Trickle-down evolution: an approach to getting major evolutionary adaptive changes into textbooks and curricula

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Synopsis Although contemporary high school and college textbooks of biology generally cover the principles and data of microevolution (genetic and populational change) and speciation rather well, coverage of what is known of the major changes in evolution (macroevolution), and how the evidence is understood is generally poor to nonexistent. It is critical to improve this because acceptance of evolution by the American public rests on the understanding of how we know what we know about the emergence of major new taxonomic groups, and about their adaptations, behaviors, and ecologies in geologic time. An efficient approach to this problem is to improve the illustrations in college textbooks to show the consilience of different lines of fossil, morphological, and molecular evidence mapped on phylogenies. Such "evograms" will markedly improve traditional illustrations of phylogenies, "menageries," and "companatomies." If "evograms" are installed at the college level, the basic principles and evidence of macroevolution will be more likely taught in K-12, thus providing an essential missing piece in biological education.

Introduction

In autumn 2005, the "intelligent design" trial took place in Dover, Pennsylvania. That trial was a test of whether "intelligent design" was accepted as science by the scientific community, and whether it could be legitimately introduced as science in science classrooms. Judge John E. Jones III's decision, to the relief of scientists and teachers everywhere, was a resounding "NO" (Jones 2005), affirming that "intelligent design" was simply a form of creationism, as the plaintiffs contended. The National Center for Science Education, of which I am president and of which many SICB members are longtime supporters, was principally responsible for coordinating the scientific case on the side of the plaintiffs, along with their attorneys from the ACLU and the law firm of Pepper Hamilton LLP, Philadelphia.

I had the privilege of serving as an expert witness in the trial. My role was to explain to the judge how scientists know what we know about the major transitions of form and function in evolution, and to show how intelligent design creationism, mainly as shown in their "textbook," *Of Pandas and People* (Davis and Kenyon 1993), intended for high school biology students, distorts what scientists understand about the major features of evolution, and how we come to understand them and test our ideas about them. That subject is the stock in trade of biologists like us, and so we have to ask ourselves: why is our message not getting out to the American public? Why do they not understand at least the rudiments of what we work on, teach, and talk about every day? Ordinary people love dinosaurs, fossil mammals, extinct sharks, and all manner of prehistoric monsters as much as they do living animals. They watch nature documentaries on television endlessly. Why do they not understand more about our science? Why is it that between a third and a half of the American people doubt that evolution has occurred at all?

Polls vary (Brooks 2001; People for the American Way 2003) depending on how the questions are asked and who is asking them; but about a quarter of the American public agree with evolution all the way. About a quarter of us think it is wrong, false, and evil. These numbers, at least in the Gallup poll, have not changed substantially in a quarter century, despite much political change and the resurgence of the Religious Right. The latter view is overwhelmingly associated with fundamentalist Christians (and other religious fundamentalists) who are not likely to modify their religious views in the face of scientific evidence. Although it is certainly not the business of science to dissuade people from their religious convictions, frank dialogue is often welcomed by fundamentalists who sincerely want to learn what

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they are up against. More importantly, I suggest, it is the 40–50% in the middle of the population, the undecided, uncommitted, or unlearned, that scientists need to reach.

One way to reach these people is to show them straightforwardly what we know, and how we know what we know, about the major changes in evolution. Why focus on this? Because it is the single area of science that is most poorly understood and most mistrusted by fundamentalists and others whom they have convinced that what scientists are telling them is wrong.

The late Stephen Jay Gould (1980) recognized three empirically separate, but phenomenologically interconnected, levels of evolution: microevolution, speciation, and macroevolution. Microevolution—change within species and populations—is not seen as a problem for most antievolutionists. They write it off as simply noise in the system, the kind of processes that give us breeds of dogs, changing resistance to antibiotics, and different kinds of turtles (it is not yet clear to "baraminologists," those who study *baramins* or "created kinds" as revealed in the Bible, whether turtles are one baramin or many). Speciation is a problem for most creationists, including "intelligent design" advocates (who often try to be coy about the subject), because there are implications for the emergence of what might be new equivalents to "created kinds." Above all, antievolutionists hate the idea that new major groups, adaptations, and behaviors can form from previous major groups, adaptations, and behaviors. This is why scientists have to emphasize this dimension of evolution much more than we now do, so that people who have had no exposure to our knowledge of macroevolution, or only to disparagement of it, can understand what we know and how we know it—rather than learning about what is allegedly wrong with it from antievolutionists. This change, I argue, should begin with the textbooks that we use.

Trickle-down education

One may or may not be a fan of "trickle-down economics," but there is reason to support "trickle-down education." This is what might be called the principle that the determination of what is important to know in a field starts at the top of the educational chain. If it is not taught at the college level, it will not be taught at the K-12 levels. Curriculum developers need to see how K-12 instruction articulates with postsecondary courses so that they can prepare their students accordingly. They want to know what concepts and skills need to be developed in K-12 in order to prepare students for college work. Scientists need to determine these things, because research begins at the university level. This makes it all the more important that scientists continue to work with K-12 educators to get these concepts taught better in high school and earlier. A different point, however, is stressed here: scientists can and must begin to improve education in evolution in the universities. That should not be difficult for most SICB members, because that is where most of them are employed.

I want to outline briefly three questions: What to teach, how to teach it, and how to get it into textbooks.

What to teach that is not being taught now

Some of the most exciting parts of our field, the concepts and discoveries that stimulate the most interest in the press, among the public, and with the people who write books and make documentaries and TV shows, concern the origins of the *major features in evolution*—principally vertebrate evolution. The field that is properly called integrative paleobiology—not just discoveries of remarkable animals and plants, nor even their phylogenetic placement, but rather what we can reconstruct about the living creature's properties, abilities, functions, and surroundings, and how they evolved—is unique. We have the data that substantiate the major changes in evolution—from the origin of jaws and bones to the emergence of vertebrates on land, from the radiation of dinosaurs to the origin of birds and flight, from the assembly of the myriad features of jaws, ears, brains, and teeth in ancient mammalian relatives to the radiation of placentals and marsupials over the past 70 million years.

Integrative biologists are used to solving historical problems through the use of a variety of lines of evidence. We use cladograms of fossils, morphology, and molecules to assemble phylogenies. We use stratigraphy and radiometric dating to establish events in time. We use paleoecology to interpret ancient environments. We use histology, geochemistry, fossil footprints, functional morphology, physiology, and biochemistry as independent lines of evidence to test our hypotheses. To us, this is normal science. To people outside our field, it often seems like magic, but it should not.

