

Essay

Misconceptions Yesterday, Today, and Tomorrow

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A recent essay in *CBE—Life Sciences Education* criticized biology education researchers' use of the term *misconceptions* and recommended that, in order to be up-to-date with education research, biology education researchers should use alternative terms for students' incorrect ideas in science. We counter that criticism by reviewing the continued use and the meaning of *misconceptions* in education research today, and describe two key debates that account for the controversy surrounding the term. We then identify and describe two areas of research that have real implications for tomorrow's biology education research and biology instruction: 1) hypotheses about the structure of student knowledge (coherent vs. fragmented) that gives rise to misconceptions; and 2) the "warming trend" that considers the effects of students' motivation, beliefs about the nature of knowledge and learning (their epistemic beliefs), and learning strategies (their cognitive and metacognitive skills) on their ability to change their misconceptions in science. We conclude with a description of proposed future work in biology education research related to misconceptions.

Recent decades have brought growing recognition that biology students in American colleges and universities are not learning as much as instructors frequently assume. Of special concern are the high numbers of students who leave undergraduate biology courses with scientifically incorrect ideas (e.g., Bishop and Anderson, 1990; Nehm and Reilly, 2007; Andrews *et al.*, 2011). This situation has led to numerous calls for reform, workshops for training instructors, and research on how undergraduates learn biology and how best to facilitate student learning. The goal of these efforts is nothing less than a revolution in how we teach biology.

Biologists who were not originally trained in pedagogy or the learning sciences have led most of these reforms. Although these biology researchers usually do not have extensive training in education, they have been able to use

their skills as scientists to improve biology education. In our estimation, these biologists-turned-biology-education-researchers are making rapid progress in establishing a scientific basis for teaching college biology. However, if the experience of the biologists on our interdisciplinary research team is representative, the transition from biology research to biology education research is fairly daunting. In particular, this transition requires catching up on decades of research on teaching and learning that has taken place in a wide array of education-related disciplines. The fear of missing a key piece of research is ever-present—with the concomitant fear of making scientifically inappropriate conclusions or creating ineffective instruction.

Maskiewicz and Lineback (2013), hereafter M&L, recently argued in an essay in this journal that the biology education research community is afflicted with these problems on a wide scale. In particular, M&L argued the biology education research community's frequent use of the term *misconceptions* is a sign biology education researchers have not kept up with education research—especially the contributions of Andrea diSessa and colleagues (e.g., Smith *et al.*, 1993/1994). M&L further argued *misconceptions* is associated with out-of-date theories of learning, and therefore, biology education researchers and instructors who use this term are likely to use ineffective instruction. For this reason, M&L concluded their essay by recommending use of the terms *preconceptions*, *alternative conceptions*, or *naïve conceptions* instead of *misconceptions*.

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We find M&L's essay promising in its recommendation that the biology education research community consider research from science education and the learning sciences to improve our understanding of how students think and learn. However, M&L misrepresented the biology education literature that uses *misconceptions*, as well as the education literature they argued was underappreciated. While we disagree with many of their assertions and recommendations, M&L's essay began what we hope will become a productive conversation. The present essay seeks to further develop that conversation. We begin by reviewing how the term *misconceptions* is used in education research today, then discuss how the meaning of the term has evolved over the past few decades. We next describe an active debate about the coherence of student conceptions and discuss implications of this debate for biology instructors. In the last section, we describe a "warming trend" in conceptual change research¹ that may yield insights useful to biology instructors.

MISCONCEPTIONS TODAY AND YESTERDAY

M&L argued that *misconceptions* is no longer used in the wider education research community and that the term connotes an outdated perspective of learning. In this section, we survey how *misconceptions* is used and defined in education research today. We explain how its current meaning differs from what it has meant in the past and describe two of the key debates in its history that account for its changing meaning over time.

