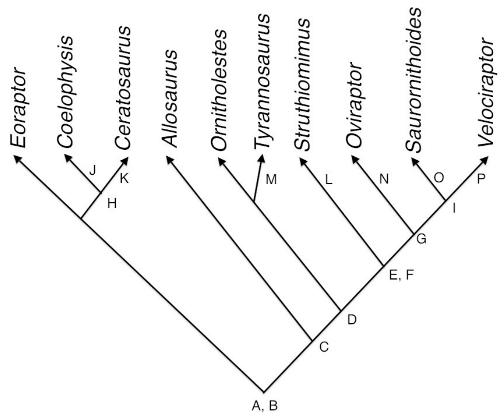

FIGURE 3.—Cladogram constructed from the data of Table 2 showing positions of character states.

ing this discussion that classifications are interpretations of the observed diversity of life, and are not objectively descriptive of it. Different classifications can be chosen based on what particular information the classification is intended to convey. This can be illustrated by having students suggest various ways to group a set of objects.

Because phylogenetic systematics is so important for revealing evolutionary patterns of relationship, I spend time having the students learn to construct simple cladograms themselves. Using a simple hypothetical data matrix (Table 1), I work with the students to construct a cladogram step-by-step (Fig. 1). The active process of constructing a cladogram helps reinforce for students that cladistic classification is based on specific character states shared uniquely by a particular group, and generates a groups-within-groups branching pattern. This exercise also emphasizes to students that the branching points in a cladogram represent character states and not taxa. This becomes important when discussing the distinction between ancestors and sister taxa.

After students understand the basics of cladogram construction, they are given an assignment to build a cladogram for a specific collection of dinosaurs (Fig. 2). They are presented with a simple character matrix for their group of dinosaurs, and a skeletal reconstruction for each taxon in the group (Table 2). The number of taxa and character states is kept small so that the assignment is manageable and instructive, rather than frustrating and confusing. As a final product, the students submit a completed cladogram with the taxonomic names and the positions of the character states properly indicated (Fig. 3). The skeletal reconstructions provided enable the students to visualize how the cladograms they have constructed have organized their particular taxa. Different groups of students are given different taxa with different character tables, but with overlapping outgroups. As a result, by combining their individual cladograms, the class as a whole will have constructed a cladogram that includes most of the major groups of dinosaurs.

Having constructed cladograms, the students are now introduced to how these branching diagrams serve as hypotheses of evolutionary relationship. When interpreted as phylogenies, the cladograms make predictions of the fossil record. Because assumptions of evolutionary relationship, or relative fossil ages, were not used to construct their cladograms, students can more readily recognize that the evolutionary predictions derived from them do not involve circular reasoning. The students' cladograms can now be used to make predictions about the order of appearance of the different dinosaur groups. The relative order of branching implies a particular temporal order in which various anatomical characters would be expected to appear in the fossil record. Cladograms can also be used to predict the presence of certain groups of dinosaurs during time intervals for which they are currently unknown (ghost lineages). The students can now begin the transition from seeing paleontology as merely descriptive to

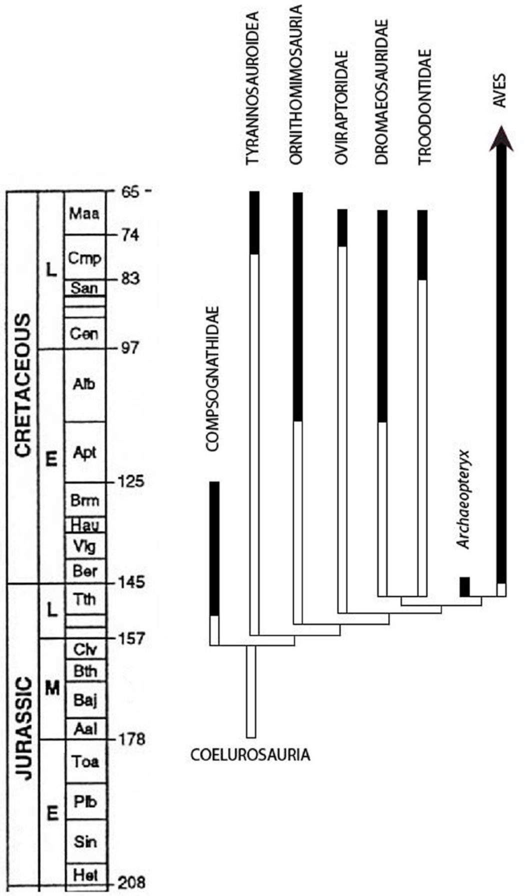

FIGURE *4*.—Time-calibrated cladogram for coelurosaur dinosaurs based on fossil evidence known by 1990. The solid bars represent time intervals during which fossils are known, and the open bars represent predicted ranges for which fossils not known ("ghost ranges").