Figure 1 shows an example of a major transition in evolution. This illustration might usefully be called an "evogram." The diagram is complex, and it takes a while to explain all its features. This should

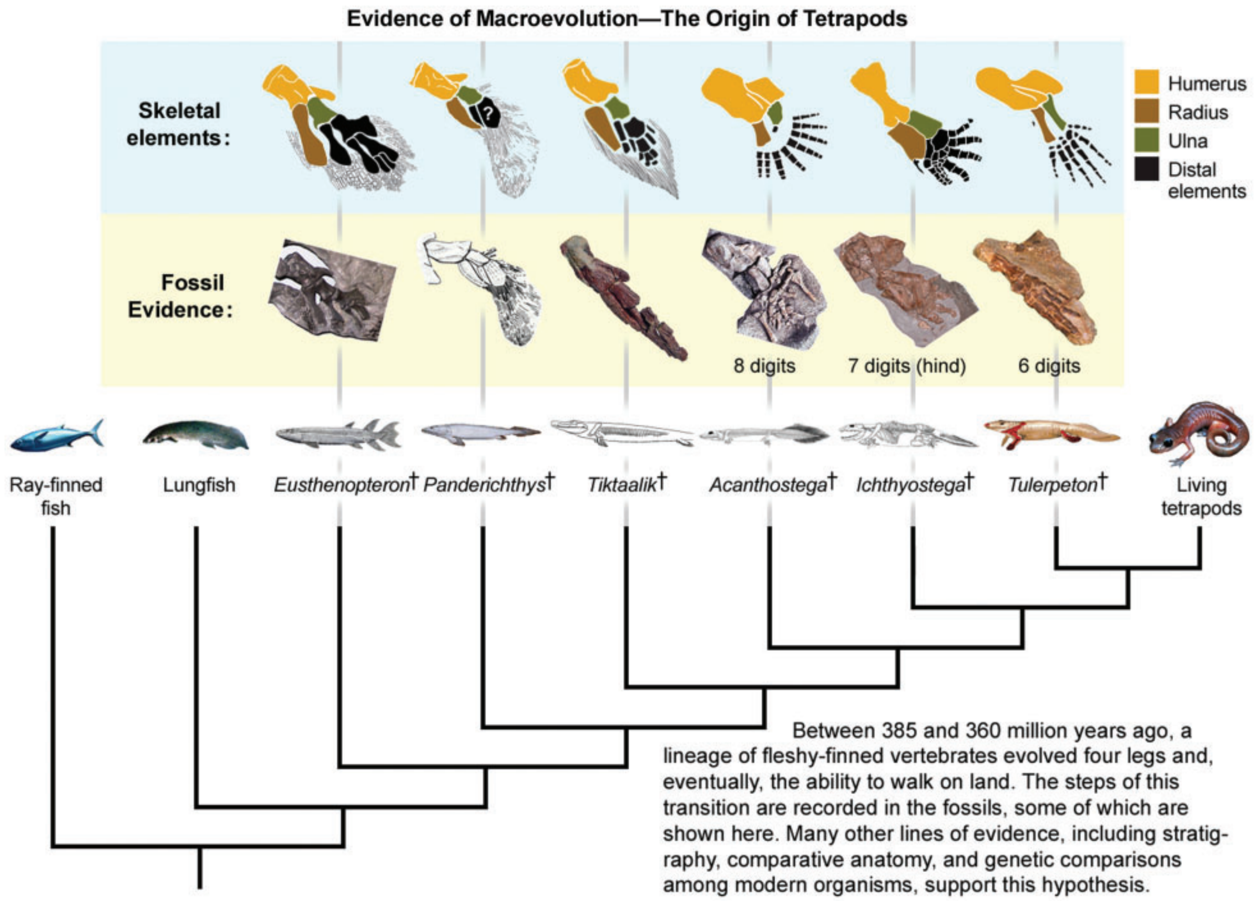


Fig. 1 "Evogram" by Brian Swartz and Josh Frankel of UCMP, developed by Brian Swartz for the Dover "intelligent design" trial. This kind of diagram conveys an integration of information succinctly and economically, and shows the consilience of independent lines of evidence. To the nodes on the phylogeny could be added important clade names or salient synapomorphies or features relevant to the assembly of major evolutionary features.

not worry us; integrative biology requires several independent lines of evidence. There is a set of fossils, which are illustrated in one row, much as they are seen as fossils and in photographs and drawings. A second row interprets the structures of their limbs: corresponding bones are presented in corresponding colors. Even though their shapes may change, their connections remain the same, and they are homologous, therefore. The backbone of the cladogram demonstrates the phylogenetic relationships among these forms, as established by another entirely separate base of information. To the nodes of this cladogram could be added important clade names (such as Sarcopterygia or Tetrapoda), important synapomorphies, or evolutionary trends (such as the reduction of fingers on the limbs, to show the progression of change of features toward land life).

The principles that are taught along with this evogram embody the general approaches of integrative biology (Brooks and McLennan 1991; Harvey and Pagel 1991). A cladogram is basic to understanding evolutionary relationships. Whenever we want to talk about the evolution of a structure, a function, or a behavior, we need to compare any hypotheses against a phylogenetic hypothesis (or against several of them). The functional hypotheses are not derived from the cladogram (otherwise they have no content other than to restate the phylogeny); rather, they are derived from inferences based on other lines of evidence (Padian 1982, 1995, 2001) and tested against the phylogenies. Different functional (process) hypotheses may match, to greater or lesser extents, the phylogenies (patterns) of character change in clades, and will make those hypotheses more or less robust.

If high school and college students can be shown how to grasp what is represented in an evogram, they will understand how we conduct our research on macroevolution. That means that the scientists win, and not the antievolutionists. Our field is no longer misconstrued as mysterious guesswork or speculation. Fossils are not seen as "direct ancestors" or "transitional forms" between one and the next one, but rather as representatives of lineages that share certain features with more basal and more derived forms at the same time.

How to teach it

To convey the meaning of evolution—particularly macroevolution—to students and the rest of the public, they need to understand the comparative method in biology. In discussing macroevolution, this entails how we reconstruct and test hypotheses about phylogenies, morphological change, adaptive and behavioral change, and structural change in an integrative way. That is, how we weigh various independent lines of evidence against each other to demonstrate consilience (Whewell 1837; Wilson 1998). Our challenge is how to teach people who are not learning this in school, how we do the science that we do—how we know what we know. Most of this knowledge, of course, is (or should be) delivered through textbooks, on which both students and instructors (who cannot be experts on every phase of evolutionary biology) must rely.

How well, then, do current textbooks at the college level explain basic macroevolutionary principles? I undertook an examination of the major textbooks on sale in the United States that supply courses in high school biology, introductory college biology, and upper division courses in evolution, comparative vertebrate anatomy, and vertebrate paleontology. Surprisingly, there is almost no illustrated representation of the methods that we use in comparative biology to study macroevolution. Almost none of the main problems of the field, as one would readily find them in issues of the journal *Paleobiology* for the past 30 years, are discussed in current texts on evolution. Although some of the ingredients are there in the text and (or) illustrations, there is nothing like the evogram portrayed in Fig. 1, and relatively little explanation of these issues and methods. As a result, students receive a poor concept of how we know about how the major changes in evolution have taken place.