M&L's assertion that *misconceptions* is rarely used in science education and learning sciences journals today is simply not true. A review of the leading journals identified by M&L (*Journal of Research in Science Teaching*, *Science Education*, *Journal of the Learning Sciences*, and *Cognition and Instruction*) shows that *misconceptions* appeared regularly in articles published in 2013 (see Crowther and Price, 2014). And within the last three years, each of these journals published articles specific to *biology* teaching and learning that used the term (e.g., Pugh *et al.*, 2010; Hickey and Zuiker, 2012; Opfer *et al.*, 2012; Heddy and Sinatra, 2013). Therefore, the use of *misconceptions* in biology education research mirrors its current use in science education and learning sciences journals.

Many authors today do not explicitly define what they mean by *misconceptions* (as M&L noted), and it would improve communication if authors provided an operational definition of *misconceptions* in the context of their studies. In some areas of education research, for example, *misconceptions* has specific connotations regarding the hypothesized structure of student knowledge (a topic addressed further in this essay). Yet the most common use of *misconceptions* in education research today is as a label for the noncanonical ideas students express in science (as in, for example, Pugh *et al.*, 2010; Hickey and Zuiker, 2012; Opfer *et al.*, 2012; Heddy and Sinatra, 2013). A recent report from the National Research Council (NRC) on discipline-based education research defined *misconceptions* in this vein as "understandings or explanations that differ from what is known to be scientifically correct" (NRC, 2012, p. 58).

¹We define conceptual change (sensu Duit and Treagust, 2003) as learning that requires a fundamental restructuring of the learner's conceptual structures to move from nonscientific conceptions to conceptions consistent with scientific understanding.

In most uses of the term, *misconceptions* furthermore refers to scientifically incorrect ideas that are persistent and commonly held, rather than to *any* incorrect explanation in science. In this essay, we use the phrase "scientifically incorrect ideas" as shorthand for this definition.

While today most education researchers use *misconceptions* as described above, yesterday the term was associated with certain perspectives in scholarly debates about student knowledge and learning. We highlight two historical debates and describe their implications for *misconceptions*. In the first debate, ongoing more than 30 years ago, *misconceptions* was linked to a perspective that knowledge was stored in layers in the mind (descriptions of the competing perspectives derive primarily from Gilbert and Watts, 1983—see this article for detailed discussion); for new knowledge to be acquired, knowledge in earlier layers had to be correct (prominent theorists in this perspective included Gagné, 1970). Under this perspective, students' scientifically incorrect ideas were considered flaws in their knowledge that needed to be eliminated or repaired for knowledge acquisition to be successful. This perspective could result in a "cognitive deficit" view of students' knowledge: one that emphasized what students could not do or did not know in science (Hogan and Maglienti, 2001). We refer to this as the "deficit" perspective of student knowledge. In strong contrast to the deficit perspective was a perspective that viewed knowledge to be the product of intentional, active, and ongoing construction on the part of the individual (consistent with Piaget's constructivist theory²; see, e.g., Piaget, 1971, 1985; Brainerd, 1978). Rather than being static, knowledge was thought to be continually reshaped in the face of new information or experience. Under this perspective, students' scientifically incorrect ideas were not considered flaws, but part of a natural developmental process. Rather than perceiving students' ideas as deficient, this perspective respected them as "personally viable constructive alternatives" to scientific knowledge (Gilbert and Watts, 1983, p. 67). Researchers in this perspective used different terms for students' scientifically incorrect ideas, including *alternative frameworks* and *alternative conceptions*. We refer to this as the "constructive" perspective of student knowledge. Researchers in science education and the learning sciences today predominantly accept the constructive perspective, *irrespective of the term they use for students' scientifically incorrect ideas*.

Importantly, although this debate has more or less ended, it accounts for the fact that a mix of terms for students' scientifically incorrect ideas appears in the education literature today.³ Many researchers, as discussed earlier in this essay,

²Key tenets of constructivist learning theory are that: learners actively construct their knowledge rather than passively receive it, new knowledge is built on learners' existing knowledge, and existing knowledge affects how learners perceive new information and experiences.

