Tracing a Prospective Learning Progression for Developing Understanding of Evolution

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Paper Commissioned by the National Academies Committee
on Test Design for K-12 Science Achievement, 2005.

Evolution is perhaps the central coordinating theory in biology (Mayr, 1991; Mayr, 1997). As suggested by Figure 1, evolution accounts for life's diversity--its variation at genetic, habitat, and species levels.

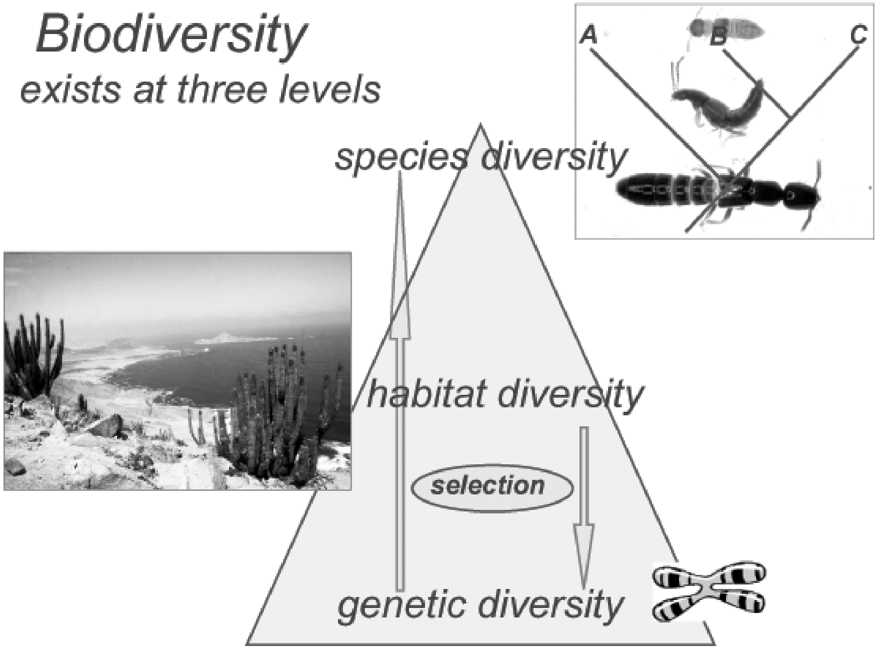


Figure 1. Life's diversity ranges from microscopic to macroscopic levels.

Although life's diversity is one of its most visible characteristics, nonetheless developing an explanation for contemporary and past diversity is an enormous intellectual challenge. Evolutionary theory rests on a network of foundational disciplines, ranging from genetics to ecology and geology, so that understanding evolution requires coordinating multiple disciplines and perspectives e.g., (Boggs, 2003). Rather than understanding isolated concepts, learning about evolution requires synthesis and coordination among a network of related ideas. The synthetic character of these relations present significant challenges for learning, teaching, and assessment, because it is unlikely that grasp of any single conceptual distinction, like that between mutation and selection, will be sufficient to leverage understanding of evolution.

Our approach to assessment follows from a perspective that views learning in complex domains as a matter of developing central conceptual structures (Case, 1990), or "big ideas," that coordinate and integrate otherwise discrete conceptual elements. For example, the concept of natural selection in evolution subsumes a variety of otherwise unrelated events (e.g., changes in a particular ecosystem, sexual dimorphism) so that they can be seen as instances of, and contributors toward, the explanatory system encapsulated by selective pressure. Big ideas are generative: They define a grammar of the discipline, not a simple collection of ideas. For example, natural selection is a mechanism for change that spawns inquiry about particular ecologies (e.g., What are the agents of selection?) even as it serves as a general explanatory framework. Although natural selection is a concept that should be taught in schools, it is also an active area of contemporary research, so that it is generative for practicing scientists too. For example, a contemporary issue of *Science* features the role of natural selection on diatom metabolism, the formation of ecological guilds, and the history of canid extinction (Armbrust, Berges, Bowler, Green, B, Martinez, & Putnam , 2004; Bonsall, Jansen, and Hassell, 2004; Van Valkenburgh, Wang and & Damuth, 2004).

Considering instruction, an orientation toward core ideas focuses instruction and assessment on a comparatively small set of foundational concepts and traces a prospective *developmental corridor* (Brown, 1996)—a *pathway* for learning across school-grades and ages. A developmental corridor suggests that central concepts are introduced early in schooling and are progressively refined, elaborated, and extended throughout schooling. Teaching central concepts, or “big ideas,” helps teachers align curriculum tasks with learning performances, resulting in greater coherence and alignment between teaching and learning (Schifter & Fosnot, 1992). Such alignment is essential for valid assessment. A focus on big ideas supports assessment by suggesting dimensions for assessment (the big ideas) and by orienting assessment toward *clusters of standards* adhering to big ideas, rather than toward standards considered in isolation. In short, big ideas summarize and distill what is important about a discipline for purposes of teaching, learning, and assessment. They are also fruitful, meaning that learning about them leverages further learning, so that assessment can play a key role in an instructional system.

Although textbook definitions of concepts usually serve as an image of their nature, decades of research in learning suggest that these analogies are somewhat misplaced (Bransford, Brown, & Cocking, 2000). Even everyday concepts, such as color, are influenced by contexts of activity, so that what one learns is nearly always embedded within particular situations, and aspects of these situations govern how a concept is employed (Goodwin, 2000). What holds for the everyday is amplified in scientific reasoning: Scientific concepts are never developed without participation in specialized forms of practice, such as creating instruments, inventing representational systems, developing models. Concepts are contingent upon these practices e.g. (Gooding, 1990; Goodwin, 1994). To know that the Earth is round as a matter of received authority is far different than appreciating the models, and how they were constructed, that support drawing this conclusion. The former is valuable knowledge, but the latter is scientific knowledge.

Traditionally, standards describe the scientific ideas that we wish students to learn, but ideally, standards should articulate the knowledge, skills and forms of activity that students must learn in order to understand these scientific ideas. Hence, big ideas must be specified in ways that provide a window to the kinds of practices that engender their development. We represent this blend of knowledge, skills and forms of activity that support the development of knowledge and skill as *learning performances* (Reiser, Krajcik, Moje, & Marx, R., 2003). Learning performances refer to cognitive processes and associated practices linked to particular standards. For example, students learning about evolution need to make arguments from comparative data and to distinguish between competing interpretations of these data. It is important to specify these processes as explicit learning objectives. To illustrate, consider the following benchmark from AAAS about differential survival:

Differential survival: Individual organisms with certain traits are more likely than others to survive and have offspring (5F2-I, AAAS Benchmarks).

On the face of it, the standard clearly indicates one of the central mechanisms of evolution, the so-called "survival of the fittest." Yet, upon closer inspection, the standard is written in a manner that only hints at the skills and forms of practice that might be constitutive elements of understanding it. Consequently, Reiser, et al. (2003) amplify this single standard as three related learning performances:

Students *identify and represent mathematically* the variation of a trait in a population.

Students *hypothesize* the function a trait may serve and *explain* how some variations of a particular trait maybe advantageous in a given environment.

Students *predict, supported with evidence*, how variation of the trait will affect the likelihood that individuals in the population will survive an environmental stress.

This re-statement of the standard of differential survival more clearly specifies the skills and knowledge expected. For example, students are expected to represent variation mathematically, implying that they must have the opportunity to learn about the mathematics of distribution and associated displays. These learning expectations could be elaborated further, if useful for the design of instruction and assessment. The expression of a standard as a learning performance clarifies the cognitive processes that constitute the standard, and ideally, points to some of the forms of participatory practice that support (and in fact, constitute) learning about it.

With this expansion of standards-as-learning-performances, we undertake to illustrate how learning performances oriented around foundational concepts (big ideas) of evolution can articulate temporal sequences supporting students' long-term cognitive development. Accordingly, this report is organized as follows: In the first section, we present the core conceptual structures, the big ideas, that we consider as fundamental for learning about evolution. Big ideas are generative, in that reasoning about them typically spawns rich sets of questions, investigations, and models of evolutionary products and processes, and we have employed this criterion in our selection of candidates.

Developmental corridors suggest that core concepts need to be available in some practical form to younger students yet still present challenge for understanding in depth at later grades (Lehrer & Schauble, 2004). In this way, potential learning progressions can be identified, so we also used this criterion in our selection. Finally, we relied heavily on the Standards documents of the AAAS and the NRC, especially when these standards pointed to prospective pathways for development.

Our candidates for central ideas focus on foundations of evolutionary thinking, but they also include relevant mathematical tools and systems of notation, because understanding evolution and related foundations involves constructing models, chiefly mathematical descriptions, of nature e.g., (Kline, 1980). We consider too forms of argument that appear necessary for sustaining claims made by evolutionary theory, again because much of the contemporary study of evolution involves a coordination between model-based reasoning and appeals to the historic record (Rudolph & Stewart, 1998; Van Valkenburgh, et al., 2004). Much of the study of evolution employs comparative methods, not solely, or even primarily, experiment (Young, Brodie, & Brodie, III, 2004).

In the second section, we describe research that addresses student learning about the central concepts identified, although we focus primarily on students' understandings of evolution. In the third and concluding section, we develop a cartography charting the development of core concepts, and associated learning performances, across three grade bands: primary grades, elementary grades, and middle school. At each grade band, we focus on the big ideas that research suggests should be accessible to students within each grade band. However, because the research evidence about student learning is incomplete, and even contradictory, the learning performances that we describe could also be viewed as signposts for the nature of research that would be needed to construct a more compelling account of prospective development. We intend our description to set the stage for developing more nuanced understanding of evolution during a high school biology course, but we leave the final stage of construction to the reader.

