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Feature
Approaches to Biology Teaching and Learning

Common Origins of Diverse Misconceptions: Cognitive Principles and the Development of Biology Thinking

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Many ideas in the biological sciences seem especially difficult to understand, learn, and teach successfully. Our goal in this feature is to explore how these difficulties may stem not from the complexity or opacity of the concepts themselves, but from the fact that they may clash with informal, intuitive, and deeply held ways of understanding the world that have been studied for decades by psychologists. We give a brief overview of the field of developmental cognitive psychology. Then, in each of the following sections, we present a number of common challenges faced by students in the biological sciences. These may be in the form of misconceptions, biases, or simply concepts that are difficult to learn and teach, and they occur at all levels of biological analysis (molecular, cellular, organismal, population, and ecosystem). We then introduce the notion of a *cognitive construal* and discuss specific examples of how these cognitive principles may explain what makes some misconceptions so alluring and some biological concepts so challenging for undergraduates. We will argue that seemingly unrelated misconceptions may have common origins in a single underlying cognitive construal. These ideas emerge from our own ongoing cross-disciplinary conversation, and we think that expanding this conversation to include other biological scientists and educators, as well as other cognitive scientists, could have significant utility in improving biology teaching and learning.

INTRODUCTION TO DEVELOPMENTAL COGNITIVE PSYCHOLOGY

Developmental cognitive psychology is a discipline that has not been closely connected to most biology education efforts, but may offer novel perspectives and insights. Cognitive psychologists study how organisms take in information about their environment, form internal representations of the information, and process or manipulate those representations to select and execute actions (Holyoak, 1999). Developmental cognitive psychologists study how these processes change over time as a result of environment, experience, and maturation. The large and growing field that is *developmental cognitive psychology* includes several professional societies and a number of peer-reviewed journals (e.g., *Journal of Cognition and Development*, *Cognitive Development*) devoted to just this area of research.

Early research efforts in developmental cognitive psychology were led in the 1950s by Swiss researcher Jean Piaget, who was a psychologist and philosopher with early interests in zoology. While most scholars would agree that some aspects of Piagetian theory have become foundational assumptions underlying the entire field, other Piagetian ideas have largely been discarded. One aspect of Piagetian theory that is no longer widely accepted is the idea that development proceeds in qualitative stages, and that within each particular stage thought has unique qualities that apply across many different subject domains. Rather, modern researchers agree that development can be characterized via the notion of early partial competence (Smith *et al.*, 1988). In other words, the

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core competencies of many advanced cognitive abilities are present from early infancy, but nevertheless undergo substantial developmental change. One critical component of Piaget's view that underlies virtually all modern research on cognitive development is the idea that cognitive development is an active process.

COGNITIVE CONSTRUALS—INFORMAL, INTUITIVE WAYS OF THINKING ABOUT THE WORLD

Many modern scholars believe that as children actively seek to understand, explain, and predict the world around them, they develop implicit or explicit informal theories about how the world works. As contrary evidence accumulates, children may or may not revise these theories. These theories give rise to what psychologists refer to as *cognitive construals*. A cognitive construal is an informal, intuitive way of thinking about the world. It might be a set of assumptions, a type of explanation, or a predisposition to a particular type of reasoning. Three such cognitive construals—teleological thinking, essentialist thinking, and anthropocentric thinking—may have particular relevance in understanding challenges and misconceptions commonly encountered in biology classrooms. In this paper, we attempt to make connections between each of these three cognitive construals and several areas of challenge in undergraduate biology teaching and learning. In addition, we explore how seemingly disparate biological misconceptions and misunderstandings may indeed have common origins in a single cognitive construal that undergraduate students may find implicitly useful in their thinking outside the realm of biology. In considering these explorations of the connections between biology education and developmental cognitive psychology, however, we suggest that readers keep in mind the following. First, there is not necessarily a simple one-to-one correspondence between a particular challenge or misconception and a particular cognitive construal. A given construal may give rise to a number of misconceptions and challenges, and any given misconception or challenge may be the result of multiple construals. Second, although all the cognitive construals that we discuss below are well documented in the cognitive developmental literature, modern research in cognitive development has focused largely on how these construals present in younger individuals, primarily during the period between birth and puberty. As such, in most cases little empirical attention has been paid to the developmental trajectory of these cognitive construals as students progress through middle school, high school, and college. In such cases, we will summarize what is known about the relevant arc of development in younger children, and extrapolate to our older populations of interest.