³Maskiewicz and Lineback (2013) provided a list of some of the alternative terms authors used for *misconceptions*, but did not always accurately attribute terms to authors. For example, Clement (1993) distinguished preconceptions as ideas students hold before instruction that may or may not be misconceptions. He described replacing his earlier use of the term *misconceptions* with the term *alternative conceptions* (i.e., not preconceptions). The terms actually used by the authors cited in Maskiewicz and Lineback were: *alternative conceptions* (Clement, 1993), *misconceptions* (Fisher and Moody, 2002), (primarily)

use *misconceptions* to refer to understandings or explanations that differ from what is known to be scientifically correct (NRC, 2012). Others employ alternative terms to mean the same thing; for example, Adadan *et al.* (2010) used *alternative conceptions*. Still others use multiple terms as synonyms; for example, Babai *et al.* (2010) used *intuitive conceptions*, clarifying them as “misconceptions, alternative, or naïve conceptions” (p. 20); Chi (2005) primarily referred to students’ scientifically incorrect ideas as *misconceptions* but used this term interchangeably with *naïve explanations* and *naïve conceptions*; Nehm and colleagues have used *misconceptions* (Nehm and Schonfeld, 2008) as well as *naïve ideas* (Nehm and Ha, 2011). And some researchers justify their choice of *misconceptions*; for example, Fisher and Moody (2002) used several alternative terms but selected *misconceptions* as their primary term “to underscore the cognitive transformation required in order to achieve the scientific view” (p. 56). The variety of terms in use today indicates the larger education research community has neither rejected use of *misconceptions* nor converged on an alternative term.

A second, more recent debate about student knowledge resulted in new connotations for *misconceptions*, however. It is the debate about the “coherence” of student conceptions (see, e.g., Hammer, 1996; diSessa, 2006; Taber, 2008), which began yesterday (more than 20 years ago) and continues today. We will explore this debate in more detail in the next section, but because it included another definition for *misconceptions* and had implications for alternative terms, we introduce it here. In the coherence debate, *misconceptions* implied the hypothesis that students’ ideas emerged from cognitive structures composed of ideas that were cohesive and integrated with other ideas (Hammer, 1996; diSessa, 2006; Taber, 2008). This view held that students had stable ways of thinking about topics, because their knowledge was coherent or theory-like (Taber, 2008). In opposition to this “misconceptions” view (aka “conceptual framework” view⁴), diSessa (1988, 1993) argued that student’s *naïve ideas* (one of diSessa’s terms for what we have been calling students’ scientifically incorrect ideas) did not exist as coherent theories, but were constructed in the moment from more fundamental knowledge elements. In this view, student knowledge was considered to be fragmentary rather than cohesive or theory-like (Hammer, 1996; diSessa, 2006; Taber, 2008). DiSessa called this the “knowledge in pieces view” (diSessa, 1988, 1993).

The knowledge in pieces view also challenged another aspect of the conceptual framework view—its perception of the relationship between naïve (student) and expert (scientist) knowledge. This was the aspect highlighted in the Smith *et al.* (1993/1994) article on which much of M&L’s argument was based. The conceptual framework view was perceived

alternate conceptions (Abraham *et al.*, 2012), and (primarily) *misconceptions* (Chi, 2005). The term *naïve ideas* was accurately attributed to Nehm and Ha (2011), as was the term *alternative conceptions* to Wandersee *et al.* (1994).

⁴This position in the second debate is referred to by several names, including “misconceptions” and “conceptual framework.” To alleviate potential confusion arising from the multiple meanings of the term “misconceptions,” both in education research and in our essay, we hereafter refer to this position as the “conceptual framework” view or perspective, while recognizing that many refer to this as the “misconceptions” view or perspective instead.

as emphasizing differences between naïve and expert understandings of a topic (Smith *et al.*, 1993/1994; Hammer, 1996). In contrast, the knowledge in pieces view held that learning was a process of reorganizing intuitive (naïve) ideas into expert knowledge and that intuitive ideas were still present in expert knowledge (diSessa, 1993; Smith *et al.*, 1993/1994).