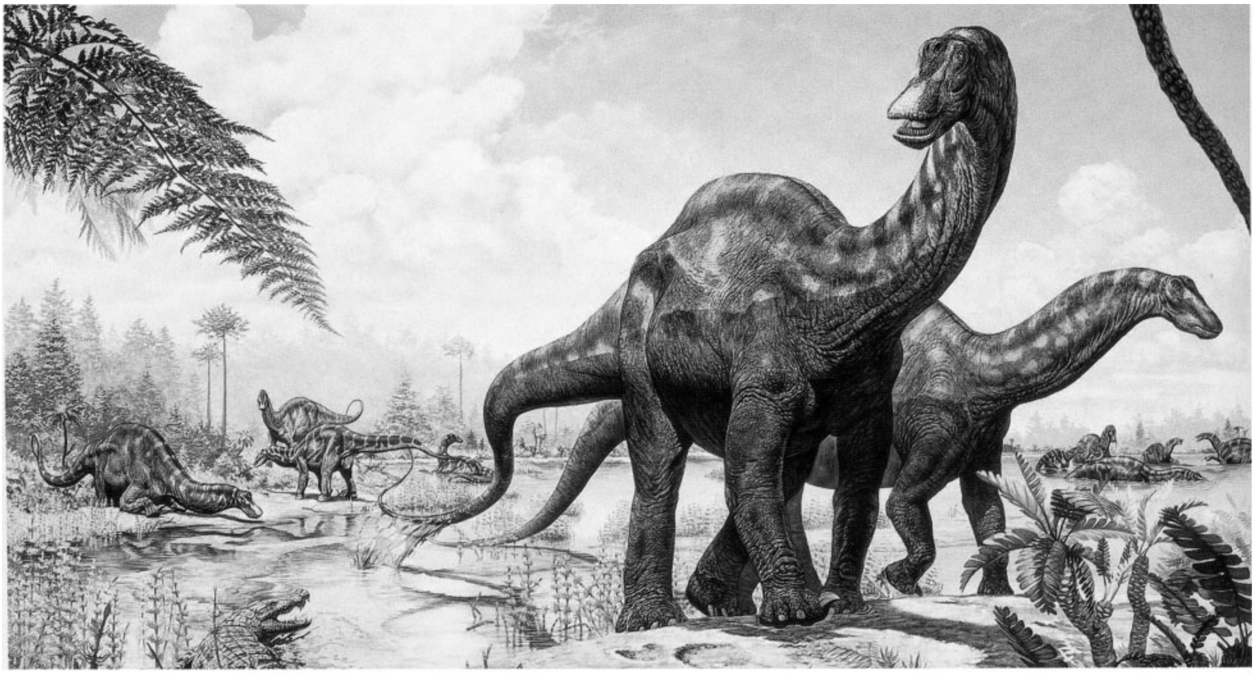
The high school situation

The best-selling high school biology textbook is Ken Miller's and Joe Levine's (2006) *Prentice-Hall Biology*. Ken Miller is a professor at Brown University and was also an expert witness in the Dover "intelligent design" trial, a person of tremendous energy and unfettered advocacy for evolution. His coauthor, Joe Levine, is equally energetic, having worked for years at WGBH in Boston on NOVA programs for public television. One would expect, therefore, a strong treatment of evolution in their text. Apparently, it is too strong for many districts; it was rejected by conservative members of the Dover (PA) school board in 2004 because it was allegedly "laced with Darwinism" (Humes 2007), and it continues to face criticism in other states, largely fueled by the canned diatribes of antievolutionists in the Discovery Institute.

Consider, then, the sample page in Fig. 2 from the current version of *Prentice-Hall Biology*, which deals with the age of dinosaurs. There is no real sense of evolution or how it is studied. Animals and plants "appeared," "ruled," "lived," and "became extinct." There is a reference to new discoveries in China, but no methodological sense of how scientists do their work or reach their conclusions. Students are told that "Many paleontologists now think that birds are close relatives of dinosaurs," but it was established beyond reasonable doubt more than two decades ago that birds evolved from small carnivorous dinosaurs in the Late Jurassic, and are themselves members of Dinosauria (Padian and Chiappe 1998). The text also uses the abhorrent construction "many scientists think," as if it were decided by vote ("many"), as if the opinions of stockbrokers or milkmen on this topic were of interest ("scientists"), and as if the whole exercise were simply conjecture ("think").

This, of course, is not the only treatment of large-scale evolution in the book. There are two-paragraph sections on "Adaptive Radiation," "Convergent Evolution," and so on, but they can do little more than define the terms and assure students that such things exist. In contrast, the coverage of microevolution and genetics is much better and more extensive, but these subjects are also less controversial and better understood by teachers and biologists in general. Textbooks like this weigh on average about four pounds, more than the *Oxford Annotated Bible with the Apocrypha*, but they do little teaching, serving instead as encyclopedias of bold-faced vocabulary words and concepts. This is not Miller's and Levine's fault; it is the result of a bloated, out-of-control industry that is forced to worry more about how much white space is on a page than about whether a subject is being usefully and accurately communicated.

Miller's and Levine's text is arguably the best of the bunch at the high school level. They are not failing to present a more accurate, integrated picture of macroevolutionary research because they do not want to do so, or because they do not know how, but because the system does not permit them to do so. Like other publishers, they have to face 50 different



During the Mesozoic Era, dinosaurs were dominant. *Dicraeosaurus* (foreground) was a plant-eater that grew to about 20 meters in length.

Jurassic Period During the Jurassic (joo-RAS-ik) Period, dinosaurs became the dominant animals on land. Dinosaurs "ruled" Earth for about 150 million years, but different types lived at different times. At 20 meters long, *Dicraeosaurus*, was one of the larger dinosaurs of the Jurassic Period.

One of the first birds, called *Archaeopteryx,* appeared during this time. Many paleontologists now think that birds are close relatives of dinosaurs. Since the 1990s, scientists working in China have found evidence for this hypothesis in other fossils that have the skulls and teeth of dinosaurs but the body structure and feathers of birds.

Cretaceous Period Reptiles were still the dominant vertebrates throughout the Cretaceous (krih-TAY-shus) Period. Dinosaurs such as the meat-eating *Tyrannosaurus rex* dominated land ecosystems, while flying reptiles and birds soared in the sky. Flying reptiles, however, became extinct during the Cretaceous. In the seas, turtles, crocodiles, and extinct reptiles such as plesiosaurs swam among fishes and marine invertebrates.

The Cretaceous also brought new forms of life, including leafy trees, shrubs, and small flowering plants like those you see today. Unlike the conifers, flowering plants produce seeds enclosed in a fruit, which protects the seed and aids in dispersing it to new locations.

At the close of the Cretaceous, another mass extinction occurred. More than half of all plant and animal groups were wiped out, including all of the dinosaurs.

