In response to overwhelming empirical evidence supporting the use of active learning, collegiate biology instructors across the United States are revising their instructional practices. Wishing to quantify their efforts, instructors often use course-specific assessments to measure learning gains or compare the effectiveness of various instructional methods (e.g., I). As the number of discipline-based education researchers has grown, the types and scales of research questions have increased, including asking how specific pedagogical methods influence students’ understanding of specific concepts (e.g., cellular division) or development of certain skills (e.g., critical thinking). Answering such questions depends on the availability of valid and reliable assessment tools.

In the last decade, discipline-based education researchers have developed numerous assessments designed to measure students’ conceptual understanding and are course-specific (e.g., Enzyme-Substrate Concept Inventory (4); Genetics Concept Assessment (5); and the Introductory Molecular and Cell Assessment (6)). Development of such assessments has been invaluable to enhancing the community’s understanding of which instructional practices promote learning. However, we believe it is time to begin developing instruments to assess at the programmatic level foundational conceptual understanding and higher-order cognitive skills (HOCS), or critical thinking skills, which we define as the ability to apply knowledge to a real-world problem, evaluate information, and create solutions.

Our appeal arose from data collected from a university in the west. These data indicated that common misconceptions (e.g., teleological, anthropocentric, and essentialist, defined in Table 1) persisted across all academic levels (Figs. 1–4), and most assessments primarily focused on students’ use of lower-order cognitive skills throughout their program of study (Table 2). In this Perspectives article, we argue for providing students ongoing and purposeful opportunities to develop higher-order cognitive skills, which we assert provide a means of challenging misconceptions. We acknowledge the difficulties in developing a disposition toward critical thinking (7) and that students possess robust misconceptions (e.g., 8, 9). Therefore, we are also calling for programmatic efforts and monitoring of both students’ HOCS and conceptual understanding (i.e., ongoing formative assessment), aided by the development of one or several programmatic-level concepts and skills assessment tools.

The goal of this article is three-fold. First, we are calling for biology education researchers to develop programmatic-level assessment tools for departments to monitor and measure students’ changes in conceptual understanding and HOCS throughout their degree completion. Second, we

INTRODUCTION

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The goal of this article is three-fold. First, we are calling for biology education researchers to develop programmatic-level assessment tools for departments to monitor and measure students’ changes in conceptual understanding and HOCS throughout their degree completion. Second, we
provide insight into the misconceptions and HOCs literature and demonstrate that the use of evidence-based teaching practices can assist students in developing their conceptual understanding and HOCs. Finally, we call for departments to develop a plan for promoting and assessing conceptual understanding and HOCs.

**DISCUSSION**

**Difficulties in dismantling misconceptions and developing higher-order cognitive skills**

**Dismantling misconceptions.** The literature is rich with empirical evidence indicating how difficult it is to confront and dismantle students’ misconceptions in biology (e.g., 8, 9) and is equally rich with evidence emphasizing the importance and difficulty of developing students’ HOCs (e.g., 10). In agreement with prior research, we contend that receiving a bachelor’s degree in a field of knowledge should be an indication that an individual has developed conceptual understanding and the ability to think critically within the area of expertise (e.g., 11). However, our data indicated that students near graduation may not display sufficient conceptual understanding or HOCs. Specifically, our data indicated that students nearing the completion of their bachelor’s degree retained biology-specific misconceptions (Figs. 1–4). Furthermore, others have shown that over the course of their undergraduate degree, college students show very limited improvements in their critical thinking skills (12).

Unfortunately, a vast quantity of data suggests that such issues begin early in a student’s career, as students’ prior knowledge may include misconceptions. Accordingly, students are liable to associate new concepts with misconceptions if instructors do not address such misconceptions (9). Instructors assist in facilitating learners’ refinement of their knowledge (for essays with varying viewpoints see 13, 14); thus, large learning gains are related to an instructor’s ability to dismantle misconceptions.

In theory, the number and variety of misconceptions students could hold are infinite. Fortuitously, Coley and Tanner (15, 16) suggested that students’ misconceptions can often be classified into predictable categories. They coined the term “cognitive construals” to describe seemingly unrelated biological misconceptions that are linked to intuitive ways of thinking, such as teleological, essentialist, and anthropocentric arguments (see our Table 1). These three categories of misconceptions provide instructors and researchers a foundation for predicting, exploring, and challenging students’ biological cognitive construals. Pedagogical and assessment practices promoting conceptual

### TABLE I.

Types and examples of cognitive construals.