MISCONCEPTIONS RELATED TO TELEOLOGICAL THINKING

Consider which of the following statements you may have encountered in your own biology teaching and learning experiences. Some relate to molecular biology, others to transformations of matter and energy, and still others to evolution.

- Genes turn on so that the cell can develop properly.
- Birds have wings so they can fly.
- Plants give off oxygen, because animals need oxygen to survive.
- Individual organisms adapt and change to fit their environments.
- Evolution is the striving toward higher forms of life on earth.

These represent just a few examples of common biological misunderstandings encountered by teachers of biology from elementary school to college, as well as those promoting the understanding of science among the lay public. Biology instructors tend to perceive these challenges as unrelated and grapple with them in the classroom individually, as misconceptions in need of correction. However, these ideas may be more closely related in their origins than they initially appear. Specifically, all of these conceptual challenges relate to students' need to answer the question of "Why?" in their studies of biology. Cognitive psychologists have shown that our minds are strongly biased toward causal explanations (e.g., Kahneman, 2012). We are quick to generate causal stories for any event brought to our attention: a slump by our favorite athlete, a perceived snub by a colleague, or a larger than average yield of zucchini from our garden. One common type of causal reasoning is known as *teleological thinking*, which is reasoning based on the assumption of a goal, purpose, or function. Kelemen (1999a) argues that teleological thinking is a central component of adults' everyday thought. When reasoning about others' behavior, adults make the teleological assumption that people's actions are directed toward certain goals (e.g., he frequented the gym so that she would notice him; she saves money so that she can retire). Similarly, they presume that human artifacts, such as chairs and coats, are designed by their creators to fulfill some intended purpose (e.g., chairs are to sit in; coats are to keep us warm). As Kelemen emphasizes, teleological thinking provides an important component of adults' intuitive interpretations of why events occur or why objects have the properties that they do.

The developmental arc of teleological thinking involves a pattern of "pruning." Kelemen has shown that teleological thinking is widespread (or in her terms, "promiscuous") among young children and becomes more selective and constrained with development (Kelemen, 1999b, 2012). For example, in one study of students in first grade through college, the youngest participants favored teleological explanations for a broad range of phenomena, including properties of nonliving objects (e.g., "The rocks were pointy so that animals wouldn't sit on them and smash them") and of animals (e.g., "Cryptoclidus had long necks so that they could grab at fish and feed on them"). College students were more selective; they rejected teleological explanations for nonliving objects, but 67–81% of them still preferred teleological explanations for biological properties (see also Kelemen and Rossett, 2009). Nor is this merely an educational by-product; Casler and Kelemen (2008) found that teleological explanations were common among Romani adults exposed to little or no formal education, suggesting that teleological thinking may be a basic feature of our cognitive architecture.

Teleological thinking is a widespread cognitive construal that is useful in helping us make sense of many aspects of the world around us. However, this natural form of explanation is often extended inappropriately in the domain of biology. Students at all levels commonly explain biological structures and processes by reference to their supposed purpose, goal, or function. Indeed, this theme runs through the apparently disparate set of examples presented above. In all of these examples, biological phenomena are seen to be caused by the ultimate functions or outcomes of the phenomena. The first three examples occur on the cellular, organismal, and ecological scales, respectively, and all involve the use of an outcome as a causal explanation. The activation of genes *results* in proper development (ideally), but is *caused* by chemical signals and triggers in the cellular environment. Having wings certainly enables (some) birds to fly, but it is unlikely that selection forces acting on an avian ancestor anticipated this outcome and directed evolution accordingly. And students' assertion that plants give off oxygen, because animals need oxygen to survive has been documented by multiple research groups (see Driver *et al*., 1994; American Association for the Advancement of Science [AAAS], 2012), impeding students' ability to understand the biochemical origins of the oxygen released by plants, as well as the role of oxygen in cellular respiration within plants themselves.