The coherence debate has several implications today, which we will discuss more fully in the next section. But an important implication for the present discussion is that this debate united a set of terms previously in opposition—for example, *misconceptions*, *alternative conceptions*, *alternative frameworks*—because they were perceived as holding similar views of students’ ideas (of their cohesiveness and relationship to expert knowledge). In the ongoing coherence debate, *misconceptions* and alternative terms are considered synonyms.

In summary, the status of *misconceptions* today is this: using *misconceptions* does not communicate an outdated view of student learning, and using alternative terms does not communicate a more contemporary view. Thus, changing the term we use is not the key to becoming up-to-date in education research. There are two other areas of education research, however, that we believe have important implications for how biology education researchers and instructors think about and develop students’ ideas in science tomorrow. We examine each of these areas in turn: first, research related to the aforementioned coherence debate and its instructional implications; and second, the “warming trend” in cognitive psychology research that considers the role of motivation and other learner characteristics in conceptual change.

COHERENCE OF STUDENT CONCEPTIONS AND IMPLICATIONS FOR INSTRUCTION

In this section we more fully describe two competing hypotheses in the “coherence” debate and illustrate these two hypotheses with an example from biology education. We then review some of the studies that have investigated the explanatory power of these hypotheses. We conclude this section by considering the implications of the coherence debate for biology instructors.

The debate about the coherence of student knowledge originated more than 20 years ago and continues today (this paragraph derives primarily from Taber, 2008—see this article for detailed discussion; also Hammer, 1996; diSessa, 2006). Positioned on one side of the debate is the hypothesis that the scientifically incorrect ideas students express derive from theory-like knowledge structures that are stable and cohesive. Some researchers had observed that students applied their scientifically incorrect ideas consistently over time and across a range of phenomena, and posited a theory-like knowledge organization to account for this. Because a tenet of constructivism is that learners interpret new information based on their existing knowledge, these researchers held that scientifically incorrect ideas organized as theories could impede learners’ ability to construct or integrate expert understanding of concepts. Thus, instruction must challenge (Taber, 2008) or even eliminate or overcome (Hammer, 1996) students’ incorrect ideas in order for students to develop scientific understanding. As noted in the preceding section, this “conceptual

framework” view⁵ grouped together the formerly disparate perspectives that gave rise to terms including *misconceptions*, *alternative conceptions*, *alternative frameworks*, and *naïve conceptions*, because they all regarded students’ scientifically incorrect ideas to be fully formed, stable, and connected (Hammer, 1996; diSessa, 2006; Taber, 2008); and they all emphasized the differences between novice and expert knowledge (Smith *et al.*, 1993/1994).

Andrea diSessa and colleagues (diSessa, 1988, 1993; Smith *et al.*, 1993/1994) challenged the conceptual framework view of student ideas by advancing a new hypothesis (knowledge in pieces⁶) that could account for other researchers’ observations that students’ scientifically incorrect ideas⁷ were NOT coherently or consistently applied across contexts (Taber, 2008). Instead of being stable and theory-like, diSessa and colleagues argued, students’ “intuitive” or “naïve” science ideas were spontaneous, transient, and context-dependent constructions that arose from the activation of small, intuitive, and fragmentary knowledge structures. These hypothetical fragmentary knowledge structures were called “phenomenological primitives,” shortened to “p-prims” (diSessa, 1988, 1993). p-prims were abstract and fundamental principles students used to make sense of the world (see Hammer, 1996, for an accessible introduction). For example, experience with sound, light, and heat may cause students to develop the p-prim “closer means stronger” (e.g., lights get brighter when you get closer to their source), and this p-prim may be activated (inappropriately) to explain why it is hotter in the summer.