I. Core Concepts

Our distillation of central concepts for evolution was informed by considering evolution as an explanation for how *biological diversity* is generated, maintained, and changed. By emphasizing biological diversity, even young students are in a position to inquire about the nature of life, its history, and its embedding (and interactions) within the environment. We selected as core ideas those that contribute toward developing understanding of how evolution and biological diversity are co-constituted, from a child's perspective. In this developmental view of learning (see, for example, NRC Standards, 1993, pp. 103-107), understanding of evolution and diversity is <u>not</u> a one-time phenomenon, perhaps reserved for the high school (and beyond). Instead, we envision learning about evolution as developing relations among a (relatively small) set of core concepts throughout schooling. Our candidates are:

(1) *Diversity*. Biodiversity occurs at three levels: diversity of species, diversity within species (among individuals, determined by genetic diversity) and diversity of habitats (see Figure 1). Species are the units of evolutionary change, the genetic diversity among individuals the engine of evolution, and habitat, in the form of environmental variables, the agent of natural selection.

(2) *Structure-Function*. Structures, such as mouthparts or leaves, perform functions that allow individuals to survive. Structure-function relations are the cornerstone of adaptation.

(3) *Ecology/Interrelationships*. Living things populate a particular habitat and are embedded within a complex system. What affects one population of organisms is also likely to affect the other populations that live in that habitat. Changes in

habitat are apt to affect the functioning of the ecology and thus the chance that individual organisms will survive and replicate.

(4) *Variation* can be characterized as either *random* or as *directed*. Random variation results from genetic recombination and genetic mutation. Directed variation, called *natural selection*, results (mostly) from habitat variables, and acts to bias otherwise random genetic drift. The interplay between random and directed variation is the foundation of life's diversity.

(5) *Change* occurs at different scales of time and organization. Growth refers to change in single organisms or collections of organisms within a lifespan. Microevolution refers to change in distributions of characters over comparatively brief intervals of time (e.g., the Grants' study of the beaks of the finch, antibiotic resistance in bacteria). Macroevolution works on distributions of characters over longer intervals of space and time. It creates a life history that extends over large-scale space and time.

(6) *Geologic Processes*. Understanding geologic processes is important for comprehending the time-scale involved in much of evolution and for developing hypotheses about the course of evolution. Geologic processes are key to developing descriptions of past environments and for reconstructing the life history of the planet.

We propose two additional core conceptual structures. Each represents a "habit of mind" that is important for developing and articulating the conceptual underpinnings of evolutionary theory.

(7) *Forms of Argument.* Evolution relies on model-based reasoning and also on historic interpretation (Rudolph & Stewart, 1998). For example, geochemical processes can produce remnants of life—fossils. *Historic reconstruction* and *comparative study* of the fossil record provides evidence about continuity and change in species over geologic time and hence testable hypotheses about patterns of survival and extinction (Van Valkenburgh et al., 2004). At the same time, *models* of genetic transmission serve to account for the basic mechanism of inheritance that is the essential grist for the Darwinian mill.

(8) *Mathematical Tools*. Evolutionary processes are complex. Such complexity is managed by mathematical descriptions, including:

Measurement refers to a process of assigning unit-values to an attribute. Key considerations include the nature of the unit and the nature of the scale of the unit.

Data creation refers to the process of constructing attributes and their measures, and then structuring these measures in light of a question of interest.

Distribution is a mathematical tool that structures variation. Armed with knowledge of distribution, *random* processes can be distinguished from *directed* processes.

Venn diagrams represent intersections and complements of sets of characters. These are helpful for beginning to think about likeness and difference among organisms.

*Cladogram*s structure distributions of characters into subsets and supersets. With its emphasis on species as the units of evolutionary change, it is used to make inference about the life history of a species, the evolutionary relationships among species and groups of species (clades).

II. Review of Research

Because teaching and learning evolution encompasses a network of central conceptual structures and associated practices, we have selected studies representing trends in research on evolution, rather than exhaustive review of research to every discipline referenced by the study of evolution.

Microevolution

Most research has been directed toward documenting how students reason about microevolution: processes regulating change in populations of organisms over comparatively brief spans of time. Several decades of research suggest that beliefs in teleology (i.e., evolution represents progress), and in self-directed design (e.g., organisms evolve in response to their perceptions of need), are robust and hard to dislodge, even in the face of concerted instruction (Anderson, 2002; Anderson, 2001; Bishop, 1990; Brumby, 1979; Brumby, 1984; Catley, 2001; Clough, 1982; Clough, 1994; Demastes, 1996, 1995; Greene, 1990; Halldon, 1988; Jensen, 1996; Kargbo, 1980; Lawson, 1988; Lucas, 1971; Passmore, 2002; Rudolph, 1998; Settlage, 1994; Sinatra, 2003; Southerland, 2001; Stewart, 2001). For example, working with two groups of children (aged 9 and 12) from the Netherlands, Samarapungavan (1997) found that students explained speciation and diversity consistently (i.e., they had theories), but most of these theories were based on some variation of essentialism (species are static). Many children appeared to color essentialism with Hollywood views of dinosaurs, and attributed modern diversity as stemming from the dinosaurs. Only a small minority (less than 10%) described the emergence of new species from a more primitive common ancestor. (Samarapungavan, 1997) further suggested:

> *"One way in which all five consistent (alternative) frameworks differ from Neo-Darwinian theory is in their neglect of the phenomenon of within species variability. The five frameworks treat within species variation as an uninteresting or trivial phenomena. It is likely that the lack of attention to within species variability will make it hard for many novices to restructure to Neo-Darwinian theory."*

Similarly, (Evans, 2000) reported that most children between 5 –12 years of age attributed origin of species to essential kinds, or to spontaneous generation. Southerland et al. (2001) found that teleological explanations closely followed by anthropomorphic reasoning comprised the prominent category of response to questions concerning explanations of biological phenomena. When compared across grades 2, 5, 8, and 12 the relative frequencies of these responses did not change. Similar findings across several decades and cohorts of students suggest that Darwin's theory of speciation is not widely accepted.

Perhaps one of the sources of essentialism is students' tenuous grasp of the mechanisms of natural selection and random variation, especially mutation. Despite several years of instruction, high school students, undergraduates and even medical students have difficulty understanding the role of natural selection (Brumby, 1984; Clough, 1982; Halldon, 1988; Lawson, 1988; Lucas, 1971). This body of work further suggests that even when students define natural selection appropriately, their knowledge is largely inert. Students typically cannot deploy natural selection to understand the role of variation in populations, the effects of novel traits on survival in populations, and the mechanisms of resistance in bacteria and insects. Settlage (1994) found that part of students' difficulty may be attributed to their poor understanding of variation and of mutation acting in populations.

A notable exception to this largely dismal record is found in the work of Stewart and his colleagues (Passmore, 2002), and in the work of Reiser and his colleagues (e.g., Sandoval, 2003). Passmore and Stewart suggest that instruction about evolution be rooted in the models that scientists use in their field to test and evaluate various types of data. They suggest that the model of natural selection be used to engage students in inquiry projects where they use the model itself to construct an understanding of natural phenomena. They advocate students should "understand how natural selection can be used as a framework to think about evolutionary change" and to "participate in inquiry that mirrors the practice of evolutionary biology in important ways." Sandoval and Reiser (2003), working with middle school students, stress the importance of equipping students to think about individual variation as a precursor to working in natural selection. The mathematics of variation (e.g., distribution) can be learned by students in the elementary grades when distributions are developed as models of situations involving measurement or natural variation of a sample of organisms (Lehrer & Schauble, 2004; Petrosino, Lehrer, & Schauble, 2003), and it seems that earlier exposure to the mathematics of variation could serve approaches like these that emphasize microevolution.

Macroevolution

Macroevolutionary processes, those regulating change at the level of species and above in geologic time, have received much less attention in the research community.

One of the prime obstacles to reasoning about macroevolution is the sheer scope of geologic time. (Trend, 2001) found that many teachers reduce geologic time to three periods: extremely ancient, moderately ancient, and more recent. Within each time period, there was a distinct lack of consensus on time-of-occurrence of events. Moreover, participants did not believe that aspects of deep time and past environments were of any great significance in the interpretation of geological specimens.(Dodick, 2002; J. Dodick, & Orion, N., 2003) suggests that understanding of deep time is indeed vital to understanding evolutionary biology, and in the curriculum, "From Dinosaurs to Darwin," (J. Dodick, & Orion, J, 2003) focus on reconstruction of evolutionary changes rather than on genetic mechanisms. By concentrating on fossils found in strata as students went into the field, and by situating fossils in a conceptual framework with a time dimension, students with no prior geology background were able to describe and explain macroevolutionary events. The role of fieldwork "both improved the subjects' ability in understanding the 3-D factors influencing temporal organization, as well as providing them with experience in learning about the types of evidence that are critical in reconstructing a transformational sequence."

Ecology

Ecology is the study of interactions among organisms and their environment. Study of ecology is essential to understanding evolution, because ecology sets the environmental context for evolutionary change. Without a grasp of ecology, it is difficult to understand the underpinnings of mechanisms of natural selection: adaptation, niche, and system. Which aspects of an environment are important to a species depend on the evolutionary history of the species. For example, the chemical composition of leaves might exert selection pressure for the insects that eat them, but this chemistry may be inconsequential for other species in the ecosystem. The study of ecology also sets the stage for appreciating the meaning of diversity. Why is the diversity in tropical rain forests so much greater than that experienced anywhere else on the planet? Study of ecology also forms a framework for understanding the very idea of adaptation, a concept that seems transparent but can be very elusive. Not all structures can be said to result from selective pressure. How might one discern the difference?

Unfortunately, the literature on students understanding of ecology is replete with examples of the difficulties of understanding such concepts as multiple simultaneous occurrences, and dynamic equilibrium. identified three dimensions which hinder understanding of ninth-graders learning ecology: (a) microlevel matter-energy transfer, (b) the spatial distribution of elements of the ecology, including simultaneous occurrences of these mechanisms in space, and multiple roles of biotic elements, and (c) the effect of time, especially the effect of long term evolutionary forces on ecosystems. (Eilam, 2002) reported that students typically did not conceive of biotic webs as formed by random mutations during lengthy evolutionary processes, but instead entertained a Larmarkian view of structured chains of organisms that depended on one another as a function of their needs. Deficits also emerged in student's understanding of the long-term effects rendered by evolutionary processes on organisms' structures and functions, and the influence those have, in turn, on the final structures of feeding webs in ecosystems (e.g. evolutionary forces that select webs rather than chains; an organism's inability to feed on just any other organism due to its biological structure as selected in the course of evolution.) The author suggests: "These results might call for instruction affording students' acquisition of more substantial knowledge of evolutionary processes and dynamic equilibrium."