The last two statements listed at the beginning of this section, seemingly unrelated to the first three, are common misconceptions about evolution that can also be linked to teleological thinking (e.g., Kelemen, 2012). The idea that organisms intentionally change their traits in order to better adapt to their environment and then pass these traits on to future generations is a well-known misunderstanding of what biologists refer to as *adaptation* (Bishop and Anderson, 1990; Passmore and Stewart, 2002; Stern and Roseman, 2004; AAAS, 2012). This is clearly teleological thinking; it substitutes a goal or purpose (better adaptation to the environment) for a causal explanation (variation and differential reproductive success). As such, it presents an intuitively attractive explanation for students, but can derail the development of their thinking about populations of living things, the differential survival of different members of a population, and how differential survival can drive changes in a population of organisms over time. Likewise, students who hold the common misconception of evolution as a collective striving toward "higher" forms of life—often including humans as the "most highly evolved" life form—mistake evolution for a purpose rather than a process.

In summary, teleological thinking may underlie a variety of seemingly unrelated biological misconceptions, and may thereby play a role in hindering students' transitions from novice to more expert thinkers in the biological realm. No doubt many readers will be able to recall other misconceptions they have encountered in undergraduate biology education that appear to be associated with teleological thinking.

MISCONCEPTIONS RELATED TO ESSENTIALIST THINKING

Teleological thinking is probably not the only cognitive construal driving biological misconceptions. Consider the statements below, which do not appear to be mediated by a teleological mind-set.

- Homeostasis keeps the body static and unchanging.
- Members of the same species are almost identical in their physical characteristics.
- If left alone, a wetland ecosystem will remain a wetland indefinitely.
- Because different cells in an organism have different physical characteristics, they must contain different DNA.
- Changing a single gene in an organism results in a new kind of organism.

The statements above represent misunderstandings that cross many biological domains, including molecular genetics, evolution, physiology, biotechnology, and ecology. What they share is the assumption that a core property or feature of a biological structure, species, or system determines its overt features and identity. This assumption may derive from a cognitive construal known as *essentialist thinking*. Essentialist thinking refers to a set of assumptions that people make about concepts. In cognitive science, the term *concept* is used in a more restricted way than in common parlance. For cognitive scientists, concepts are mental representations of categories, along with related knowledge. For example, our concept *bird* is a mental representation of everything we know about birds. Concepts can involve many different kinds of knowledge, including features (small, colorful, has feathers, flies), episodic memories (that flight of parrots you saw on Telegraph Hill in San Francisco), declarative knowledge (birds are dinosaurs), or mental images. Critically, concepts are *summary* representations. We do not file away every single bird-relevant thought, fact, or experience we have ever had. Rather, we selectively represent salient knowledge about birds and myriad other entities in terms of averages (Murphy, 2002).

In cognitive science, essentialist thinking is a cognitive construal in which concepts include not only summary representations of knowledge about category members, but also an assumption that there is some unobservable essential property (an "underlying reality" or "true nature") common to members of a category that conveys identity and causes observable similarities among category members (Medin and Ortony, 1989; Ahn *et al.*, 2001; Gelman, 2003). This is not a metaphysical claim about the structure of the world, but rather a psychological claim about assumptions implicit in people's representations of some concepts. Nor is it a claim that people are explicitly essentialist; essentialist thinking may be implicit in the way they represent and use knowledge. Nor do people even need to know what the essential property might be; they need only behave as if there is one.