Fig. 2 An example of how major macroevolutionary change is covered in high-school textbooks, from Miller and Levine (2006, Figs. 17 and 18, p. 432). Some basic facts and patterns can be conveyed, but little about how scientists know what they know and the methods they use. Courtesy of Pearson Education; illustration of *Dicraeosaurus* courtesy of Mark Hallett, © 1990; used by permisson.

"content standards" documents in 50 different states (of all developed countries, only the United States does not have a national curriculum). It is a fine line to walk: some states penalize publishers for devoting *more* attention to a topic than they require, as well as for less attention. The state science standards are not usually written by scientists, and their language may strongly conflict among states. Evolution is the most controversial subject in biology for K-12 curricula; although genetics is presented extensively and straightforwardly in K-12 books, much less room is allowed for evolutionary subjects than is warranted by their central importance to biology.

For decades, most K-12 science curricula at the state and local levels have been determined by specialists in science education curricula, teacher focus groups, professional writers in publishing houses (most with little scientific experience), and pressure groups—not by scientists. There is little hope of changing this K-12 system substantially anytime soon because the inertia, the lack of coordination, and the entrenchment of historically invested interest groups militate against it. Although the struggle should not be given up, scientists can lead in another way by example, specifically by making college books better. The argument is that if these concepts are taught more strongly at the college level, beginning with introductory biology, K-12 students will not be prepared for college-level work unless they are introduced to the concepts in high school. Therefore, if the college-level texts cover these concepts better, the K-12 books will eventually have to follow suit. An even stronger argument is the inverse of this: if we do not improve college texts, the concepts will never be taught in precollege.

A further and indispensable dimension to this problem is that no matter what is presented in text books, if teachers are not intellectually prepared to teach the concepts, the ideas will not get through to students. There are two responses to this challenge. First is that evolutionary biologists, regardless of specialty, can and should work with local teacher organizations to help implement these concepts at the state and local levels. The second is that science teachers are intelligent, educated, and enthusiastic, and if the material in texts is written at an appropriate level, with appropriate support from supplementary teaching materials that come with the textbooks, and from websites (for example, *http://evolution.berkeley.edu/*) and published literature, teachers are perfectly capable of pursuing their craft by learning new material and communicating it to their students. We are talking here about the greatest narratives in the history of life. If there are biology teachers who cannot understand them or get their students excited about them, frankly, they should probably seek another profession.

College-level textbooks

How well, then, do college-level texts treat what scientists understand about major evolutionary transitions? One of the best indications is the illustrations, an extremely important component and a major expense of textbook production. To be effective, the illustrations in a book must have a consistent style, and be clear and engaging. They convey in images what the texts can deliver only in words. So the focus here will be on the effectiveness of illustrations as a proxy for the totality of coverage that is also reflected in text, self-tests, ancillary exercises, teacher instructions, and activities that articulate with other disciplines. The integration of information shown in the evogram in Fig. 1 will be used as a model against which illustrations in contemporary texts are compared.

I studied a range of books in general (introductory) biology and in advanced undergraduate courses in evolution, vertebrate paleontology, and vertebrate comparative anatomy and evolution. In general, I found three kinds of illustrations: phylogenies (cladograms or trees, sometimes calibrated against a geological column), "menageries" (illustrations of the diversity of animals in a particular group), and what might be called "companatomies" (illustrations of the diversity of structure in a particular group). Phylogenies, in general, are critically important for showing the relationships of organisms under study, especially when they provide at least some of the principal characters used to construct the phylogenies (an essential feature for showing how we know what we know). "Menageries" and "companatomies" are useful for depicting discussions in the text (when present) of the structure of diversity in the groups; however, without some clear evolutionary context, such as a phylogeny provides, they simply show several "kinds" of organisms or structures, and so are equally easily interpreted by creationists as illustrating "created kinds." I will argue here that none of these kinds of illustrations is adequate by itself; rather, a truly effective illustration of evolution has to include elements of all three.

Let me clarify at the outset that in my view these are all fine books in their own ways, and most will fit the usual expectations for textbooks in a course, given competent instruction, and individual tastes of instructors. Here, however, the focus is narrowed to ask how well the illustrations in these books explicitly show evolutionary connections, like the "evogram" in Fig. 1. To test this yourself, merely leaf through any of these books (particularly those in vertebrate morphology) and identify how many figures are phylogenies, "menageries," and "companatomies"—compared with "evograms" that explicitly demonstrate evolutionary change. Then see how many missed opportunities there are in these illustrations to add an explicit evolutionary component, and, therefore, teach tree thinking and the continuity of adaptive, ecological, and behavioral change. This is what, it is argued here, needs to be improved and can be relatively easily achieved.

Introductory biology

For several recent editions, Campbell's and Reece's *Biology* (6th edition, 2002), the leading seller at the introductory college level, has contained cladograms of the diversity of life, which is a bonus over most texts of a decade ago (and even some of today); some have major diagnostic features, such as the vertebral column and the amniote egg, labeled at appropriate nodes; others are drawn against a geologic time column. There are also menageries and companatomies in the book, as well as illustrations of individual organisms and structures, but these are not integrative illustrations, and so do not illustrate well how we know what we know about the major transitions in evolution. Moreover, even in the most recent edition (Campbell et al. 2008) phylogeny is not taught until *after* the unit on evolution, so there is no opportunity for students to learn how scientists integrate phylogenetic analyses with hypotheses about evolutionary process.

Evolution textbooks

Among upper division texts on evolution there is a wide variety of approaches. Strickberger's *Evolution* (3rd edition, 2000) is textually strong in emphasizing major features in the evolution of life and the fossil record, but it is defeated by its old-fashioned illustrations of wavy-lined trees of life, discarded nomenclature, and outdated portrayals of relationships. A student would, however, get a stronger sense of the general importance and the understanding of major evolutionary transitions from the text of this book than from most others in the field.

Freeman's and Herron's *Evolutionary Analysis* (4th edition, 2007) is popular for its strong approach to microevolution; however, it has virtually no coverage of macroevolution. There is a box in one chapter that uses independent contrasts to explore evolutionary change in three related species of bears; however, the story of the "three bears" is merely an exercise in arithmetic, with no real evolutionary value. Their fourth edition also has a passage on the "law of succession" (invented in the early 1800s) that seems unrelated to the rest of the text, and elsewhere a menagerie of fossil whales, but missing are the real details of what is known of how and in what sequence cetacean characters and ecological habits evolved, although these topics have been well understood for years. The authors describe the phylogeny and evolution of organisms from a molecular perspective only, as if no evidence from fossils could bear on phylogenetic questions (to the authors, "many scientists believe" that birds and dinosaurs are related). Their treatment of "adaptive radiation" takes up two pages with no examples illustrated; in the authors' third edition (2004) their sole illustrated example was based on switches in host plants of a single genus of beetle. This book needs a major infusion of up-to-date, expanded coverage in both text and illustration in order even to begin to explain macroevolution.