Summary

Most studies of evolution suggest that appreciation of evolution as an explanation for life's diversity presents a number of conceptual challenges, despite the apparent simplicity of the theory. In our view, these challenges are symptomatic of the complex relations among micro processes of natural selection and random genetic variation, macro processes of geologic events and speciation, and their interaction--considering organisms and species as participants in ecologies distributed over space and time. These complex co-ordinations suggest the importance of designing education to support learning of central conceptual concepts throughout schooling.

Our review suggested a glaring omission. The concept of clades, (natural, monophyletic groups of species) and the top level of the evolutionary hierarchy (fig. 2), (comprising genome, individual and species), are missing in current educational constructs of what it is to understand evolution (American Association for the Advancement of Science, 2001). The phylogenetic perspective is hardly new. Indeed, Darwin can rightly be cited as the first cladist. Arguably Darwin's most radical claim was that all of life had descended from a common ancestor. Perhaps to reinforce this contention the only figure he included in the Origin of Species (Darwin, 1858) was a branching diagram depicting the origin of clades, and the persistence though time of some, and random extinction of others. The resulting hypothesis of relationships is a cladogram tracing the history of extant taxa back though time to a common ancestor (fig 3). These are exciting conjectures that are subject to contemporary testing and revision.

As such they need to be embraced by the evolution education community. Without a phylogenetic perspective an understanding of the full gamut of evolutionary processes cannot be developed.

Fig. 2

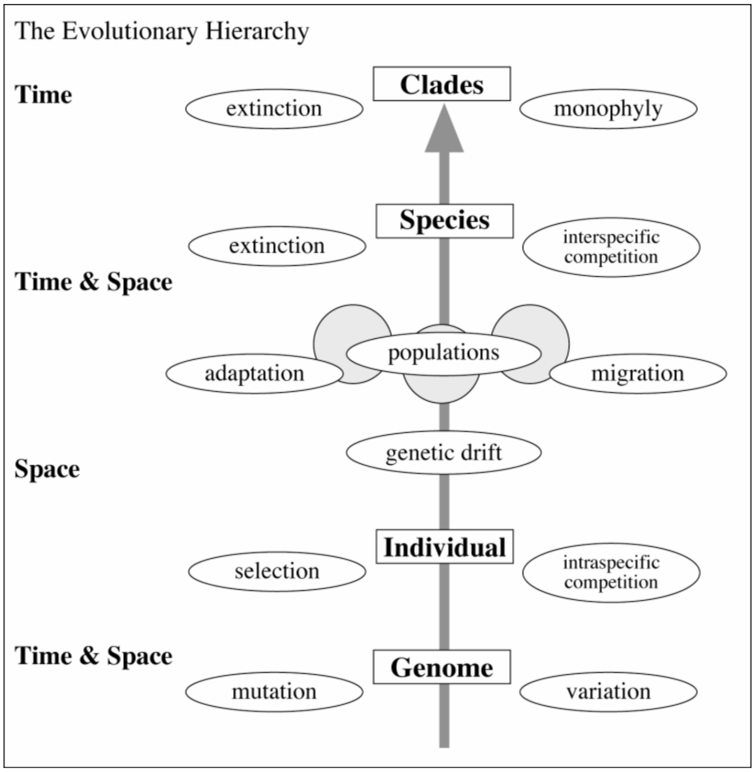
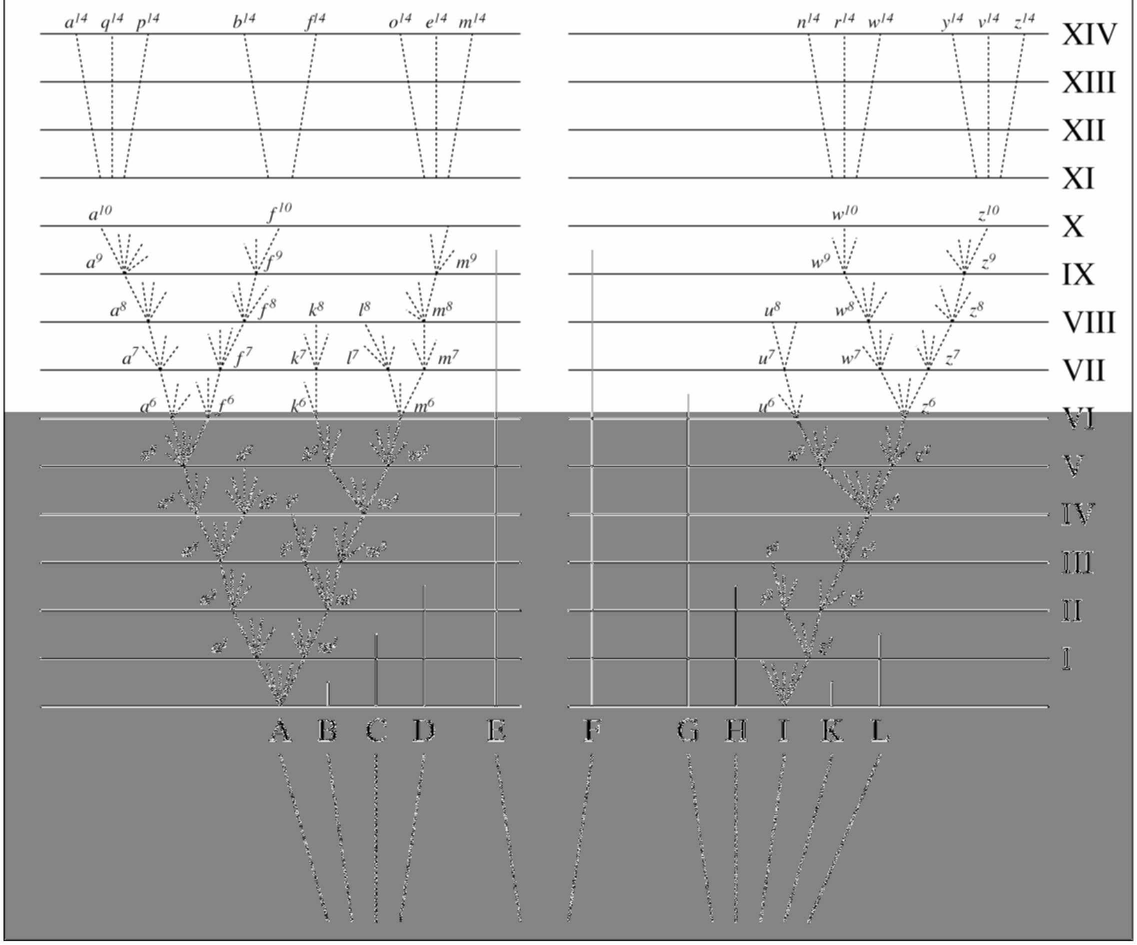


Fig. 3

Darwin's attempt to reconstruct a phylogeny of ancestor - descendent species relationships from "Origin of Species," 1858.



III. A Prospective Learning Progression by Grade Band

K- 2

AAAS Natural Selection & Evolution Benchmarks [Big Idea Referenced]

Living things are found almost everywhere in the world. There are somewhat different kinds in different places. [Diversity, Ecology]

There is variation among individuals of one kind within a population. [Variation]

Different plants and animals have external features that help them thrive in different kinds of places. [Structure – Function, Ecology]

Offspring are very much, but not exactly, like their parents and like one another. [Variation]

Some kinds of organisms that once lived on earth have completed disappeared, although they were something like others that are alive today. [Change, Geologic Record]

Big Ideas, K-2 Rationale

Children's perception of similarities and differences among kinds of organisms (i.e., diversity at the species level) is a good foundation for developing conceptions of organisms as representing sets of attributes. This feature level description is a stepping-stone toward developing analytic categories employed by evolutionary biologists who rely on characters, such as the length of the beak of the finch or a particular sequence of DNA, to conduct investigations. At this age level, attributes are morphological, and the challenge that children face is to characterize them in ways available to other children (other children can use the descriptions as guides to seeing). Investigations about these attributes form a basis for expressing similarities and differences among species (e.g., natural kinds of organisms from a child's perspective). Attributes often serve functions, and children can investigate form-function relationships.

Growth of organisms serves as a gateway to thinking about change, albeit over comparatively brief periods of time. Mathematical tools are ways of articulating these core concepts. For example, children can measure heights of plants and lengths of caterpillars, use Venn diagrams to reason about similarities and differences between moths and beetles, and represent change by successive differences of measures (e.g., changes in the difference in height of a plant from one occasion to the next). Measuring and representing measures are an initial step toward modeling, as children distinguish between represented and representing worlds and take the first steps toward using representations in the conduct of inquiry.

K-2 Expression of Big Ideas

Diversity.

Attribute/Character. Organisms can be regarded as entities that are characterized by distinct attributes (also called characters), such as number-of-legs or (measure-of) length.

Comparative analysis. Kinds of organisms share morphological attributes in common, but they also have distinct morphological attributes. For example, children compare the mouthparts of different species of insects, or, as we illustrate later, children compare the attributes of an organism at different stages in a life cycle.

Structure-Function.

Attributes (characters) often serve specific functions. For example, what function is served by the proboscis of a butterfly?

Ecology.

There are relationships between habitat and the kinds of organisms that live there. Children pose questions about “who lives here?” and develop means for finding out. For example, how do insects living in water differ from those living on land?

Variation.

There are individual differences among everyday “kinds” of life. Children notice and record these differences by creating attributes and values.

Change.