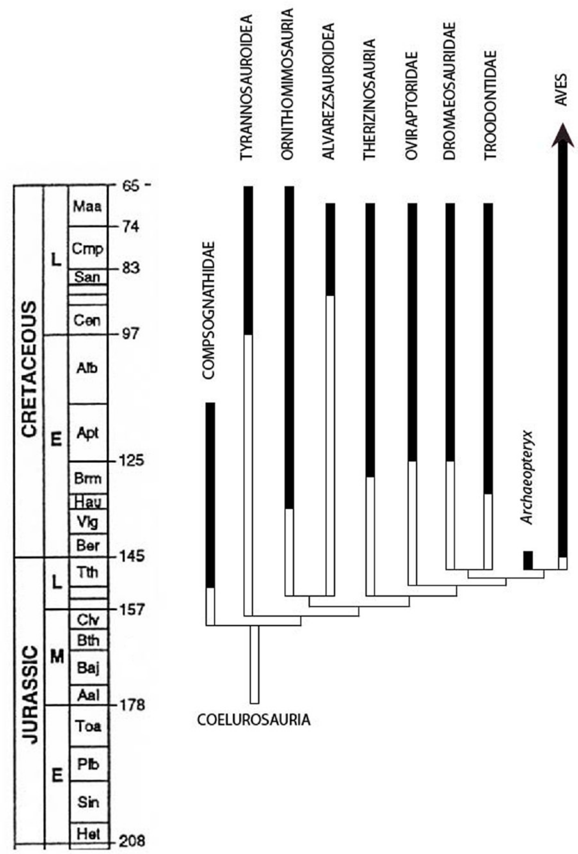

FIGURE *5*.—Time-calibrated cladogram for coelurosaur dinosaurs based on fossil evidence known by 2000. The solid bars represent time intervals during which fossils are known, and the open bars represent predicted ranges for which fossils are not known ("ghost ranges").

seeing it as a predictive science.

By maintaining the focus on patterns of relationship, it is less likely that prior conceptions of ladder-like evolution will be reinforced. Cladograms also provide a way to emphasize that the goal of paleontologists is not to find ancestors, or missing links, but to determine the relative degree of relationship between known species. Furthermore, it becomes apparent that transitional forms will be found by moving down the tree to more primitive and less derived forms. Cladograms can also predict the character states that would be expected in yet undiscovered transitional forms.

I use the predictive character of cladograms later in the course to show how these predictions can be confirmed by future discoveries. The extraordinary rate of new discovery in dinosaur paleontology provides an excellent opportunity to illustrate how evolutionary hypotheses either can be confirmed or overturned. Contemporary discoveries and debates also reveal paleontology to be a dynamic, theory-driven science.

Recounting the history of dinosaur fossil discovery during the course provides an effective way to continue to emphasize the predictive elements of evolutionary models. One way to do this is to show cladograms that represent the state of knowledge of the fossil record at different times in the history of discovery. Especially useful are cladograms that are superimposed on the geologic time scale, and indicate the time intervals during

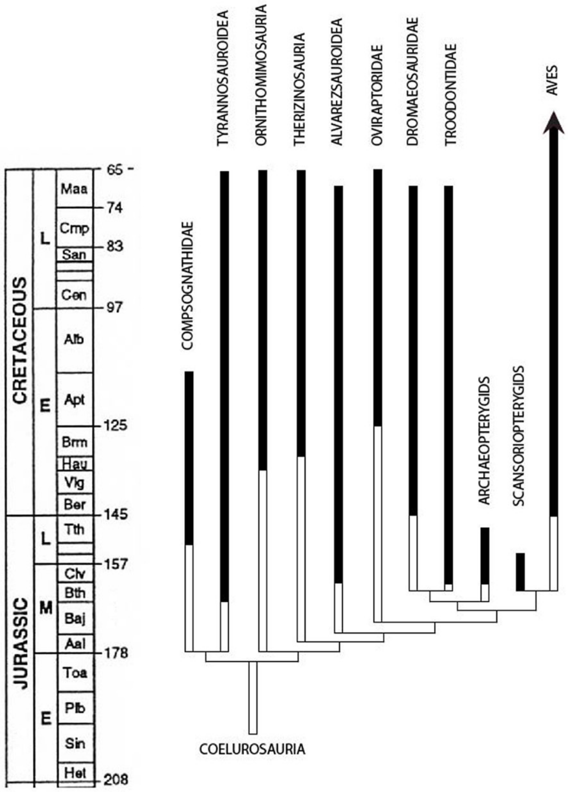

FIGURE *6*.—Time-calibrated cladogram for coelurosaur dinosaurs based on fossil evidence known by 2010. The solid bars represent time intervals during which fossils are known, and the open bars represent predicted ranges for which fossils are not known ("ghost ranges"). Compared with Figures 4 and 5, note the additions of new dinosaur groups, the changes in some sister group relationships, the extensions of known fossil ranges, and the movement of predicted ranges further into the past.

which fossil representatives of various taxonomic groups are known. This enables a visual comparison of the minimum predicted time ranges for the various dinosaur groups with their currently known fossil ranges. The resultant ghost ranges become areas of particular interest for future discovery.