The knowledge in pieces perspective interpreted constructivism to imply that students’ knowledge fragments were resources upon which they drew to think about and understand new phenomena (Taber, 2008). In this view, expert knowledge resulted from a reorganization of intuitive (naïve) knowledge, and expert knowledge furthermore included intuitive ideas (diSessa, 1993; Smith *et al.*, 1993/1994). Thus, instead of challenging students’ ideas, this perspective argued instruction should guide students in reflecting on their knowledge, finding contexts in which their intuitive ideas were and were not productive, and refining their existing knowledge toward expertise (diSessa, 1993; Smith *et al.*, 1993/1994).

At a theoretical level, the ongoing coherence debate boiled down to this: Were students’ incorrect ideas stored fully formed in a conceptual framework (conceptual framework view) or were students’ incorrect ideas constructed in situ from smaller, intuitive knowledge fragments (knowledge in pieces view)?

An example illustrates these two hypotheses. Consider the common, but scientifically incorrect, idea that “need drives evolution” (e.g., cheetahs evolved to run fast because they

⁵In addition to being called the “conceptual framework” and “misconceptions” perspective in the literature, this position in the coherence debate has also been referred to as the “conceptions” perspective.

⁶In addition to being called the “knowledge in pieces” perspective, this position in the coherence debate has also been referred to in the literature as the “conceptual resources,” “phenomenological primitives,” or “p-prims” perspective.

⁷We acknowledge that diSessa and colleagues may not agree with referring to students’ ideas as “scientifically incorrect” in association with the knowledge in pieces perspective. We do so to maintain consistency in this essay.

need to run fast to catch prey). If this conception was theory-like, we would expect students to consistently apply it in analyzing situations in which need could conceivably cause evolution (i.e., their ideas would be stable and cohesive). Furthermore, we would expect this conception to be associated with a theory of inheritance that included the idea “traits that arise as a result of need can be inherited” (i.e., their ideas would be connected and cohesive). On the other hand, if the idea that “need drives evolution” arose from p-prims, we might postulate a more general “need as a rationale for change” p-prim, which might be activated in response to some questions about evolution but not in response to others (i.e., their ideas would be spontaneous and context dependent).

Researchers have begun to test the explanatory power of the conceptual framework and knowledge in pieces views of student knowledge. Two studies investigating the structure of student ideas in physics, for example, concluded the knowledge in pieces view best explained student reasoning (diSessa *et al.*, 2004; Clark *et al.*, 2011). A study in chemistry education found p-prims offered the best explanation for some scientifically incorrect student ideas, but determined that other ideas were best explained by conceptual frameworks (Taber and Garcia-Franco, 2010). In a study of students’ ideas about biological phenomena, Southerland *et al.* (2001) found evidence supporting a “need as a rationale for change” p-prim (described in the above example) among students throughout grades 2–12, yet could not conclusively rule out the conceptual framework perspective. Several other researchers have also asserted that an inclusive view admitting both conceptual framework and knowledge in pieces perspectives is necessary to fully explain student knowledge (e.g., Hammer, 1996; Hammer *et al.*, 2005; Taber, 2008). These researchers furthermore maintained that the knowledge in pieces hypothesis did not claim *all* knowledge was structured as p-prims, but that p-prims were a previously undescribed level of knowledge structure that accounted for patterns in student thinking that conceptual frameworks could not.⁸ This is an active area of theory development. Recently, for example, Brown (2013) described a new view of student conceptions in which students’ knowledge structures form, change, and grow dynamically. In his description, conceptual framework and knowledge in pieces are complementary views that focused on different aspects of students’ knowledge. In summary, it is reasonable to conclude that both conceptual framework and knowledge in pieces views have value in explaining student conceptions.