The focus on change is at the level of individual organism.
Organisms change over the course of their life span (e.g., plants grow taller). Children record these changes in a variety of ways, and they compare the nature of change across organisms of the same species or they compare individuals from different species.

Geologic Record.

Students are introduced to fossils as artifacts and to some of the processes that created them. For example, A good introductory activity with mud fossils can be found at:
http://interactive2.usgs.gov/learningweb/teachers/mudfossils.htm

Forms of Argument.

Models represent key aspects of the natural world but are not identical to that natural world. Children in this age band distinguish between representing and represented worlds, a key step in symbolizing natural processes

Comparative analysis. Children engage in rudimentary comparisons between species, or between different life stages of the same species. They also compare species living in different kinds of habitats. This sets the stage to develop later more elaborate and more inferential comparisons.

Mathematical Tools.

Measure. Children develop and employ ratio-based measures, such as length metrics or counts of the number-of-legs of an organism. The emphasis is on developing understanding of the nature of the unit and the relation between the unit and the attribute being measured.

Venn diagram. Children employ Venn diagrams as tools for comparative analysis.

Arithmetic, especially differences. Children use differences in measures of an attribute to characterize growth. For example, they compare successive heights of a growing plant or animal. They use these successive differences to compare the growth patterns of two different organisms of the same species or two different organisms from different species.

Big Ideas and Standards Expressed as Learning Performances

Diversity

Develop Attributes.

Pose questions. What are the parts of this organism?

Describe. For an organism, describe what you see.

Define. For an organism, describe (draw, tell, highlight in video) what you see so that others can see what you see (connect claim to evidence).

Measure. Measure each attribute defined.

[Measure can be decomposed into a set of related learning performances. For example, *define* the unit of measure. *Iterate* and *accumulate* units. *Compensate* for non-zero origins of measure (i.e., treat any point as the zero-point). *Partition* and *index* each partition to enable accumulation of non-integer quantities.]

Determine Similarities and Differences at Individual-Species Level.

Pose questions. How are these kinds of organisms the same and different?

Compare. Compare values of same attributes for two or more organisms.

Use Venn Diagrams to visualize relationships. Create Venn diagrams of attributes of the same organism at different stages of the life cycle or of two different species.

Structure-Function

Pose questions. What does this attribute do?

Develop a system of observation. How can I “see?”

Develop evidence. How can I tell whether or not the attribute has the conjectured function?

Ecology

Pose questions. Where do different kinds of organisms live?

Describe a large-scale space where organisms live, such as a school's playground, or a nearby body of water, by drawings, photos, and rudimentary maps.

Compare the types of organisms living in two or more distinct places. (The expectation is again large grain size, for example, comparisons of aquatic and land insects).

Variation

Pose questions. How much alike are individuals of the same kind? How many different types of living things do I notice?

Represent similarity and difference by photos and drawings. (Drawings demand selection of attributes and in rendering them, children often notice characters that might escape their attention in a photo.)

Compare individuals of the same kind or compare individuals representing different kinds. (These descriptions are at morphological – attribute level.)

Change

Pose questions. What happens when an organism grows?

Measure. One or more attribute at selected points in the growth cycle.

Represent change. As drawings, diagrams, stories, mathematically.

Compare representations of change. Compare representations of change (Initial modeling step, separating represented and representing worlds) with an eye toward highlighting what each selects and omits, and the consequences thereof.

Geologic Record

Pose questions. How can fossils be described? How are fossils made? (It is very important that students have tactile experiences with fossils that are embedded in a rock matrix as well as extracted "stand alone" specimens.)

Represent fossils by drawings, photos, impressions.

Compare one or more fossils to extant organisms.

Forms of Argument

Models.

Pose questions. What's the use of a model?

Represent an aspect of the natural world. Draw, photo, video, create a data display.

Invent a model for one or more natural system investigated.

Evaluate the utility of the model.

Comparative analysis.

Pose questions. How are 2 different species (kinds) alike or different? How are 2 different habitats alike or different?

Represent attributes of organisms being compared. Draw, photo, etc.

Compare organisms or habitats mathematically (e.g., Venn diagrams, tables of characters)

Mathematical Tools

Measure.

Invent a unit of measure.

Use units of measure to create a measurement.

Employ measurements to characterize aspects of a natural system.

Venn Diagram.

Employ Venn Diagrams for comparison.

Compare Venn Diagrams to at least one other representation (e.g., lists of attributes)

Arithmetic.

Describe change arithmetically. (e.g., order successive differences over time to characterize change)

Example: Classroom Investigations in grades 1-2

We illustrate how these learning performances could be realized during the course of classroom investigations in the early grades. We draw on three classroom investigations. In one first-grade classroom, children asked about changes in tomatoes and pumpkins left in a corner of their school's playground. They went on to model these changes with a compost column constructed to represent "rot" (Lehrer, Carpenter, Schauble, & Putz, 2000b). In another (second-grade) classroom, children investigated the growth of different species of flowering bulbs, and compared growth between these species of plants (Lehrer & Schauble, 2002; 2003). Our third example draws from three grade 1-2 classrooms where children studied the life cycle of the monarch butterfly.

Children constructed attributes, described change, made conjectures about structure and function, and compared attributes of earlier and later stages of development (Lehrer & Schauble, 2005).

Investigating Change in Tomatoes and Pumpkins

Children in a first-grade classrooms investigated changes in pumpkins and tomatoes left out in the sun. To keep interpretable records, they had to decide together on a variety of representational conventions (e.g., Lehrer & Schauble, 2000). Originally, students used color to capture the changes that they observed. The choice of color was made on the basis of resemblance; children used color to stand for color. However, after a couple of weeks, students noticed that color was not the only attribute that was changing—the tomatoes and pumpkins were also becoming squishy in some regions, and spots of mold began to grow. To record the location and extent of these squishy spots, children decided to use shading and other kinds of surface patterns. This second representational convention, the surface pattern, preserved some aspects of appearance (i.e., location and approximate proportion of area covered), but not others (e.g., the pictorial record did not literally resemble the tactile quality of squishiness). These representational conventions emerged in response to an ongoing problem experienced by these children: What about change was worth recording and how could it best be recorded, especially for purposes of comparing change in pumpkins and in tomatoes? Pumpkins proved especially troublesome: How could the size of pumpkins be characterized? Early reliance on eyeballs provoked controversy about which was really "biggest," so children had to generate an attribute and measure for standard comparisons. They chose to measure the length of a string around the "fattest" part of the pumpkin.

Comparisons between pumpkin and tomato were facilitated with Venn diagrams, as depicted in Figure 4 (Lehrer et al., 2000b).

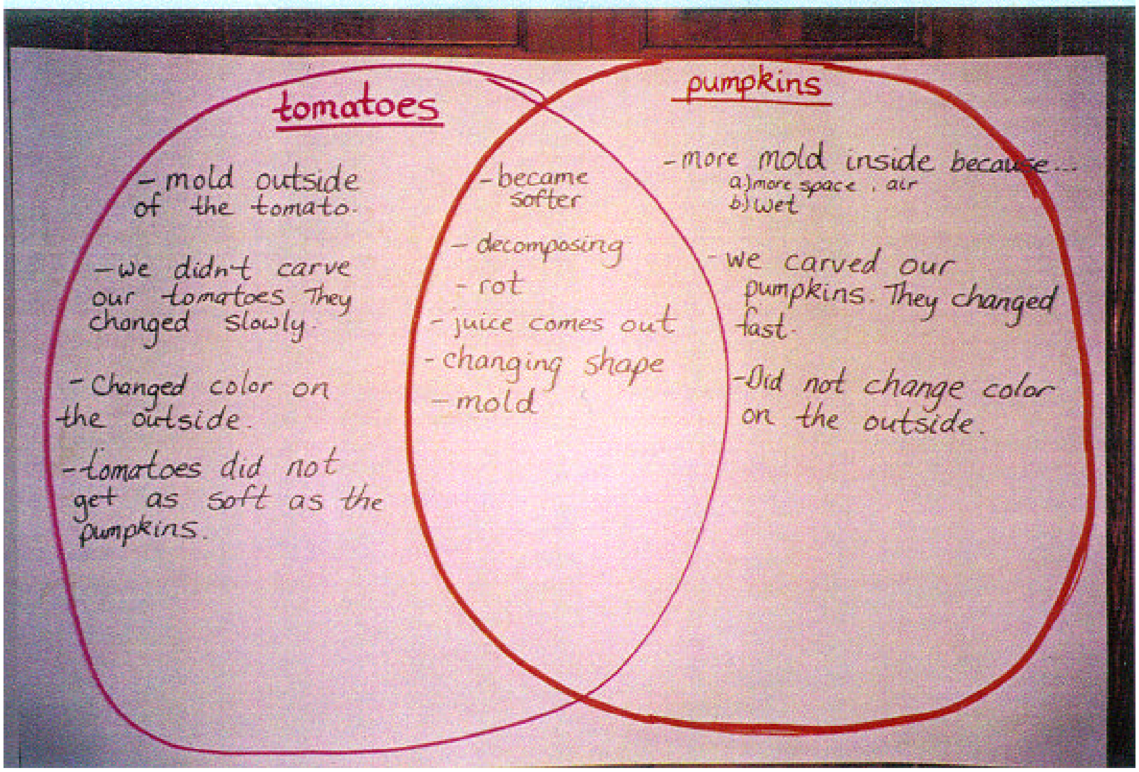


Figure 4. First graders compare pumpkin and tomato growth with Venn diagrams.

As the weather changed, students found that change outdoors slowed. This raised the question of how they might continue to study change. Their teacher proposed a compost column as a model but insisted that the children determine what should be included. Deciding which aspects of the outdoors to include involved children in some of the essential aspects of modeling, as they debated whether or not to include Styrofoam litter and the like. Hence, models served the purpose of allowing children to continue their investigations, as displayed in Figure 5 (Lehrer & Schauble, 2003).

Name Stephanie 1-4-96 B
Compost Columns
I see mold, garbage, and leaves.
The mold is white on the drt.
The food the (larva) lorin ate the food.
What has changed? The tomato is changed.