Mark Ridley's *Evolution* (3rd edition, 2004) unfortunately does not even go that far; his principal diagram related to this aspect of macroevolution is a bubblegram purporting to show the general relationships and sequence of diversification of the major clades of vertebrates (which he incorrectly labels as "fish → amphibian → reptile → mammal"). His source is Simpson (1949), which leaves out the rather considerable advances in the understanding of vertebrate paleobiology, phylogeny, and macroevolution of the past half century. Another illustration, appropriated from Tom Kemp, purports to show the evolution of mammals and their relatives (synapsids), but it is merely a menagerie of drawings of skulls, skeletons, and names, with no temporal context and no adaptive or ecological information. Another figure provides a phylogeny of early tetrapod ancestry, calibrated to a geologic time scale, but no illustration of adaptive changes. This, as with the synapsid example, is left to the text to explain. Whereas the synapsid example is well enough discussed to provide a basis for further student inquiry, the tetrapod example concludes with the bewildering statement that Devonian tetrapods had seven to nine digits and that "modern tetrapods presumably just happen to be derived from five-digit ancestors, and have retained that condition." No illustrations in the text ostensibly reflect what is known of major transitions of form, function, and behavior.

Douglas Futuyma's *Evolutionary Biology* series (3rd edition, 1998), now discontinued, gave students at least a glimpse of what was actually known about the evolution of synapsids and the origin of mammals. This, its principal example of macroevolutionary change in animals, included a phylogenetic tree with the names of (a great many) mammalian out-groups, and letters at each node of the tree were keyed to specific features that evolved at that point (again, based on Kemp's work). Morphological change was featured in the text, not just mentioned, as were illustrations (not extensively explained) of a few of the structures and animals in question. Futuyma's (2005) revised and abridged successor, *Evolution*, has not kept up this effort in the direction advocated here, although it has treatments of other macroevolutionary topics throughout the text. This is a hole that can be fixed.

A new entry in the market, Barton et al.' s *Evolution* (2007), is sadly lacking in explanations of macroevolutionary change at the level of form, function, and behavior, although as might be expected its coverage of evolutionary developmental biology is good in showing the genetic basis of morphological change. A scant three pages of text cover evolutionary innovations since the Cambrian; much of that text is outdated or debatable, and the only figure in the book that appears to document macroevolutionary change is the obligatory cladogram with limbs of basal tetrapods, although it is in a completely different part of the book. One may hope for better in the next edition.

It might be argued that general texts of evolution, even at the upper division level, cannot be expected to provide extensive coverage of major changes in clades, adaptations, and behaviors, and how we understand them. This can be countered on three grounds. First, this is what C. H. Waddington famously called "the whole real guts of evolution." Without it, the explanation of evolutionary theory is as incomplete as explaining geology without plate tectonics. Second, we know a great deal about many such transitions, and we should be giving due attention to these advances in our teaching, as we do to new findings in genomics, evo-devo, molecular genetics, and so on. Third, because these macroevolutionary changes are so poorly understood by the public in general, as well as by biology students, it is all the more important to teach them. It is not merely that they are poorly understood, but that the public is tremendously interested in this dimension of evolution, as news stories, documentaries, and magazine articles continually demonstrate. The historical imbalance in the coverage of microevolution and macroevolution in textbooks reflects the fact that the vast majority of evolutionists are microevolutionists (those who work on population-level and genetic change) who generally have little or no training in macroevolution. This imbalance needs to be redressed in texts if students are to have a full education in evolution, and instructors, even if they are not well versed in macroevolution, should expect and demand such coverage.

Textbooks on vertebrate paleontology

Regardless of the situation in evolution texts, it would be expected that demonstrations of macroevolutionary change, particularly among the vertebrates, would be found in the illustrations of upper division textbooks on vertebrate paleontology and evolution. Not so, however. Robert Carroll's (1988) text is an omnibus of anatomy, morphology, taxonomy, and stratigraphy that provides both a sweeping and a highly detailed picture of evolution throughout the vertebrate clade. However, it seems not to be greatly in use at present for several reasons. It is larger and denser than many undergraduates (and their professors) can handle; much of the knowledge in the book is now two decades old, although it is not all automatically outdated, therefore. More importantly, at the time the book was written there were no well-documented phylogenetic (cladistic) trees for most extinct vertebrate groups. The explosion of phylogenetic work since then has resulted in hundreds of cladistic analyses, but these were too late for inclusion in Carroll's book. Consequently, it lacks the kinds of "evograms" necessary to convey evolution pictorially.

About the only vertebrate paleontology text in current use is Michael Benton's (2005; now in its 3rd edition). It contains a great many cladograms, menageries, and companatomies, but sadly no integrative illustrations of macroevolutionary change. The cladograms are illustrated with nodes that specify synapomorphies diagnostic of the respective levels, but there is no intrinsic sense of the evolution of major features, adaptations, or behaviors. That dimension is relied upon in the text alone. The text is quite readable, and Benton usually provides a good sense of how we know what we know, and how we go about our work. But his book almost completely lacks the illustrative dimension of macroevolutionary explanation advocated here.

Textbooks of comparative vertebrate morphology

In textbooks on comparative vertebrate morphology and evolution, the picture is somewhat brighter.

Several texts provide explicit, well organized, colorful illustrations of vertebrates and their structures. They differ somewhat in their emphases, and also in their approaches to illustrating major evolutionary changes. In general, they provide phylogenies (with and without calibrated geologic time), menageries, and companatomies that are explained to a greater or lesser degree in the texts; however, integrative illustrations like evograms are fewer than they could be. A companatomy from Pough et al.'s *Vertebrate Life* (4th edition, 1996) (Fig. 3), for example, illustrates various configurations of the structure of the axial musculature in basal chordates (lamprey, hagfish, shark, and teleost). Students can readily see where the muscle segments come from in the bodies, and can perceive a variability among these animals. However, the illustration is not strictly evolutionary: a creationist would easily interpret four different animals with four different structures, reflecting created kinds, as easily as an evolutionist would interpret change in form and function. It is not implied, of course, that these four forms are successively ancestral to each other; in fact, no evolution is implied at all. The introduction of a cladogram into the illustration, with synapomorphies at each transitional node to indicate successively shared features, would make the evolutionary component clear. At least three such illustrations are found in the latest edition (Pough et al. 2005, p. 17, 427, and 441).