For my class, I have used the time-calibrated phylogeny of the dinosaurs published by Sereno (1999) as a basic template with which to work. Using this as a starting point, I have modified it according to the knowledge of the fossil record existing at different times over the last several decades. The coelurosaurs are an excellent group to illustrate how new discoveries serve to test previous hypotheses of evolutionary relationships (see Turner et al., 2007; Brusatte et al., 2010; Zanno, 2010; Xu et al., 2011). For example, Figure 4 is a cladogram of Coelurosauria based on the fossils known by 1990. There are large ghost ranges for the taxa that are interpreted as most closely related to birds, and no bird-like dinosaur fossils predate the first known birds. However, cladograms based on the fossil record known by 2000, and 2010 (Fig. 5, 6) show significant changes. The ghost ranges are significantly filled in as geologically older fossil specimens are discovered, and the predicted ranges themselves are moved further back in time. Furthermore, previously unknown coelurosaur dinosaur groups are recognized, and, by 2010, fossils of some bird-like dinosaurs are discovered that predate the earliest birds. These cladograms provide a visual way of illustrating how evolutionary predictions of the fossil record can be substantiated and/or modified by new discoveries.

The predictive power of evolution was further elaborated to the students by reviewing the character states predicted by the cladograms for the various bird-like dinosaurs. With the first discovery of filamentous body coverings in the compsognathids (Chen et al., 1998), and the subsequent discovery of feather-like structures and true feathers in several coelurosaur and maniraptoran dinosaurs (Ji et al., 2001; Xu et al., 2003), new expectations for the anatomy of coelurosaur dinosaurs were generated. Placing the observed integumentary structures of these many exceptional fossil discoveries into a phylogenetic context results in an evolutionary model that can be tested against new fossil discoveries and evidence from other disciplines, such as embryology (Prum and Brush, 2003). The same can be done with other observed skeletal features of these taxa. A wide range of observational data can be superimposed on time-calibrated cladograms to produce a summary of evidence for an evolutionary hypothesis. Padian (2010) refers to these information-rich diagrams as "evograms."

The media coverage of new fossil discoveries, rather than being perceived as announcements of bizarre curiosities to be added to our museums, or of triumphal discoveries of elusive "missing links," can be used to tell the much more interesting story of how our evolutionary models are being continually confirmed and refined. Skeletal information from new fossil discoveries provide additional reference points for predicting character states not yet observed in particular dinosaur groups. Describing the subsequent discovery of fossils showing these predicted characters serves to show the students the important role of hypothesis testing in paleontology. These new discoveries are not just interesting peculiarities, but fit into a broad theoretical framework that gives those discoveries special meaning. Paleontological science seeks not just to describe, but to understand and explain. Evolution provides that explanatory framework.

CONCLUSIONS

Undergraduate students will enter classes in geology and paleontology with many common misconceptions about evolution and the fossil record. This prior knowledge must be explicitly recognized and engaged in the classroom. If it is not engaged, new course content will likely be either rejected, or integrated into the student's previous conceptions, resulting in a distorted understanding.

Presenting scientific concepts in their historical context can be an effective way to engage mistaken views. Teaching the history of the discipline has the dual benefit of showing how currently accepted scientific theories developed in competition with other competing views, and presenting a more human and realistic picture of the scientific enterprise. Students will likely encounter their own prior misconceptions in these historical accounts, and see the reasons why they were abandoned in the past.

The fundamental evolutionary concept of common descent is illustrated by the image of a branching tree or bush. This simple but powerful image provides an effective way to counter many student misconceptions. Perceiving the tree of life is a matter of pattern recognition. The vast body of paleontological evidence supporting common descent is in the historical, geographic, and anatomical patterns that are present. It is these patterns that we should emphasize when presenting our science. One important way to emphasize patterns over the particulars is to present fossil data within a phylogenetic context. This requires students to understand the basics of constructing and interpreting cladograms.

Because there is a common public perception that evolution is inherently untestable, it is important that students be presented with real examples of how hypotheses of evolutionary relationships can generate predictions that are subject to testing. Hypothesized patterns of evolutionary relationship generated by phylogenetic analysis yield predictions of the relative order of appearance of different anatomical characters in the fossil record, extend the known temporal ranges of fossil taxa, and produce expectations concerning the general character states of transitional forms. Because of the continued rapid pace of new fossil discovery, the recent history of paleontological research can be used quite effectively to illustrate how particular evolutionary hypotheses have been supported by subsequent fossil discoveries.

The primary recommendation of this essay is that paleontology should always be taught historically. Paleontology is not a static descriptive science, but a continually evolving process of building explanatory models. The more students are invited into that history of discovery and theory-building, the better.

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