Fig. 5. A first grade student characterizes change in the compost column.

Comparative Study of Plant Growth

Students in primary grades represented the growth of flowering bulbs planted under different conditions (in soil or water), using paper strips to depict the heights of plant stems at different points in the growth cycle (Lehrer & Schauble, 2002, 2003). Depiction of height required a transformation in children's thinking from considering the plant as an intact whole to thinking of it as a *set of attributes*, height being the most salient. Children wondered if the strips of paper representing height needed to be green, or could this attribute be safely ignored? Could color instead signify different kinds? (see Figure 6) What would an ordering over time imply?

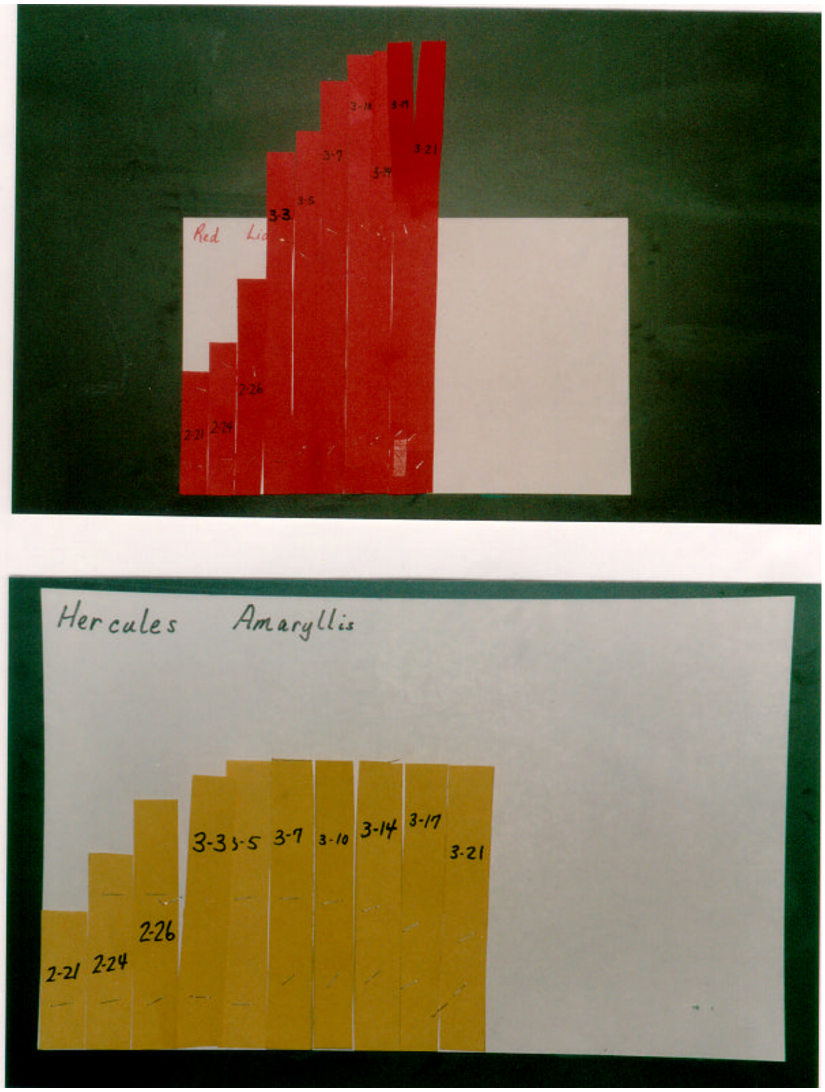


Figure 6. Children’s paper-strip inscriptions of changes in the heights of different species of flowering bulbs over time.

Representing and comparing heights required working out standard ways of measuring and a firm understanding of the mathematics of measure, which was developed systematically during this investigation. Indeed, it is worth noting that understanding an attribute and understanding how to measure it are related ideas, regardless of the grade of the “scientist.” For instance, students invented and compared different units of measure (e.g., pencils, tiles). One calculation of total growth is displayed in Figure 7.

QuickTime™ and a
TIFF decompressor
are needed to see this picture.

Figure 7. A student represents use of tiles to calculate the amount of growth between the first and 26th day for two different plants.

When children raised the question *how much faster* one plant grew than another, their attention turned from comparing final heights to noting successive differences in the lengths of the strips from day to day. These questions relied on the arithmetic of comparative difference, a form of mathematics within their grasp. After constructing another display, they noted that the amaryllis grew faster at the beginning of the life cycle and then slowed, whereas the paperwhite narcissus grew very slowly at the beginning and then “catched up.”

Study of the Life-Cyle of the Monarch Butterfly

Students in three grade 1-2 classrooms investigated the life cycle of monarch butterflies, observing with both eyes and magnified video cams, transitions from egg to adult. (See http://www.vanderbilt.edu/modeldata/ for teachers' descriptions of student thinking, lesson plans, etc.) Student investigations provided rich opportunities for learning performances related to diversity, change, and comparative study. Children defined attributes, represented and defended their choices, characterized change, and compared butterfly and larval stages of growth. In the sections that follow, we illustrate how teachers supported learning performances for the central concepts of diversity, change, and argument.

Diveristy. Learning performances for this grade band include defining and employing attributes to answer questions. For example, children from each class summarized changes they observed and presented these to children in the other classes. The form of presentation was a story, with dialogue. This is one way that teachers supported relations between scientific and textual literacies. In the episode that follows, one child (C) noticed that caterpillars got "fatter" over time. His teacher reminded him, so that children in other classes could benefit, that the meaning of fatter was not transparent:

> C: The caterpillar needs to store more and more food as it grows, so it gets fatter and fatter.
>
> T: And fatter was an interesting idea that we talked about and we had to have a discussion so that if somebody in my homeroom uses a descriptive word like

fatter, that we all understand the word fatter in the same way. Tim, can you tell the boys and girls what we mean by fatter?

C: Bigger around (Gestures with his thumb and finger to form a circle. His partner simultaneously gestures to encompass the circumference of his wrist with his thumb and finger.)

T: Yeah, we tested that with our wrists today….And you (gestures to seated children in other classes) might have a different understanding of fatter. If ship somebody tells you fatter, we don't know if you think the same thing that we think so we thought it was important to tell you that.

During the course of their investigations, children made many proposals for attributes, including discerning mouthparts of the organism and the pattern of stripes on the body. They also invented means to estimate the amount of leaf consumed each day. Each of claims was subjected to the test of "evidence." This emphasis was re-voiced by one of the teachers during the whole-group sharing; Note how the teacher reminded children that claims must be supported:

T: You know, one thing I have heard a lot from Mrs. Charles is: "What is the evidence for your thinking?" So, when you listen to someone sharing from a homeroom, you want to be asking yourself: Hmm, how did they know that? What's the evidence? Is it something that you observed? Is it something that you saw happening? How did they know that? And, check yourself: How would <u>you</u> know that, when you hear someone saying something? And you might not be able to come up with the answer for that, and that's good because we want to question that then.

Change. Learning performances include representing change over time. Children noted transformation in selected attributes, especially length and “fatness” during the larval stage. They developed measures of these changes, using mm. units of lengths of string (unfortunately, some caterpillars did not survive these measurements). Children also wondered about transformations: What happened to the leaf that the caterpillars were eating? These gave rise to secondary investigations of appropriate texts, supported by children’s observations (the caterpillars that ate more grew more). Children represented their findings from text, and from first-hand observations, as stories, such as:

> How does the leaf become part of the caterpillar?
>
> “The caterpillar eats the leaf. The caterpillar gets bigger and fatter. The leaf goes into its stomach,” said Samantha.
>
> “The mouth chews the leaf. The leaf goes into the stomach and sits there. The body keeps the good stuff and gets rid of the bad stuff. The bad stuff becomes frass. The good stuff stays in the body,” said Carla.
>
> “I think the leaf becomes part of the wings,” said McKayla.

Children also represented change over the course of the life cycle by drawings. Teachers pressed children to think about the features of change highlighted in their drawings and drew children’s attention toward comparing different drawings with respect to which aspects of change were selected and which were suppressed. This mediation by teachers supported the learning performance of comparing representations for the big idea of change.

Argument. Teachers seeded two forms of argument. The first, modeling, was accomplished by continued emphasis on representational forms and metatalk about what these forms selected and neglected about the natural world. Everyone could “see” the same thing with the video-cam, yet everyone did not select identical attributes for further investigation, and their drawings were very different. This discrepancy drew attention to the distinction and functions of separation between representing and represented worlds.

The second form of argument supported by teachers was *comparative analysis*. Children in each class constructed a Venn diagram representing similarities and differences between larval and adult stages of butterfly. One of these is displayed in Figure 8. This comparison led to further speculation: What might be the function of the change? Several children in each class noted that the food sources for the same organism had now changed. Butterflies could use their “noses” to obtain “honey” from flowers instead of eating the leaves of the plant. By engaging in these comparisons, students also met learning performances for *structure-function* and again, *diversity*.

