6

Measuring College Learning in Biology

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This contribution offers an overview of prior efforts to articulate and measure learning outcomes in biology, presents a streamlined set of essential learning outcomes for undergraduate biology education, and offers a set of recommendations for the improvement of learning outcomes assessment in the discipline. To generate a set of essential learning outcomes, the authors synthesized across a number of existing learning outcomes frameworks. The resultant framework contains five essential concepts (evolution, information flow, structure and function, pathways and transformation of matter and energy, and systems) and six essential competencies (model, apply quantitative reasoning, engage in argument from evidence, engage in scientific inquiry and experimental design, analyze and evaluate data, and appreciate and apply the nature of science). The authors' discussion of assessment in biology begins with a description of existing assessment tools and others under development, and concludes with a set of principles to guide the development of future biology assessments.

Introduction

The call for reforming science education by enhancing student engagement, providing faculty development opportunities in pedagogy, and overhauling science curricula has been made in many national reports, including *Bio2010: Transforming Undergraduate Education for Future Research Biologists* (NRC 2003), *Scientific Foundations for Future Physicians* (AAMC and HHMI 2009), *Vision and Change in Undergraduate Biology Education* (AAAS 2011), and the *President's Council of Advisors on Science and Technology* report (EOP 2012). These reports and many others emphasize the need for recruiting students to be science majors and for retaining them in these disciplines to ensure a scientifically trained future workforce in the United States. Also needed are highly creative leaders capable of dealing with the challenges presented by a more globalized and economically competitive world. To this end, it is imperative that we create a scientifically literate society, one that embraces science as an important endeavor and supports science literacy as vital to the overall well-being and success of our country. To achieve these goals, biology education should be transformed to better align with them.

Biology is a broad and ever-changing discipline composed of many subdisciplines with diverse and far-reaching applications. Students interested in studying how to conserve the planet's species, fight cancer, treat infections caused by multiresistant microorganisms, develop better biofuels, increase crop yields, treat and prevent genetic diseases, stop the spread of infectious pathogens, or predict local and global changes due to climate instability would all most likely enroll in a college biology course. Therefore, it is not surprising that many students arrive at college with the intention to major in a subdiscipline of biology and will enroll in an introductory biology course before graduation. Given the importance that the study of biology has to students, their institutions, and society, it is crucial that we continue to improve science education

through teaching and learning research, faculty development, and curricular reform.

One important step in reforming biology curricula is for faculty to clearly articulate and agree upon the essential concepts and competencies that all biology majors or majors in a subdiscipline of biology must know and be able to do upon graduation. If faculty shared this common vision, then new teaching materials, creative classroom and laboratory activities, and assessments could be designed, thus positively impacting biology students. Moreover, faculty development programs could be better focused if there were a more united view of biology concepts and competencies. Unfortunately, it is difficult to achieve faculty consensus regarding goals for biology courses, given the diverse nature of the discipline. After students complete their introductory biology courses, they commonly focus on a specific area or subdiscipline such as microbiology, cell and developmental biology, ecology, biochemistry, or molecular and cellular biology. Biology departments also employ faculty whose doctoral training and research are equally diverse. As a consequence, individual faculty and thus biology departments are likely to come to different decisions about the goals of any given introductory biology course and the goals of the major.

Despite these challenges, establishing goals for both introductory courses and biology majors has recently received considerable attention. In this paper, we focus in particular on the *Vision and Change in Undergraduate Biology Education* (2011) effort, a collaborative project spanning more than five years involving academic scientists, educators, students, and administrators. This work was significant not only because of the sheer number of participants but also because it has significantly impacted administrators and faculty across the nation. In addition, national agencies such as the American Association for the Advancement of Science (AAAS), National Science Foundation (NSF), and Howard Hughes Medical Institute (HHMI) initiated and supported the project. Discussions began in 2007 with more than two hundred biologists and

stakeholders from around the country. In 2009, the conversations continued with an additional five hundred people, including students, faculty, and administrators. Ultimately, the 2011 *Vision and Change* publication articulates critical core concepts and competencies and makes numerous pedagogical recommendations for improving undergraduate biology education. An additional conference in 2013 continued the work and resulted in another publication devoted to implementing change (AAAS 2015). Additional work by science educators has continued to work on better defining the essential concepts and competencies for the subdisciplines of ecology, physiology, and molecular biology (Brownell, Freeman, Wenderoth, and Crowe 2014). Others have used the *Vision and Change* report as a guiding document to begin developing concept inventories and other assessments (see, e.g., Couch, Wood, and Knight 2015 and the BioMAPS project).