| Cognitive Construal | Definition | Examples
|---------------------|------------|---------|
| Anthropocentric     | Assigning human characteristics to non-human objects or phenomenon. | The main force that drove their evolution was the need to increase in size to become less susceptible to land-based predators. (PubA:Gr11:231)
| Essentialist        | Assuming similar classes of items function in the same way in similar situations. | Changing a single gene in an organism results in a new kind of organism.
| Teleological         | Systems or individuals work in a specific manner to achieve an end goal. | An organism may become adapted to a particular environment through its interactions with it. (PubA:Gr12:277)

- Information presented in this table is based on Coley and Tanner’s 2012 (15) and 2015 (16) work.
- Examples are taken from the textbooks analyzed in Tshuma & Sanders (17) paper, indicating teleological and anthropocentric examples are often found in textbooks. PubA refers to the textbook that was analyzed; Gr refers to the grade level of text; the last number refers to the number of pages on which the statement was written.
- This statement has both anthropocentric and teleological errors.

![Mean Agreement with Each Type of Misconception Statement Stratified by Academic Level](image)

FIGURE 1. Students were asked to indicate their agreement (0 = strongly disagree, 5 = strongly agree) with anthropocentric, teleological, and essentialist misconceptions. No significant interaction was found between students’ academic level, between students enrolled in freshman level courses, sophomore, and upperclass courses (junior and senior level, F(4, 352) = 0.961, p = 0.429). Participants were given a list of six misconceptions (two for each type of cognitive construal) and asked to indicate how well they agreed or disagreed with the statement and then provide a brief description of their understanding. Some students did not provide responses for all six statements. The number of statements answered per grade-level is as follows: freshmen (n = 354), sophomore (n = 492), junior (n = 476), and senior (n = 258).
understanding (as opposed to memorization), developing HOCS, and building students’ metacognitive abilities are associated with restructuring students’ misconceptions to accurately reflect biological knowledge (18). In particular, we argue that the same pedagogical strategies shown to be effective in promoting HOCS are also key practices associated with dismantling misconceptions.

Developing HOCS. Higher-order cognitive skills represent a skill set associated with students being able to apply information to real life, use information to solve problems and create solutions, and use their knowledge to evaluate information (19). Undergraduate students struggle with HOCS (11, 20); for example, students may not demonstrate a commitment to rational inquiry, a necessary component of critical thinking. As undergraduate students progress from their freshman to final year of college, they do not demonstrate large, if any, gains in HOCS (12, 21). Research indicates that critical thinking (which includes using HOCS) can be improved over the course of one semester (22); however, creating a critical-thinking disposition requires years of reinforcement (7). To date, effective course design has meant aligning curricular activities and assessment procedures with learning objectives (23–27); however, these alignments may not necessarily include a focus on students’ cognitive abilities. In addition to providing students with low-stakes practice, assessment techniques influence students’ approaches to thinking (i.e., the use of primarily lower-order or higher-order cognitive skills when studying) (5, 28). When instructors employ assessments requiring HOCS, students are motivated to participate in deeper-learning strategies—approaches that prompt them to move beyond factual recall and instead focus on developing their conceptual understanding and ability to apply the information to an authentic circumstance (i.e., HOCS) (5, 28). Collegiate instructors need to provide students the opportunity to develop their HOCS, skills we assert help to develop students’ conceptual understanding.

Instructional practices promoting conceptual understanding and HOCS. Under the assumption that an individual obtaining a Bachelor’s in a particular field of study should have both conceptual understanding and domain-specific higher-order cognitive skills (11), it would be appropriate that an undergraduate degree program focus on both of these elements. Luckily, a great deal of overlap exists between the instructional approaches associated with improving conceptual understanding and those associated
with developing HOCS. Active-learning strategies including, but not limited to, discussions, inquiry, data analysis, and concept maps have been associated with improved conceptual understanding (29–31). For example, the use of discussion has been shown to be an effective method for allowing students to identify their own misconceptions (31). To address students’ misconception that enzymes only work inside of an extremely narrow temperature range, instructors are encouraged to ask their students to discuss how enzymes work when an individual has a fever. Following discussion, students develop an experiment to test their hypotheses (31). Of course, providing students with inquiry opportunities related to each of their misconceptions can be costly in terms of materials and time. Alternatively, by presenting students with data, instructors can also create cognitive dissonance (31). Moreover, instructors can encourage students to evaluate whether the data concur with their thinking, providing an excellent opportunity to promote deep learning as well as conceptual understanding. The literature provides an ample variety of active-learning strategies, and we encourage instructors to employ strategies supported by empirical evidence that build conceptual understanding and promote HOCS (for some immediate applications, see, e.g., 29, 31, 32).