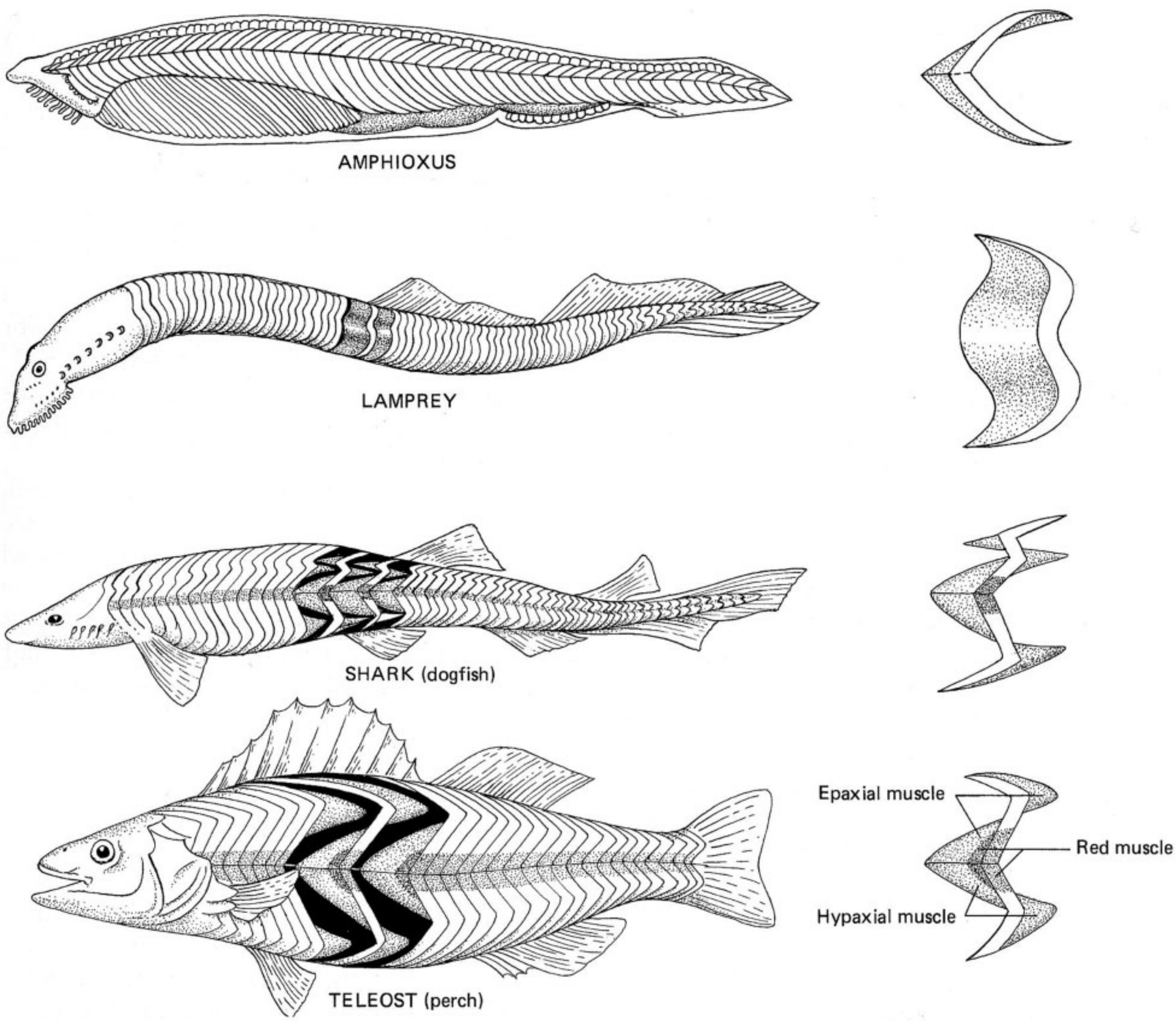


Fig. 3 A combination figure of "menagerie" (different kinds of animals) and "companatomy" (comparable structures in different animals) from Pough et al. (1996, p. 85; courtesy Pearson Education, used by permission). Both aspects of the illustration are useful; the addition of a phylogenetic element (Fig. 1) with specific synapomorphies at each node would make the diagram more clearly evolutionary. More recent editions of this text (e.g., Pough et al. 2005) have improved some aspects of the narrative, but not the illustrations.

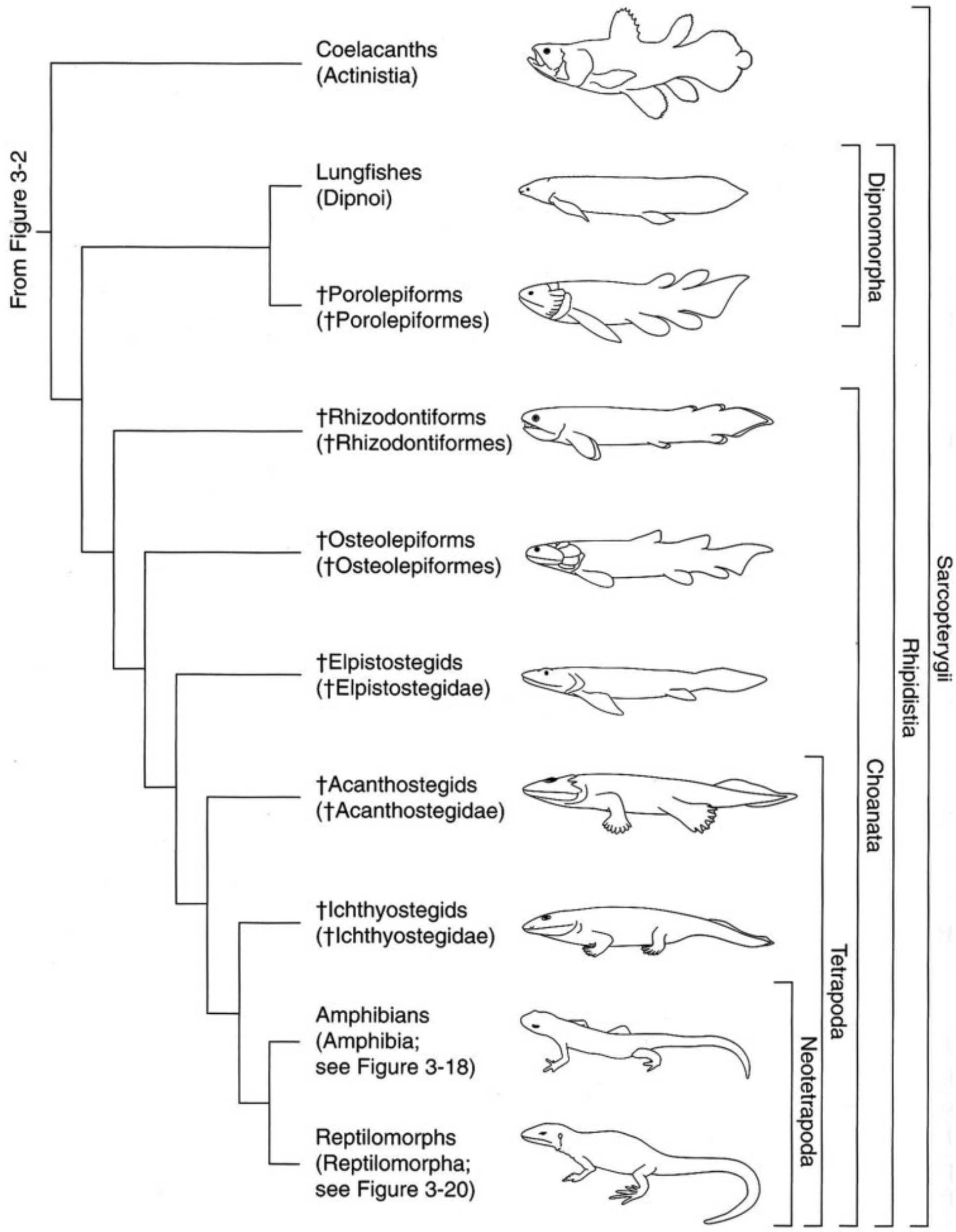


Fig. 4 A phylogeny from Liem et al. (2001, p. 74; courtesy Cengage Learning, used by permission). Relationships, names of taxa, and sketches of the animals convey form and classification. Again, the addition of synapomorphies would show better what is structurally and functionally evolving, and the characters on which the phylogeny is based.