One consequence of essentialist thinking is that an entity's category membership is ultimately based on the presence or lack of an *essential* property, rather than on superficial features. If a pigeon somehow survived a tragic accident in which it lost its feathers, wings, and beak, we would probably agree that it was still a pigeon. Conversely, changes to an essential property should result in changes to category membership. If our pigeon undergoes substantial genetic mutation, and thereby loses its beak, feathers, and wings, we may concede that it is no longer a pigeon (Keil, 1989; Rips, 1989). Another consequence of essentialist thinking is the idea that members of a category are relatively uniform with respect to shared properties. For example, if you learn that one robin has enzyme PX42, you might think it likely that all robins would have enzyme PX42. If the properties of category members are caused by an underlying essential property shared by all category members, then the essence should give rise to similar properties in all category members (Rips, 1975; Osherson *et al.*, 1990; Coley and Vasilyeva, 2010). In essentialist thinking, variability among members of a category is disregarded as noise, resulting in concepts that simplify the bewildering array of information in the world into manageable chunks. Moreover, the assumption that category members share an underlying essence that is responsible for category membership and observed characteristics allows us to instantly and effortlessly make inferences about novel exemplars: this tiger will behave in this way, that turkey will taste that way. In sum, essentialist thinking allows us to explain and predict an otherwise incomprehensibly complex world.

There is substantial evidence suggesting that essentialist thinking is an early and pervasive cognitive bias (see Gelman, 2003). For example, by age two, children readily infer that living things from the same category will share internal features and nonvisible functions despite differing appearances (e.g., Gelman and Coley, 1990; Gelman and Markman, 1986; Coley, 2012). Indeed, children are often overzealous in their essentialist thinking; in studies using a "switched at birth" paradigm in which they are queried about whether a child will share biological and learned properties with birth parents or adoptive parents, preschoolers (like undergraduates) believe that a child will resemble its birth parents in biological characteristics (such as eye color), but also believe (unlike undergraduates) that that child will resemble its birth parents in learned characteristics as well (e.g., beliefs and preferences; Solomon *et al.*, 1996; Taylor *et al.*, 2009).

We propose that essentialist thinking may apply to our intuitive understanding of biological entities and systems, as well as species. If underlying essential properties cause external features, then the outward characteristics exhibited by members of any biologically relevant category—be it cells, species, or types of ecosystems—should be relatively uniform, static, and predictable. This construal unites the first three seemingly unrelated misconceptions listed above. First, the mistaken perception that homeostatic processes keep the internal environment of organisms constant and unchanging belies a lack of understanding of the temporal and spatial dynamics of living systems. The second statement represents students' tendency to overgeneralize the characteristics of the members of a species. Students often do not recognize the extensive variation among individuals of the same species, which in turn creates an impediment to understanding the role of variation in the mechanisms of natural selection (Greene, 1990; Anderson *et al.*, 2002; Shtulman, 2006). The third statement represents the application of this cognitive construal to ecology, and reflects the common misconception that the "natural state" of an ecosystem is static, rather than a succession of different communities.

Essentialist thinking may also underlie the last two statements at the beginning of this section, both of which concern students' understanding of the relationship between DNA and physical traits at the level of cells or organisms. In these two examples, essentialist thinking could lead students to assume that a simple one-to-one correspondence exists between 1) essence (DNA) and 2) observable properties and identity (physical traits and biological classification). This has two clear implications. First, entities that display different observable properties (physical traits) should show corresponding differences in essential properties (DNA). Likewise, changes in essential properties (DNA) should imply changes in observable properties (physical traits), and by extension changes in identity (biological classification). When coupled with the observation that students may readily replace their intuitive notions of "essence" with a quasi-scientific notion of DNA (see Gelman and Rhodes, 2012), these extensions of essentialist thinking may lead to the last two misconceptions listed above. Students often assert that different cells in a multicellular organism contain different DNA (Hackling and Treagust, 1984; Banet and Ayuso, 2000; Lewis and Kattman, 2004; Lewis *et al.*, 2000; Smith *et al.*, 2008; Shi *et al.*, 2010). While consistent with essentialist thinking, this conceptual stance reveals a lack of awareness of or appreciation for differential gene expression, a key mechanism by which different subsets of genes are expressed in different cells of an organism, resulting in dramatically different features (e.g., shape of a neuron vs. shape of a skin cell, different leaf shapes in different parts of the same plant). Relatedly, in the era of biotechnology and genetic modification, it is striking that not just students, but the general public, may view modification of a single gene in an organism (e.g., the addition of the spider silk gene to goat embryos) as a fundamental change in the underlying essence of the organism, which implies a new biological identity and classification.