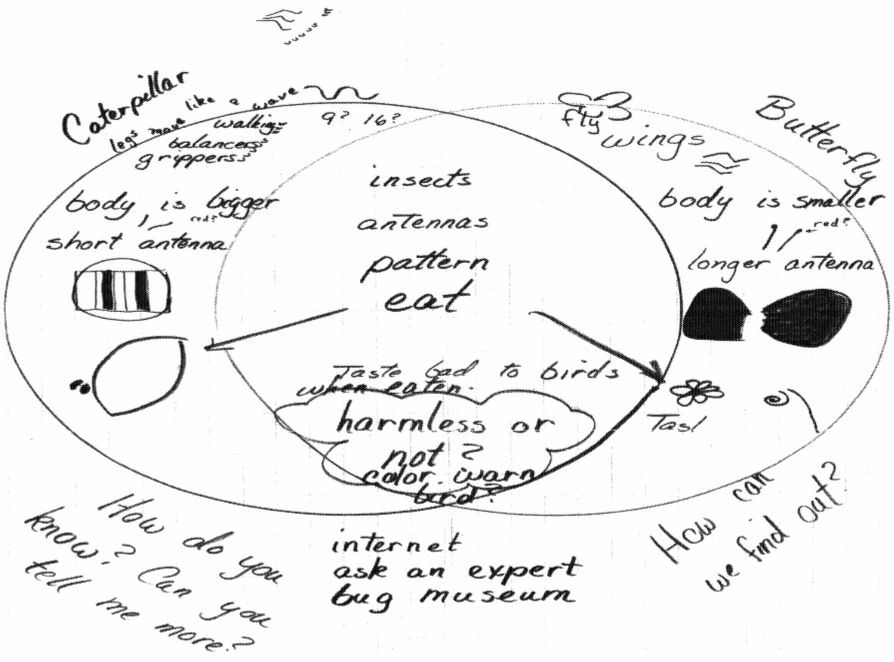


Figure 8. Venn representation of metamorphic change during the life cycle of the monarch.

Implications for Assessment

These classroom episodes suggest a key role for teachers in supporting children's inquiry about the natural world. The specification of big ideas as learning performances points to how one might reasonably determine whether or not children in fact have the opportunity to learn these central concepts. As we mentioned previously, concepts are realized in particular forms of practice. Looking across the examples, there is evidence that teachers were engaging children in genuine inquiry, in constructing relations between claims and evidence, and in generating and appropriating rich representational resources.

All of these indicate alignment between instruction and what is deemed worthy of assessment by the specification of learning performances. On the assessment side of the coin, classrooms provide opportunities for assessing individual performance (e.g., the particular representations constructed by children, their claims and evidence in the form of representations, stories and related communications) and also, for assessing qualities of the classroom learning environment. For example, recall that in the third example, the teacher asked students to consider relations between claims and evidence: “So, when you listen to someone sharing from a homeroom, you want to be asking yourself: Hmm, how did they know that? What’s the evidence?”

3-5 Band

AAAS Natural Selection & Evolution Strands

A great variety of kinds of living things can be sorted into groups in many ways. [Diversity]

Fossils can be compared to one another and to living organisms according to their similarities and differences. Some organisms that lived long ago are similar to existing organisms, but some are quite different. [Geologic Record]

Waves, wind, water, and ice shape and reshape the earth's surface by eroding rock and soil in some areas and depositing them in other areas, sometimes in seasonal layers. [Geologic Record]

Changes in an organism's habitat are sometimes beneficial to it and sometimes harmful. [Structure-Function]

For any particular environment, some kinds of plants and animals survive well, some survive less well, and some cannot survive at all. [Diversity]

Individuals of the same kind differ in their characteristics, and sometimes the differences give individuals an advantage in surviving and reproducing. [Structure-Function; Variation]

Some likenesses between children and parents are inherited. Other likenesses are learned. [Variation]

Some plant varieties and animal breeds have more desirable characteristics than others, but some may be more difficult or costly to grow. [Structure-Function]

Expression of Big Ideas for 3-5 and Rationale

The focus again is on *diversity*. Different kinds of organisms are re-visited with an eye toward characterizing relationships between qualities of an environment and the kinds of organisms that inhabit it. For example, aquatic insects have attributes in common with terrestrial insects, but the differences between them are significant. This theme builds on the previous experiences constructing attributes of organisms and of careful description of similarity and difference. But the emphasis now is on coming to see attributes as related, so that knowing that an organism has attribute x, it is also likely that it has attribute y.

S*tructure-function* is revisited, this time with more of an emphasis on test. How can conjectures about structure-function be reasonably assessed? What constitutes evidence of a relationship? This increased scope leads toward considerations of relations between qualities of habitat and qualities of the organisms living there. *Ecology* grows out of this expanded set of questions about these relations, especially when considered from the perspective of how these relations might enhance the likelihood of survival of particular organisms. *Variation* continues to be considered primarily as recording types of differences—among individuals and between species. At this point, concepts of random and directed variation are not introduced. C*hange* in 3-5 reconsiders change from the perspective of ratio, introducing students to concepts of rate and of changing rates. The geologic record is again focused on comparisons between fossils and extant organisms, with an eye toward setting the stage for thinking about descent from older to more recent forms.

The mathematical tools and forms of argument expand those introduced in the K-2 grade band. The mathematical tools for this age span include those first employed in grade 1-2 (arithmetic, measure, Venn diagrams) but now include an introduction to the cladogram (tree representation) and to coordinate systems for describing change over time. The forms of argument include comparative analysis and modeling, but the mathematical expression of these arguments is now more sophisticated, so that students can perceive relationships that might otherwise not be readily accessible. For example, the logistic curve governing the growth of many organisms is not readily visible until rendered in a coordinate system. Cladograms make relationships among different organisms more visible, expanding on the simple pair-wise comparisons introduced in earlier grades.

3-5 Expression of Big Ideas

Diversity.

Classification. The emphasis moves from definition of single characters to their coordination in systems of classification.

Comparative analysis. Species are organized in ways that reveal characters that support their relationship. This requires new forms of representation.

Structure-Function.

Characters often serve specific functions. For example, what function is served by the proboscis of a butterfly? The concept of adaptive value is introduced: How might the character affect survival?

Ecology.

The simple associations of species type and habitat is upgraded to consider *relationships* between qualities of the environment and characters of the organism.

Variation.

The themes of organismic variation and between-species variation are maintained and elaborated.

Change.

The focus on change is still at the level of individual organism but there are two major advances. First, greater emphasis is placed on function. Why might the change help ensure survival? Second, the mathematics at students' disposal includes ratio, which allows for more functional (in the mathematical sense) descriptions of change.

Geologic Record.

Students become familiar with a wider range of fossils. Good and easily obtainable examples to use would include the Cretaceous oyster fossil *Exogyra* that can be purchased for a few dollars. Encouraging *comparison* with extant oyster shells can lead to many *questions* about form, function, ecology and what might have led to their disappearance. Another very common fossil from limestone deposits are bivalve brachipods (lamp shells) that allows comparison with extant clam shells, even though they comprise a separate phylum.

Forms of Argument.

Models represent key aspects of the natural world but are not identical to that natural world. Students in this age band create more sophisticated mathematical descriptions of growth and of relations between species.

Comparative analysis. Students progress beyond Venn diagrams to cladograms, and their analyses are directed more toward claims that might be refuted, at least in principle.

Mathematical Tools.

Measure. The emphasis shifts toward measurement of relations, such as rate or surface-area to volume ratios.

Venn diagram. Children employ Venn diagrams as tools for comparative analysis.

Arithmetic, especially ratios. Arithmetic is used again to model change over time but now the emphasis is on ratios, and on rudimentary notions of function (e.g., representing change as piecewise linear segments).

Claodgrams. Students use cladograms to conduct comparative analysis among species.

Learning Performances

Diversity

Identify attributes/characters and use them to *classify* an organism.

P*redict* an attribute given the presence of another attribute.

Note: Students constructed *Venn diagrams* in K-2 that clustered organisms based on shared characters. An alternative visualization of such relationships is the *cladogram* (See Figure 9*)*; a simple branching diagram which depicts the distribution of characters among “organisms”. Such diagrams, which are testable hypotheses, are used by extensively by biologists to study evolution. Students can use these diagrams to predict membership of nested sets of kinds, predict the occurrence of a character given the presence of another character, poise questions about the diversity of groups and how this may be related to the characters which support them. Introducing students to cladograms will allow them to investigate the distribution of attributes among “organisms” and test predictions of which attributes confer membership of which sets. During this process, the idea of informative attributes, being those that are variable and shared by at least two “kinds”, will provide the seed of understanding classifications as information retrieval systems, a powerful notion.

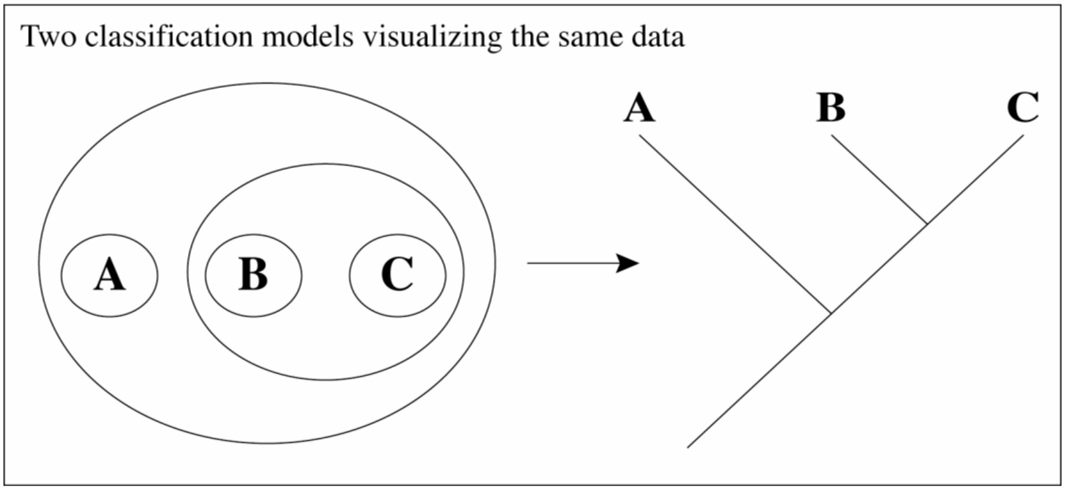


Figure 9. Relationships among three tax represented by a Venn diagram and a cladogram

Compare and Contrast Species. (e.g., Students compare and contrast the structures and functions of an organism (like a butterfly or moth) with an organism that does not have this kind of cycle. Students represent relations with cladogram (See Figure 10). Students conjecture about which taxa have more species and why that might be.

Students *construct, revise, present/defend, and critique explanations* of the constrasts observed.