Liem et al. (3rd edition, 2001) provide some particularly useful illustrations of two kinds of illustrations: phylogenies, accompanied by the "menageries" (images of relevant taxa) keyed to geologic divergences in time (Fig. 4), and companatomies (Fig. 5) showing comparisons both of homologous structures in different animals and kinematic stages in a single structure-function complex. When, as in comparing the limb in a lungfish and the Devonian tetrapod relative *Eusthenopteron* (Fig. 5), only two taxa are compared, inferences of homology and transmutation made by evolutionists are no more strongly implied than is a creationist's inference that these are simply two different, specially created taxa. More useful for evolutionary pedagogy is another figure by Liem et al. (2001) that shows the evolution of the brain among different vertebrate groups, linked phylogenetically and color-coded to show the relative expansion and morphological change in various regions of the brain.

The use of images of morphological, physiological, functional, and behavioral change linked to

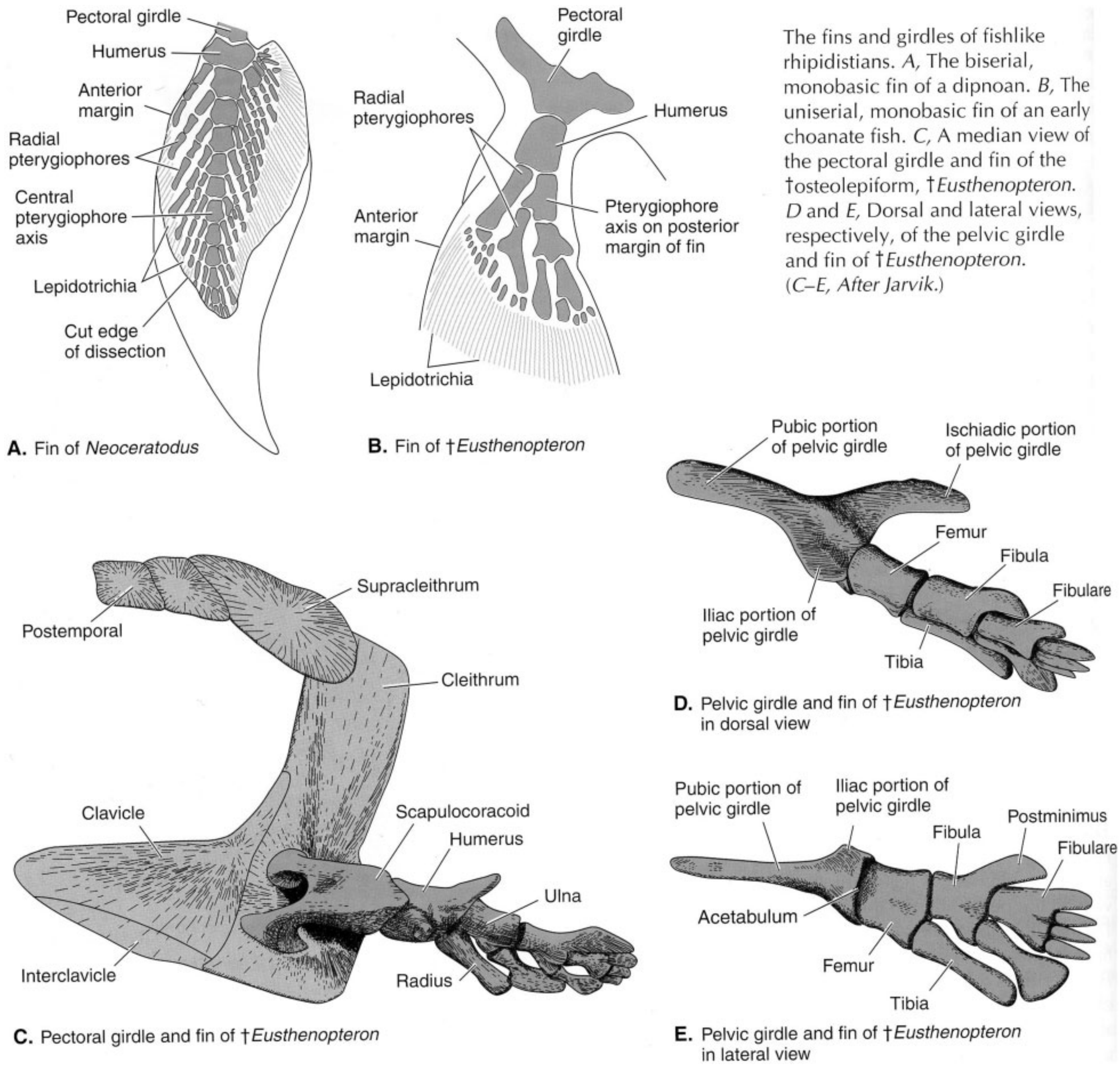


Fig. 5 Another figure from Liem et al. (2001, Figs. 9–6, p. 298; courtesy: Cengage Learning, used by permission) with several kinds of information. **A** and **B** compare limb structures in *Neoceratodus* and *Eusthenopteron*, with names to designate anatomical homologies; however, a two-way comparison does not convey evolution as well as a diagram that uses three or more comparisons and specifies what is evolving (antievolutionists can view this diagram merely as two different created kinds). **C**–**E** usefully show the reconstructed function and motion of the limb girdles.

phylogenies (which must involve more than two taxa) is critical to teaching students the importance of tree-thinking, as well as of the various independent lines of evidence by which science is constructed. Hildebrand's and Goslow's *Analysis of Vertebrate Structure* (5th edition, 2001) reproduces several such examples, including of acquisitions of key characters in the vertebrate clade, the evolution of birds, and the forelimb structure from basal vertebrates to basal amniotes. Such illustrations are useful not only in showing some of the more conspicuous synapomorphies by which the relationships of major groups of organisms are inferred, but also they can be used to demonstrate the sequences of major functional or developmental transitions, as in the evolution of the vertebrate limb, or the reduction of fingers from dinosaurs to birds, establishing that the bird's digits are topographically and phylogenetically I-II-III and not II-III-IV (Fig. 6; Padian and Chiappe 1998; Padian 2001).