In summary, essentialist thinking represents a second cognitive construal that has been well studied in developmental cognitive psychology that may provide an underlying explanation for a variety of seemingly unrelated biological misconceptions. No doubt educators have encountered many other misconceptions among undergraduate biology students that may be the results of essentialist thinking.

MISCONCEPTIONS RELATED TO ANTHROPOCENTRIC THINKING

Thus far, we have explored two cognitive construals, teleological thinking and essentialist thinking, and their connections to biological ideas. No doubt there are others involved. Consider the final set of statements below, which do not immediately appear to be mediated by either a teleological mind-set or an essentialist mind-set.

- Disturbance in ecosystems has no beneficial role.
- Cell death in an organism is unusual and pathological.
- Sexual reproduction always involves two organisms mating, and therefore plants cannot reproduce sexually.
- Plants suck up their food from the soil through their roots.
- The males of any species are usually bigger and stronger than the females.

As in the preceding sections, these apparently disparate misconceptions span biological subdisciplines but may, in fact, have common underlying origins. The cognitive construal that we propose may underlie these misconceptions is known as *anthropocentric thinking*; this is simply the tendency to reason about unfamiliar biological species or processes by analogy to humans. Analogical reasoning—trying to understand an unfamiliar idea or situation by comparing it with something that is more well known—is a common strategy used across many domains of learning. In biology, *human beings* are a familiar and accessible biological kind and are therefore a very tempting source of knowledge that is often misapplied to nonhuman living things. For example, Inagaki and Hatano (1991) found that Japanese children as young as six used their knowledge of humans to make guesses about how relatively unfamiliar organisms (a rabbit, a grasshopper, or a tulip) would react in novel situations. Although the children used specific knowledge to rule out implausible inferences, they often overattributed human characteristics to nonhuman organisms that were similar to humans (i.e., mammals) in cases in which they lacked specific knowledge. Conversely, reasoning about nonhuman species by analogy to humans can also lead children to underattribute biological properties to species that are highly dissimilar to people. Carey (1985) found that prior to the age of 10, children showed a regular decline in the attribution of biologically necessary properties to organisms that roughly corresponded to the organisms' phylogenetic distance from humans. For instance, children acknowledged that people reproduce, eat, and have a heart, but were less likely to say that insects or worms shared these properties (see also Coley, 1995). Thus, up to about age 10, children decide whether an organism possesses a certain property based on their knowledge of whether humans have that property and the perceived similarity of the organism to humans.

Anthropocentric thinking has been shown to vary with experience and with cultural assumptions about the place of humans in the natural world. For example, Inagaki (1990) found that children who raised goldfish tended to reason about a similar but novel organism (a frog) by analogy to goldfish, whereas children who had no experience with goldfish did so by analogy to humans. Likewise, Ross and colleagues (2003) found that anthropocentric patterns of reasoning increased between ages six and 10 among urban children, decreased over the same age range among rural majority-culture children, and were nonexistent among rural Native American children. Together, these results suggest that anthropocentric thinking is a common cognitive construal used when faced with a lack of more specific biological knowledge. And as with our other cognitive construals, developmental psychologists have paid little attention to the development of anthropocentric thinking past the age of 10.