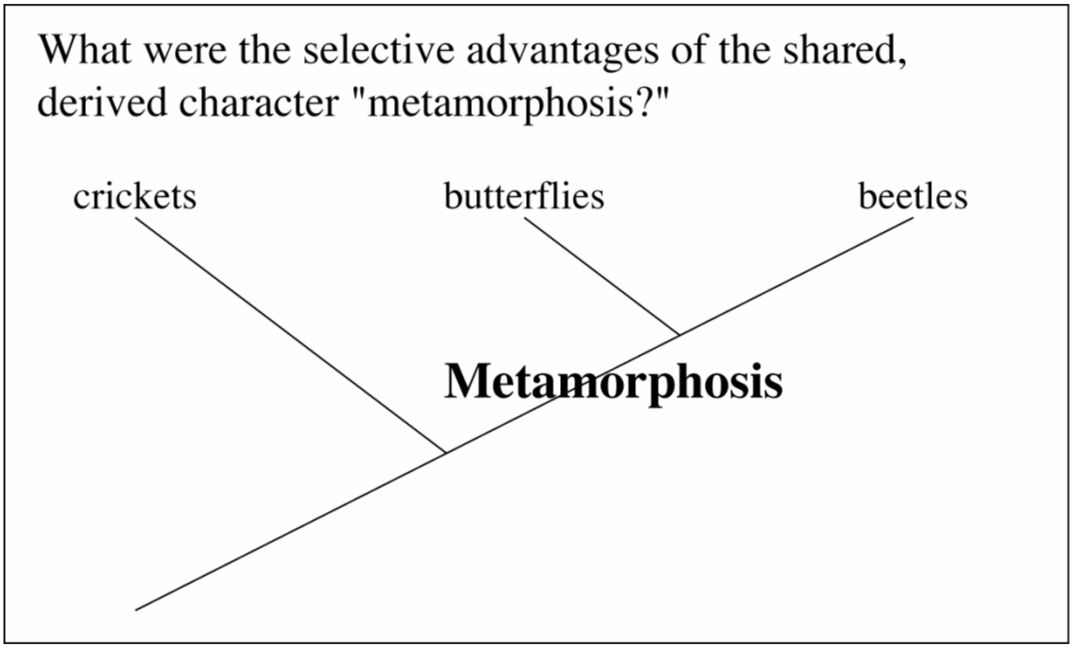


Figure 10. A Cladogram Representing Relations Among Crickets, Beetles, Butterflies

Structure-Function, Ecology

Note: Underlying premise - that structures are selected for by the environment, (*caveat sexual selection). Organisms that possess certain characters have these characters as a result of selection acting upon their kind (species) over time. It is important to stress that organisms cannot adapt during their lifetime.

Observe and *record* morphological structures of species in different habitats.[4]

Describe and represent relations between characters of species and characteristics of habitats.

Explain, supported by evidence, relations observed.

Variation

Identify characters that vary.

Represent variation in characters in multiple ways. (e.g., drawings, definitions, tables of values)

Compare representations with an eye toward their purpose.

Change

Identify attributes that change. (e.g., height of plant, number of leaves, onset of flowers, seeds).

Measure change. (e.g., measurements are taken on individuals.)

Represent and describe change with *multiple representational systems.* (e.g., describe change verbally, with drawings and diagrams, mathematically via coordinate graphs of rate).

Relate change to function. (e.g., as plants grow, the greater surface area of leaves provide increasing amounts of energy for the organism).

Geologic Record

Pose questions. How many different types of fossils are there? Where do we find fossils?

Represent fossils by drawings, photos, impressions.

Compare one or more fossils to extant organisms.

Forms of Argument

Models.

Pose questions. What's the use of a model?

Represent an aspect of the natural world. Draw, photo, video, create a data display.

Invent a model for one or more natural system investigated.

Evaluate the utility of the model.

Comparative analysis.

Pose questions. How are 2 different species (kinds) alike or different? How are 2 different habitats alike or different?

Represent attributes of organisms being compared. Draw, photo, etc.

Compare organisms or habitats mathematically (e.g., Venn diagrams, cladograms, tables of characters)

Mathematical Tools

Measure.

Invent a unit of measure relating two or more quantities.

Use units of ratio measure to create a measurement.

Employ ratio measurements to characterize aspects of a natural system.

Venn Diagram.

Employ Venn Diagrams for comparison.

Compare Venn Diagrams to at least one other representation (e.g., lists of attributes)

Arithmetic.

Describe change arithmetically. (e.g., order successive differences of ratios over time to characterize change)

Cladogram.

Employ cladograms as described for learning performances related to diversity.

6-8 Grade Band

AAAS Natural Selection and Evolution Strands [Big Ideas Referenced]

In all environments – freshwater, marine, forest, grassland, mountain, and others- organisms with similar needs may compete with one another for resources, including food, space, water, air and shelter. In any particular environment, the growth and survival of organisms depends on the physical conditions. [Diversity; Ecology]

Animals and plants have a great variety of body plans and internal structures that contribute to their being able to make or find food and reproduce. [Diversity; Structure – Function]

Two types of organisms may interact in several ways: They may be in a producer/consumer, predator/prey, or parasite/host relationship. Or one organism may scavenge or decompose another. Relationships may be competitive or mutually beneficial. Some species have become so adapted to each other that neither could survive without the other. [Diversity; Ecology]

Individual organisms with certain traits are more likely than others to survive and have offspring. Changes in environmental conditions can affect the survival of individual organisms and entire species [populations]. [Variation]

Natural selection arises from three well-established observations: (1) There is variation in traits within every species of organism, (2) some of these traits give some individuals advantage over others in survival and reproduction, and (3) those individuals that survive to adulthood be more likely to have offspring which will themselves be more likely than others to survive and reproduce. When an environment changes, the advantage or disadvantage of characteristics can change.[from *Science for All Americans*] [Variation; Change]

Many thousands of layers of sedimentary rock provide evidence for the long history of the earth and the long history of changing life forms whose remains are found in the rocks. More recently deposited rock layers are more likely to contain fossils resembling existing species. [Geologic Record, Diversity]

6-8 Expression of Big Ideas and Rationale

In this grade band, we revisit central concepts and begin to ask deeper questions about diversity and change. In particular, we engage students in considering the consequences of variation, taking structure/function and interrelationships in a system into account, in order to uncover a beginning understanding of the mechanisms that underlie change. Thus, we focus on the big ideas of variation, structure-function, and interrelationship (ecology) that come together in a description of the mechanism for change in populations of organisms. The geologic record is also brought into play by shifting the emphasis from the fossils themselves to understanding how scientists use fossil evidence to make inferences about the history of the Earth and its life forms through time. While in the earlier 3-5 band we focused primarily on noticing and describing, we now bring in learning performances involving explanation. In this section, we describe how these big ideas are unpacked at this grade level, and then in the next section consider the key learning performances associated with these core ideas.

6-8 Expression of Big Ideas

Diversity

Diversity is approached now at two levels. First, differences among species are again examined. But now, the potential role of intra-species variation is introduced as a prospective source of differences between species. Diversity is revisited with an eye toward beginning to characterize interactions among levels of diversity. Diversity is now seen as a result of mechanisms involving change, variation, and ecology. It is no longer viewed only as an extant quality of the natural world.

Structure-Function.

As students consider how organisms of the same species may differ from one another, they ask which differences among organisms would matter? Here they learn about the external and internal structures that help the organism survive, and thereby reproduce. The identification of the function of a structure is specific to the context or environment in which the organism lives.

Ecology.

The examination of interrelationships among living things in an ecosystem is expanded. What affects one species may affect others in the system, even if they are not in a direct predator/prey relationship. We also bring in the notion of competition for resources as the relevant type of interrelationship to consider when considering the consequences of variation.

The first part of the understanding concerns the ways that organisms can interact in a system, and how change in one organism propagates through the system. The simple types of connections include predator/prey and parasite/host relationships. Organisms may directly interact through these relationships, and may also influence one another through more complex relationships, such as networks of predator/prey relationships (a food web). Thus, what affects one population of organisms within an environment often will affect other populations of organisms within that environment. Under normal circumstances the relationship among organisms in a food web are stable. However, changes in the food web, such as a major change in numbers of a species or an introduction of a new species, can disrupt this stability. As a system, the central way to reason about food webs is in constructing predictions or explanations about consequences of *changing* an element in the system.

Another type of interrelationship between organisms that is critical to the understanding of change that we are working toward is *competition*. Organisms with similar needs may compete with one another for use of limited resources, including food, water, or space. Competition occurs at two levels of organization. Competition occurs between kinds of organisms (e.g., two species of birds competing for available food) and within a population (e.g., the members of a population compete for limited food or males compete for available breeding females). Competition between organisms (both within species and between species) for these resources is an essential and ever-present constraint on survival. Such competition for resources remains stable in a healthy environment; however changes in the environment (such as the introduction of a foreign species) can disrupt this competitive stability. It is precisely the pressure of competition for limited resources that allows us to consider the consequence of the variation between members of a population.

Variation.

Students consider how organisms that are of the same species also can be different from one another. Organisms can be characterized by collections of attributes (characters) that work together in systems. Characters often have measurements associated with them (such as length of a wing); thus associated with the work with this big idea is the mathematical tools for modeling this variation. What is particularly new at this grade band is the realization that these individual differences in attributes may influence the overall success of an individual in surviving and/or in reproducing compared to others of the same population.

Change

At this grade band, the focus on change shifts toward (dynamical) systems. Change occurs continuously in nature. Even in periods of stability the levels of populations experience fluctuations. Change in a population can occur as individuals change (though growth or due to change in physical conditions), and when the set of individuals in the population adds or loses members (through birth, death, migration). Changes in environmental conditions can introduce an environmental stress or pressure on organisms, affecting survival of individuals or populations. Thus, again the core idea of *levels of organization* in diversity is important in making sense of what kind of change is occurring.