What does the evidence for both conceptual frameworks and p-prims imply for instruction aimed at moving students to more scientific conceptions in biology? Although it has been argued that students’ ideas must be challenged if they are part of a conceptual framework (Taber, 2008), but can be refined toward expert understanding if they arise from p-prims (diSessa, 1993), the instructional implications of these two views of coherence are actually not so different for (at

⁸Indeed, later work by diSessa and colleagues (diSessa and Sherin, 1998) specified a type of concept called a “coordination class,” defined as “systematically connected ways of getting information from the world” (p. 1171). Coordination classes had the characteristics of being integrated and coherent (or invariant). This resonates with characteristics of conceptual frameworks.

least) two reasons. First, the two perspectives do not necessarily imply different teaching strategies: the conceptual framework perspective does not rule out the resourcefulness of students' conceptions and the knowledge in pieces perspective does not rule out strategies that induce cognitive conflict (Hammer, 1996). In fact, researchers from these two different perspectives often implement similar teaching strategies (Hammer, 1996; diSessa, 2006). Second, as diSessa himself noted, the basic constructivist teaching practice of "paying attention to [students'] naïve ideas seems powerful, independent of the details of conceptual change theory" (diSessa, 2006, p. 276). Virtually all approaches to teaching that focus on students' ideas have been found to be more effective in facilitating conceptual change than traditional approaches to instruction (Guzetti *et al.*, 1993; diSessa, 2006; Andrews *et al.*, 2011; also see Sadler *et al.*, 2013).

Because students' knowledge may include (characteristics of) p-prims as well as conceptual frameworks, it is likely that sometimes students can be coached as to what ideas are relevant in a situation, while other times they will benefit from teaching strategies that promote more extensive knowledge restructuring. However, further research is necessary to determine which teaching strategies will be most effective for different ideas and in different contexts. For example, identifying the p-prims that get activated for students in learning biology topics will facilitate the development of instruction to address them. Research has so far identified one p-prim in biology ("need as a rationale for change"; Southerland *et al.*, 2001). In addition to identifying p-prims that operate in biology topics, research is needed to describe the intermediate stages of understanding between p-prims and expert knowledge, and instructional approaches effective at moving students through the stages. Here again, instructional concerns of conceptual framework and knowledge in pieces perspectives overlap—knowing the conceptual pathways students travel from misconceptions to scientific conceptions has long been recognized as essential for effective conceptual change instruction (Scott *et al.*, 1991). If instructors expect that students will have productive conceptual resources for learning biology (p-prims), they may be inclined to look for them in student reasoning and to employ instructional strategies that help students find and build from those resources (Hammer, 2000).

THE "WARMING TREND" IN CONCEPTUAL CHANGE RESEARCH

In our opinion, one of the most promising topics in education research relevant to biology education researchers and biology instructors is the "warming trend" in conceptual change research. A theme in this research has been that conceptual change is not a purely cognitive or rational ("cold") process but is influenced by personal ("hot") factors. A growing body of empirical evidence, especially from the field of cognitive psychology, has shown that students' motivation, epistemic beliefs, and learning strategies have important roles in conceptual change (e.g., Pintrich *et al.*, 1993; Dole and Sinatra, 1998; Sinatra and Mason, 2008; Murphy and Mason, 2006). Research on the contribution of these factors to conceptual change is ongoing; therefore, the following review is intended to introduce readers to research that may be useful but is not

intended to be definitive or exhaustive. We will discuss each of these three "hot" factors (motivation, epistemic beliefs, and learning strategies) in turn, and conclude with implications for instruction.