The point of the foregoing comparisons is that with relatively little adjustment and improvement,

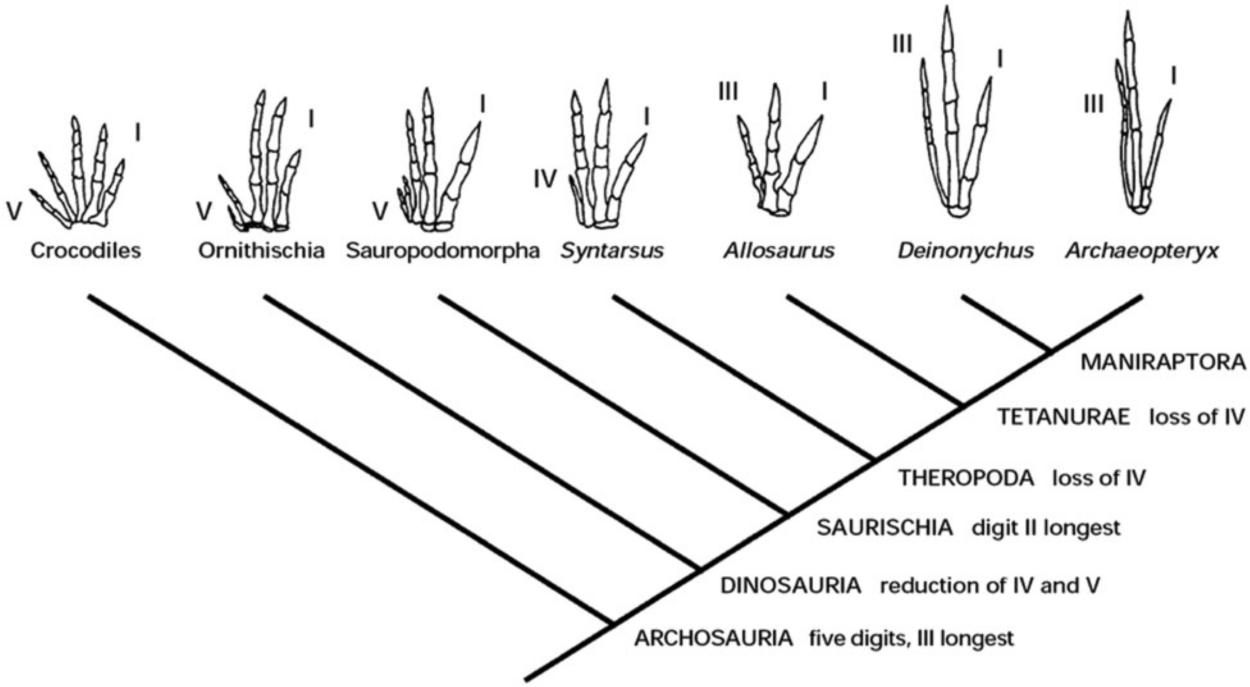


Fig. 6 A relatively simple "evogram" showing phylogeny, comparative anatomy, names of taxa, and morphological changes occurring in the evolution of birds' hands from a more basal reptilian form. From Padian and Chiappe (1998, Fig. 4, p. 7).

the illustrations in most of our college-level textbooks of biology can reflect much more accurately and integratively how we know what we know about the major changes in evolution. Figure 1 provides an example of such an illustration. The advantages of this kind of diagram are several. A variety of taxa, not just two, is compared, in an explicit phylogenetic context. The transformation of homologies is indicated and explained in the figure's caption. Functional changes are clarified. Extinct animals are no longer seen as direct ancestors of each other ("missing links"), but rather as representatives of a tree of life that help us to read the sequence of evolution of major features (not "transitional forms"). A caption can guide the interpretation of the diagram concisely, and need not merely explain what animals are represented by "A," "B," and so on, nor merely explain abbreviations of anatomical terms.

How to get this into textbooks

Those SICB members who are instructors in college-level biology have the greatest influence of all in the process of improving coverage of macroevolution in textbooks. You do most of the teaching in these fields, or you know the colleagues in your departments who do. So here are some easy ways to influence and change the textbooks. Talk to the people who adopt these books for their classrooms. Discuss this question at your faculty meetings, and consider how to approach it in your curriculum as a whole. Talk also to the people who publish these books and visit your offices every year to try to get you to adopt their books and to ask you what you would like to see improved. Even better, talk to the people who write these books. These are your colleagues too. Explain to them what they are leaving out, why it is important, and how you need to have this information presented. If you explain the needs clearly, the books will change. If you tell the publishers that you will not assign books for your classes that do not do what you need, the books will change. So the most effective thing you can do in evolution education is to use your clout. Talk directly to the salespeople, the editors, and the writers of textbooks. They have to listen to their consumers.

Here is another approach, suggested by Dr Frederick Harrison, Editor of the *Journal of Morphology*. When you, as authors, prepare an article for publication that concerns the evolution of major traits in a clade, with reference to functional, behavioral, or physiological evolution, consider preparing at least one figure that summarizes your results in terms of an "evogram" such as pictured in Fig. 1. This is the kind of diagram that will be scanned and downloaded by your colleagues to show their students when they teach, and it is also the kind of diagram that can be readily used and adapted in future textbooks. This kind of effort on your part, especially coupled with an internet approach (see subsequently), can form a substantial contribution to the public-outreach component of research grants commonly requested by agencies such as the National Science Foundation.

Immediate improvement is possible, too

It is a truism that more people every year—especially younger people—get most of their information through the internet. There are many good websites on evolution and education about evolution for students and instructors, and for the general public. The University of California Museum of Paleontology has set up several websites, such as *http://ucmp.berkeley.edu* and *http://evolution.berkeley.edu*, that try to do what textbooks cannot: to present new information and extensive help for teachers who cannot find what they need in the instructional materials available to them about evolution, particularly macroevolution. We are beginning a new one to focus on the major features of evolution and how we know about them. Our goal is to match cladograms with correlated changes in structure and function to describe major changes in the evolution of tetrapods, dinosaurs, birds, horses, primates, ungulates, carnivores, and many other groups. We also intend to show examples of our evidence for correlations between climatic change and faunal change, and between tectonics and biogeography. We call this project "Project Next Generation" because we want the next generation of our students to understand what previous generations of students have not been able to learn. To find out more, or to contribute to this website, please visit *http://evolution.berkeley.edu/macrolibrary*.

Another suggestion: consider talking to groups of teachers to help train them in interpreting these concepts of evolutionary biology to their students. K-12 teachers in general have not had the scientific background of instructors at the collegiate and university levels. They are tremendously intelligent and clever in constantly seeking ways to communicate concepts to their students. By working together, in my own experience, teachers and scientists continually surprise and delight themselves and each other in finding new and creative ways to communicate scientific concepts to students at all levels. This process is one of the greatest joys that a scientist and (or) a teacher can experience. I urge you not to miss this opportunity.

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