Five faculty submitted tests. Of these tests, 8 were from the 100 level, 18 from the 200 level, 7 from the 300 level, and 3 from the 400 level. Test questions were defined as individual prompts associated with separate points. For example, some questions included multiple parts, each with individual point values; each individual part was considered as a separate question in our analysis. Percent ratios were calculated by calculating the percentage of LOCS, Application, and HOCS per course level per the category descriptions given in the Blooming Biology Tool (18). Two authors of this paper (LMC and TMM) worked simultaneously and collaboratively to rate all questions. Questions were scored together; therefore, no inter-rater reliability value was calculated. To determine whether a difference existed between the ratio of lower-order, application-level, and higher-order test questions per course level, we ran a chi-squared test of independence. The results indicated a significant difference ($\chi^2, N = 1,160, p = 0.000$, two-tailed) between the percentages of lower-order, application-level, and higher-order course objectives across the various course levels. Additionally, Cramer’s V, a measure of association between two variables used to indicate effect size (here course-level and cognitive-level of course objective) revealed a small effect size ($\phi_c = 0.302, p = 0.000$).

### Action steps and call for research

Educational theory demonstrates that scaffolding provides a platform for building students’ knowledge and skills (34). Based on the information we have presented, we call for: 1) biology education researchers to create a program-level concept and skills inventory; and 2) departmental chairs to assist in developing a plan for faculty to promote and assess conceptual understanding and HOCS within their department. In terms of the former, we call for biology-education researchers and content-experts to collaborate to develop programmatic-level concepts and skills assessments. We believe that this type of assessment would provide a standardized method for evaluating biology programs nationwide—much like the American Chemical Society exam for chemistry. If developed, this assessment

| Course Level | LOCS (# of questions) | Apply (# of questions) | HOCS (# of questions) | Total | Percent Ratio (LOCS:App:HOCS) |
|--------------|-----------------------|------------------------|-----------------------|-------|-----------------------------|
| 100          | 389                   | 23                     | 26                    | 438   | 89:5:6                       |
| 200          | 184                   | 98                     | 77                    | 359   | 51:27:21                     |
| 300          | 164                   | 31                     | 52                    | 247   | 66:13:21                     |
| 400          | 47                    | 16                     | 53                    | 116   | 41:14:46                     |
| Total        | 784                   | 168                    | 208                   | 1,160 | 66:14:18                     |

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would also provide an avenue for conducting large-scale studies examining outcomes across multiple institutions.

For chairs and faculty members, in order for such change to occur, we recommend that departments undertake the following:

1. Develop program objectives that include conceptual understanding and HOCS. Once program-level objectives have been developed, a curriculum map, outlining when objectives will be taught, assessed, and reinforced throughout the program, is essential. Vision and Change (35) and Scientific Teaching (10) provide insight into possible program-level objectives and objective development, respectively.

2. Determine a method for evaluating students’ progression in their conceptual knowledge and domain-specific HOCS. We encourage departments to measure students’ knowledge prior to beginning in their program and then at yearly intervals or after the completion of each core course. Here, we also appeal to biology education researchers to initiate development of an assessment tool that departments can use to measure students’ conceptual understanding and HOCS; we believe this assessment could be built based upon the key concepts presented in Vision and Change (35).

3. Evaluate their current course assessment mechanisms (see Appendix I for a guide). The goal of this evaluation is to determine whether core courses continually and progressively promote students’ HOCS development. Recognizing the difficulty of creating HOCS assessments, we recommend that cohorts of faculty who teach similar courses work together to create a test bank based on programmatic objectives. By working in teams, faculty may also create a departmental test bank of HOCS questions to improve the continuity of program reform and provide future faculty members with tools to align assessments with program objectives. When writing HOCS test questions, we recommend first creating a scenario with real or hypothetical data. Using the hypothetical data set, questions can then be written to ask students whether the experimental design was appropriate (evaluation); what conclusions can be drawn from the data (application and synthesis); what hypotheses were actually being tested based on the experimental design (evaluation); and what future questions emerge from the data (creation). This model promotes faculty conversation and allows for collaborative efforts to reduce the time required by individual faculty to write higher-order questions.

In summary, undergraduate biology faculty across the nation are spending a great deal of effort and time to reform their classrooms and use evidence-based practices, and we commend them. Unfortunately, the data indicate that dismantling misconceptions and developing HOCS deserve more attention and inclusion in these efforts. We believe it is now time for departmental reform and ask that biology education researchers and content specialists come together to develop program-level assessments aimed at measuring students’ conceptual understanding and HOCS to aid in this endeavor. Individual departments may already be engaged in our second recommendation and using their own evaluation mechanisms. However, the creation of a standardized, valid, and reliable programmatic concept inventory would provide the opportunity for 1) large-scale multi-institutional studies and 2) evaluation of biology programs nationwide.

**SUPPLEMENTAL MATERIALS**

Appendix I: Model for evaluating the department’s promotion of higher-order cognitive skills

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