Learners' willingness, or motivation, to engage in restructuring their knowledge appears to be essential for them to change their conceptions in science (Scott *et al.*, 1991; Novak, 2002). The explanation for this is probably simple: conceptual change requires students to identify and resolve discrepancies between their misconceptions and scientific conceptions; if students are not highly motivated, they will be unlikely to expend the cognitive resources necessary to do this (Dole and Sinatra, 1998; Sinatra and Pintrich, 2003). A variety of motivational factors⁹ may affect students' abilities to change their ideas in science, including a desire to: learn something for its own sake, earn a good grade, prepare for a certain career, or avoid performing poorly or appearing less competent than others (Glynn *et al.*, 2011). How these factors affect conceptual change is not yet understood, but there is accumulating evidence that they do. For example, a combination of the desire to learn something for its own sake, to get a good grade, and to prepare for a certain career has been found to positively affect conceptual change (Senko *et al.*, 2011; Taasobshirazi and Sinatra, 2011). In contrast, some of these goals may be counterproductive for conceptual change. For example, high levels of grade motivation have been associated with decreased conceptual change (Ranellucci *et al.*, 2013). And students motivated by a desire to avoid performing poorly or appearing less competent than others tend to learn less than students without these concerns (Elliot and McGregor, 2001). Such fears may be particularly important obstacles for conceptual change, because overcoming misconceptions can require students to recognize and accept (sometimes in a way that is visible to peers or the instructor) that they do not adequately understand something. In addition to these factors, students' beliefs about their ability to learn a subject may affect their willingness to persist in trying to learn difficult concepts (Bandura and Locke, 2003; Britner, 2008; for a recent discussion, see Trujillo and Tanner, 2014) and limit the extent to which they undergo conceptual change (Linnenbrink-Garcia *et al.*, 2012).

In addition to motivation, students' beliefs about the nature of knowledge and learning—their epistemic beliefs (the second "hot" factor we discuss here)—are likely to affect learning and conceptual change (e.g., Schommer, 1990; Sinatra *et al.*, 2003; Mason *et al.*, 2008). These epistemic beliefs are thought to influence the learning strategies students use while studying and the way students think about the material they are learning (e.g., Schommer, 1990; Schommer *et al.*, 1992), both of which are likely to influence conceptual change. For example, a student who believes knowledge is a collection of discrete facts may try to memorize isolated facts rather than develop deeper understandings of biology concepts (Schommer, 1990). Students' epistemic beliefs appear to be complex—research is ongoing and includes fundamental questions about how epistemic beliefs should be defined and measured. Here we highlight four beliefs that may affect conceptual change (see DeBacker *et al.*, 2008). These include:

⁹For a review of motivation research, see Wigfield and Cambria (2010).

the speed at which learning happens, the simplicity or complexity of knowledge, the certainty with which things are known, and whether an individual's learning ability is innate or can be improved through effort. Of these four beliefs, the belief that learning happens quickly or not at all (speed of learning) appears to have the strongest support in the literature for being associated with learning and conceptual change (Schoenfeld, 1983, 1985; Qian and Alvermann, 1995; Schommer-Aikins and Easter, 2006). An immature belief in quick, all-or-nothing learning leads students to assume that if they do not understand something in minutes, they never will; thus they may be unlikely to keep working at something until they learn it (Qian and Alvermann, 1995). Students who consider knowledge to be a collection of discrete facts (simplicity of knowledge) may use learning strategies that emphasize memorization instead of deep understanding, and thus may fail to reach a deep understanding of important concepts (Schommer, 1990) and may be overconfident about their understanding of a topic (Schommer *et al.*, 1992). Students who believe in certain knowledge (certainty of knowing) have been shown to experience less conceptual change than students more accepting of uncertainty (Qian and Alvermann, 1995), presumably because conceptual change requires them to accept that their understanding of a concept could be improved. Finally, the extent to which students believe they have a fixed level of intelligence or whether they can increase their intelligence through effort (ability to learn; Dweck and Leggett, 1988) may affect conceptual change; students who hold a fixed view of intelligence are less likely to tackle difficult learning activities or to persist in them (Dweck, 2000), which may be important for conceptual change.