Viewing the misconceptions listed at the beginning of this section through the lens of anthropocentric thinking, things like "disturbance" and "death" are negative for humans, and therefore easily seen as inevitably harmful to a biological system or organism. However, biological research has demonstrated that these processes are key to the robustness of ecosystems and individual organisms alike. In the case of ecological disturbance, events like fires are critical for succession in many communities. In the case of cell death, there are particular genetic systems that program cell death events in the course of development to give rise to complex shapes like the fingers of a human hand. In addition, cell death is an everyday mechanism during the course of an organism's lifetime, needed to rid the body of damaged cells that could become cancerous. In the very different biological arena of reproduction, sexual reproduction in humans and among other mammals involves two different organisms mating; by analogy, it is tempting to view mating as a necessary component of sexual reproduction. However, this generates an overly narrow definition of sexual reproduction, one that excludes the many examples among plant species that undergo self-fertilization (Driver *et al*., 1994). The idea that all organisms take in food in essentially the same way that we do—such as plants sucking up food through their roots from the soil—represents another inappropriate instance of anthropocentric thinking, one that creates a serious impediment to students understanding the diverse ways in which different organisms obtain food (see Driver *et al*., 1994; AAAS, 2012). The use of the term "eating" to describe any intake of water, gases, or other molecular components by any organism, as well as the misconception that plants "eat" sunlight and air, are both naive ideas that belie the wonders of plant photosynthesis (the special cellular processes by which plants make their own food) and the critical role of plants as the source of carbon-based molecules for other organisms in many ecosystems (see Driver *et al*., 1994; AAAS, 2012). Finally, extrapolating the observation that male humans tend to be larger and stronger than female humans to other species is inappropriate. Not only are there numerous exceptions (e.g., insects, bats, rabbits, squirrels, hamsters, and whales), but this anthropocentric thinking could also lead to a fundamental misunderstanding of what it means to be male or female in different species of organisms (Driver *et al.*, 1994).

In summary, anthropocentric thinking represents yet a third cognitive construal that may provide an underlying explanation for a variety of seemingly unrelated biological misconceptions.

DISCIPLINARY BORDER-CROSSING AND ITS IMPLICATIONS FOR BIOLOGY EDUCATION

In its more recent history, the field of biology education has focused much effort on identifying common misconceptions, uncovering biological ideas that are particularly challenging for students, and developing classroom-ready tools that can measure the presence, absence, or changes of these ideas, especially in the context of undergraduate biology classrooms. Much less attention has been given to developing (or borrowing) theoretical frameworks that might provide a more synthetic or unified set of hypotheses about why so many students seem to think the way they do (Henderson *et al.*, 2011; Coley and Muratore, 2012). Some attempts have been made to explore the role of difficulties in thinking across size and scale as a potential unifying impediment in biological thinking, though this has been primarily employed with regard to misconceptions about energy and matter and the ideas of photosynthesis and cellular respiration (e.g., Wilson *et al.*, 2006; Hartley *et al*., 2011). However, theoretical frameworks such as those embodied in the cognitive construals of developmental cognitive psychology—exemplified here as teleological, essentialist, and anthropocentric thinking—are largely invisible in the biology education literature (for exceptions, see Tamir and Zhar, 1991; Rosengren *et al.*, 2012). Our purpose is not to propose that the cognitive construals presented here are necessarily *the only* or even *the most useful* theoretical frameworks from another discipline that could be used by biology educators. Although we do think that these construals hold great promise and have attempted to provide corresponding evidence, our greater purpose is to encourage biology educators to engage in disciplinary border-crossing. The theoretical frameworks of many disciplines—including the cognitive construals of developmental cognitive psychology presented here—hold great potential for revealing common origins of apparently disparate student challenges in learning biology. In fact, such theoretical frameworks could provide an entirely novel approach to biology education reform, one that moves away from attempting to correct an ever-growing list of biological misconceptions piecemeal and instead moves toward engaging students in a systematic re-examination of deeply held intuitive ways of knowing—ways that are useful in everyday reasoning outside the classroom but might represent a stubborn impediment to the development of expert thinking in biological science.

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