A critical type of change, within populations or species, puts together the idea of variation, competitive relationships, and structure/function to engage students in reasoning about what kind of change results from naturally occurring variation on attributes with important functions, in a context in which individuals are in competition. The resulting idea is called differential survival. Some individuals may be more successful in surviving and therefore in reproducing, as a consequence of how particular individuals vary in their traits from one another. The population may change in a biased direction, as a certain subset of the population are more likely to survive in the context of the environmental pressure. This is the notion of *directed variation.* This idea synthesizes a number of prerequisite ideas (competition, differential survival, environmental pressure) into an account of how change can come about in populations across time. It stops short of a full model of natural selection, which we place at the high school level (as does AAAS benchmarks), in that this basic version of natural selection does not consider geologic time or the appearance of very different (macro-level) traits. For example, students could consider examples such as longer legged grasshoppers surviving a fire, having progeny with slightly longer legs on average than the parents' generation, survival of longer beaked or heavier Galapagos finches in a period of drought, greater proportion of longer-fur animals in artic climate over several generations, and so on. But we do not consider macro-evolutionary changes such as creation of new species, or evolution of one taxa from within another, such as dinosaurs to birds.

The steps in the process are as follows. (1) There is a naturally occurring variation in heritable characteristics within a population. (2) Due to the functions these structures perform, some of these characteristics will give individuals an advantage over others in surviving to maturity and reproducing, and (3) those individuals will be likely to have more offspring, which will themselves be more likely than others to survive and reproduce. This leads to what may be small but observable changes in these characters across generations, where the numbers of members of the population with the particular character increase across generations. For complex traits like beak length, the measure of the trait may change over time, such as beaks become longer or deeper.

Forms of Argument.

Models. Students construct models of how natural selection operates on distributions of characters.

Comparative analysis. Students compare the costs and benefits of different characters across ecosystems. Students engage in comparative analysis of organisms found in different geologic strata, of the relationship between structure and functions across different species.

Mathematical Tools

The core move in middle grades is to see populations as made up of individuals that vary from one another, and to learn to focus on the functions organisms need to achieve in order to survive. These ideas are combined with an attention to the competition between organisms that leads to some individuals or some species succeeding more than others. These are the core building blocks of natural selection. To support these forms of reasoning, students employ *distribution* to represent a population as a collection of individuals, and to tease apart the measurements of an individual from the parameters of a population, such as population size, average value of a trait, and so on. They employ *cladograms* to reason about characters that appear to lead to widespread radiation of species, and contrast these to characters that are less likely to lead to such radiations.

Learning Performances

Diversity

Students *identify* characters which only evolved once and support large radiations of species i.e., metamorphosis.

Students *distinguish* between characters that evolved independently on several occasions (convergent evolution), and those that appeared only once in the history of life.

Students *explain* that convergent evolution is driven by local ecological requirements and does not typically lead to large radiations of species.

Structure-Function

Students *conjecture* about the function of certain structures.

Students *test* their conjectures by engaging in *comparative analysis*. For example, the feeding beak of true bugs (Heteroptera) is homologous between water striders, stink bugs, assassin bugs and plant bugs. The same structure is used to suck the juices of plants or the “blood” of other bugs.

Ecology

Students *identify* competitors and the resources for which they are competing in an environment.

Students *analyze* data of population levels of different organisms to identify which species are competitors and for what resources.

Students *analyze* population level data and *explain* the changes over time due to the introduction of a new competitor in the environment.

Change-Variation

Differential Survival Learning Performances

Students *predict* how variations of a trait might affect an organism's chances of surviving an environmental stress.

Students *analyze* data to discover changes in the distribution of the variations of a trait within a population, as the result of an environmental stress.

Students *construct and present/defend an explanation* about how an environmental stress will affect the distribution of the variations of a trait in future generations of a population.

Basic Natural Selection Learning Performances

Students *analyze* data to discover how the environment affects the distribution of variations of a trait over multiple generations.

Students *predict* the distribution of trait variations in future generations, based on the survival of individuals in the present generation.

Students *construct, revise, present/defend, and critique explanations* about how the variations in traits of a single species give some individuals advantage over others in surviving an environmental stress and in reproduction.

Geologic Record

Students *develop models* of geologic processes, such as sedimentation.

Students *construct, revise, and critique* these models.

Students *compare* the organisms present in different strata and *order* the appearance of organisms in time. A field trip to a local road cut or examining images can be very valuable (fig. 11).

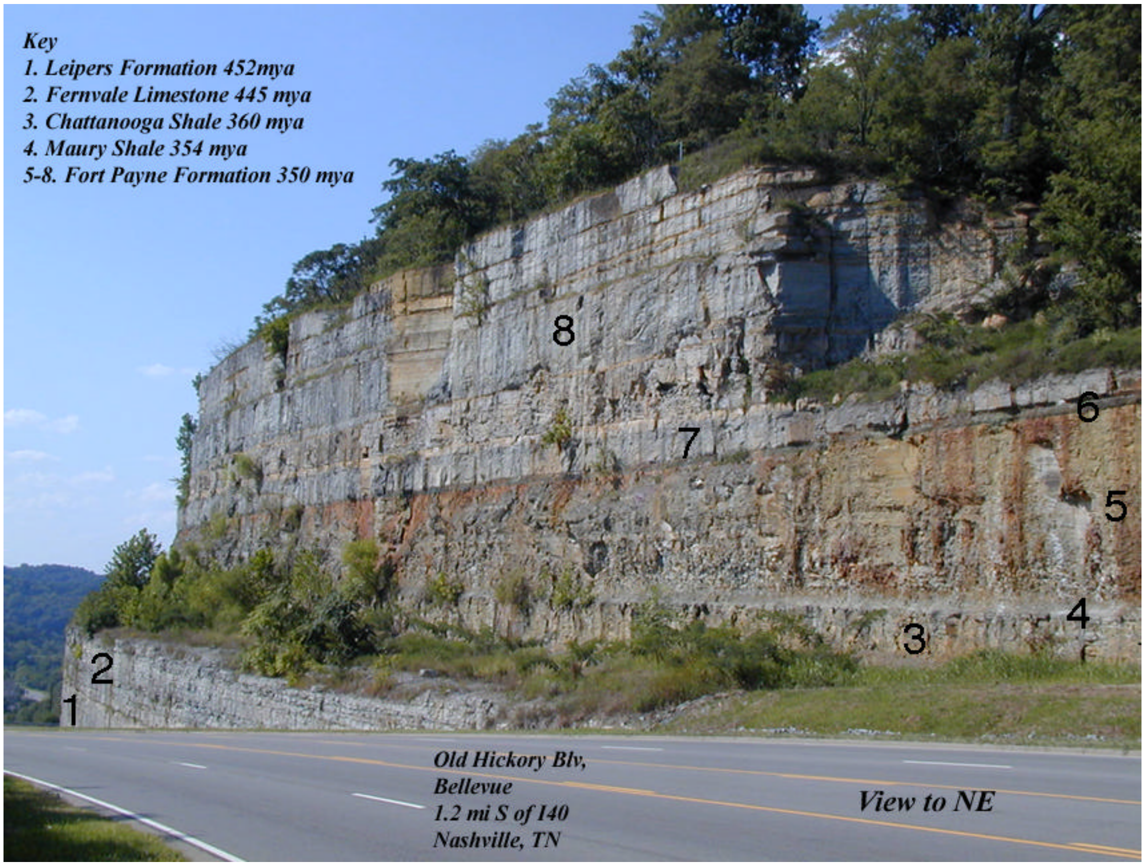


Figure 11. Road cuts are excellent opportunities to investigate sedimentation processes and the stratification of fossils.

Students *compare and contrast* organisms found in strata to extant organisms.

Forms of Argument

Models.

Pose questions. How can natural selection be modeled?

Represent an aspect of the natural world. Draw, photo, video, create a data display of a character and its variation.

Invent a model of natural selection that relies on directed variation.

Evaluate the utility of the model.

Comparative analysis.

Pose questions. What role do particular characters play in the radiation of species? How do habitats influence convergent evolution?

Compare cladograms or distributions of characters.

Mathematical Tools

At this level, students are expected to use cladograms and distributions as analytic tools.

Notes

1. The connection to the enterprise of assessment is clearly articulated in the assessment triangle (p. 44) of *Knowing what students know*. Assessment is aimed at making inferences about knowledge, and as such, characterizations of knowledge ideally orient assessment.

2. In more detail (see fig. 2), these (interacting) levels are:

(a) Genome. Variation at this level created and maintained by mutation and recombination. Important concepts/mechanisms; random nature of mutation and recombination. Exists in space and time.

(b) Individual. Phenotype determines fitness in relation to selection pressures. Important concepts/mechanisms; intra-specific competition, population size, limited resources. Exists primarily in space.

(c) Populations. Variable traits (polymorphisms), change in gene frequencies, mutations can be fixed. Important concepts/mechanisms; attributes can be measured, gene flow, reproductive barriers between populations of same species, provide a sample (sub set) of species. Exists in space and time but essentially a space construct.

(d) Species. Coherent groups of character based populations sharing a common history. Important concepts/mechanisms; speciation a result of isolation and splitting of parent species populations, extinction, adaptation occurs at this level, inter specific competition. Exists in space and time but essentially a time construct.

(e) Clades. Natural (monophyletic) units of two or more species comprising an ancestor and all descendent species. Important concepts/mechanisms; defined by sharing a most decent common ancestor (MRCA), evidence = the synapomorphy (shared, derived character), extinction important process, relationships between clades determined by phylogenetic analysis and depicted by a cladogram. Exists in time.

3. Misunderstanding the distinction between individuals and species underpins many alternative conceptions of evolutionary processes. We argue for the use of clear, unambiguous and consistent language in this and future documents dealing with evolutionary education. In particular, organisms - individuals that comprise a species or population (part of a species), be restricted to this usage. Further, when reference is made to collections of organisms; i.e. populations, species, or higher taxa, that these terms be consistently used. As the species and not the organism is the unit of evolutionary change it is particularly important to make this clear. Taxon (taxa) a wonderfully versatile but under utilized term can be correctly used to denote any taxonomic category from species to phylum. Its use should be encouraged.

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