The third "hot" factor in conceptual change is the cognitive and metacognitive strategies students use to learn. There is evidence that regulating one's cognition through use of thinking skills (cognitive strategies) and monitoring one's comprehension of new material (metacognitive strategies) affect students' ability to undergo conceptual change (Hewson *et al.*, 1998; Sackes, 2010; Vilppu *et al.*, 2013). In particular, five strategies that students use in learning (Pintrich *et al.*, 1991) may affect conceptual change. The first is rehearsal, using repetition to memorize information. Because rehearsal results in "surface processing," relying on it alone does not promote conceptual understanding (Pintrich *et al.*, 1993). In contrast, the following strategies result in "deep processing" associated with conceptual understanding (Pintrich *et al.*, 1993). Elaboration is the extent to which students reflect on and attempt to reconcile new information with their existing knowledge. Organization consists of constructing meaningful connections between information. Critical thinking is the degree to which students actively question and critically evaluate new information. Self-regulation includes planning, monitoring, and continuously adjusting one's cognitive activities. In addition to these strategies, the tendency to think deeply about problems—cognitive reflection (Fredrick, 2005)—rather than relying on intuition may also improve students' ability to undergo conceptual change. Changing conceptions requires students to be active, engaged, and reflective learners (Pintrich *et al.*, 1993).

What does the "warming trend" imply for instruction aimed at moving students to more scientific conceptions in biology? It implies that instructors cannot expect that focusing on biology concepts alone or taking students through a

rational argument in support of scientific ideas will be sufficient to facilitate conceptual change. It will also be necessary to motivate students to learn, to help them understand what it takes to learn, and to teach them strategies for improving their learning. Instructors may increase student motivation, for example, by drawing on instructional models designed to (Keller, 1987): ignite students' interest and curiosity, make material relevant to students' personal goals, and increase students' confidence in their abilities. Instructors may help students develop more sophisticated epistemic beliefs by giving students opportunities to, for example: persist in learning difficult concepts (with appropriate support from the instructor or peers), reflect on how their own ideas changed during learning, and spend more time learning important concepts in order to reach deeper levels of understanding. Biology instructors may facilitate more conceptual change in their courses by helping students to improve their cognitive and metacognitive skills. For example, in addition to teaching biology concepts, instructors could: teach students how to effectively study in their course, help students make connections between new information and existing knowledge (including between biology topics such as genetics and evolution), and "think aloud" to allow students to see how a scientist critically thinks about the validity and explanatory power of ideas in biology.

FUTURE WORK

Decades of research on student misconceptions (however named or defined) show that teaching or learning some concepts is not easy. The reasons for this are complicated and not yet completely understood. The complexity of student ideas and the complexity of the research regarding these ideas make it difficult to select a term for students' scientifically incorrect ideas that both encompasses the nature and structure of student ideas and has not previously been used in different ways. However, the question of what we call students' scientifically incorrect ideas is not the most important issue facing biology education researchers and instructors with regard to conceptual change. Whatever term researchers use, this issue may be handled by operationally defining the term and detailing the instructional approaches used.

The tougher problem the biology education research community faces is: what can instructors do to help undergraduates reconstruct their ideas in biology to align with experts' scientific knowledge? Addressing this problem requires multiple lines of research, including but not limited to: 1) identifying and describing common student misconceptions (NRC, 2012) in biology, 2) determining the origin and structure of different ideas commonly held by students, 3) assessing the effects of "hot" cognitive and affective factors on conceptual change, 4) designing and evaluating teaching strategies to effect conceptual change for different groups of students and different instructors, and 5) determining the support typical instructors need in using these strategies to effectively promote conceptual change.

As the biology education research community pursues these critical questions, we encourage moving deeper into education research and relevant research from related disciplines. In our own research group, we found that delving into the literature and critically examining the perspectives

behind the language we used facilitated change in our own conceptions of students' ideas and student learning. This, in turn, positively affected both our teaching and our research. We also found that working in an interdisciplinary research team sometimes necessitated long conversations to "translate" beliefs, ideas, and practices that differed between disciplines. It was often these conversations that revealed our ideas and challenged us to build more sophisticated understanding. We look forward to a continuing conversation in the biology education research community.

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