Other organizations have identified key concepts and skills for undergraduate biology. For example, the College Board has articulated essential concepts and competencies required for the success of incoming science majors (College Board 2009, 2012), whereas the Association of American Medical Colleges and Howard Hughes Medical Institute have outlined such a document for those who are graduating from college and will enter medical school (AAMC and HHMI 2009). Organizations that deliver high-stakes exams such as the Graduate Record Examination (GRE) subject test in biology and the Medical College Admission Test (MCAT) have also impacted curricula at colleges and universities since student success on these tests is often required for continued education in biology-related disciplines.

Despite these national-level conversations and publications, it is clear that not a single document for introductory biology or the biology major has been widely adopted by faculty teaching undergraduates. To address these unresolved needs, as part of the Measuring College Learning (MCL) project, we have (a) reviewed previous efforts that attempt to describe essential concepts and

competencies for introductory biology and the major; (b) used numerous resources to compile a detailed list of essential concepts and competencies for biology; (c) created a matrix demonstrating, with examples, how the learning expectations for concepts and skills can be articulated together; (d) described current instruments designed to measure biology learning outcomes; and (e) outlined the future of assessment instruments aimed at measuring essential concepts and competencies in the biology discipline. Our efforts build upon the foundational work of others and our in-depth conversations with the MCL Biology faculty panel[1] and have been guided by the unifying principle that biology is an experimental science. The discipline of biology is changing so rapidly that concepts are not as enduring as skills. Thus, emphasis should be placed on deepening students' concept knowledge through skill acquisition and mastery. We realize that our final product is not comprehensive and is certainly subject to continued discussion and debate.

Literature Review

In this section, we provide a review of the sources that have previously attempted to articulate essential concepts and competencies, and associated learning outcomes, for biology undergraduates. We have organized the review into sections that focus on student

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[1] The MCL Biology faculty panel included the following individuals: Cynthia Bauerle (Howard Hughes Medical Institute), Sara Brownell (Arizona State University), Clarissa Dirks (The Evergreen State College), Chris Kaiser (Massachusetts Institute of Technology), Jennifer Knight (University of Colorado, Boulder), Susan Singer (National Science Foundation), Michelle Smith (University of Maine), Nancy Songer (Drexel University), Gordon Uno (University of Oklahoma), William Wood (University of Colorado, Boulder), and Robin Wright (University of Minnesota).

learning immediately prior to, during, and after college because each of these impact how college faculty define learning outcomes in biology. Only the most recent and pertinent reports and publications are considered, particularly those that have had some traction with biology faculty. This organizational structure is meant to provide a comprehensive overview of the many stakeholders impacted by and ultimately influencing decisions about teaching and learning in undergraduate biology education.

Concepts and Competencies for K–12 Students

The National Research Council (NRC), the National Science Teachers Association, the American Association for the Advancement of Science, and Achieve (an independent nonprofit organization) worked together to create an important K–12 document called the Next Generation Science Standards (NGSS), published in 2013. These standards were designed to serve as a framework for describing a progression of performance expectations through K–12 levels that emphasize critical thinking in science. The development process included an initial development of a framework by the NRC, *A Framework for K–12 Science Education* (2012), which articulated the science that K–12 students should know and is grounded in research on student learning. The NGSS were then developed collaboratively with states and other stakeholders in science, science education, higher education, and industry and were designed to blend science practices with disciplinary core ideas. For example, a performance expectation might blend the science practice of constructing explanations with the disciplinary core idea of interdependent relationships in ecosystems. Although the framework is broad, one area that is well addressed, and mostly missing in other reports, is the focus on critical thinking. The intention of the framework is to increase the coherence of K–12 science education through the emphasis on these multidimensional standards (e.g., practices blended with concepts) at each grade band (K–2, 3–5, 6–8, and 9–12) and in sequences

across grades and grade bands. The framework was designed for state school systems and has been implemented in a handful of states, with several others adopting new standards that have a similar spirit and emphasis on blended or multidimensional standards.

Whereas the Next Generation Science Standards provide guidelines for K–12, the Advanced Placement (AP) biology curriculum and College Board Standards for College Success are directed at students transitioning from high school to college. The AP program consists of both courses and examinations in different areas, including biology. College faculty and AP teachers design the courses and exams, aiming to provide high school students with opportunities for college-level work. A tremendous amount of effort goes into making sure that the concepts and skills taught in AP courses and measured by AP exams align with college-level standards. A relatively high score on an AP exam earns students credit, placement, or both at most colleges and universities and is therefore an important driver of which concepts and competencies are taught in high school science courses. In 2009, the College Board, which also provides Advanced Placement programs and the SAT, generated the College Board Standards for College Success. Like the Next Generation Science Standards, the standards in this pre-AP document consist entirely of standards that blend science practices with disciplinary core ideas. These standards were designed for the first two years of high school (i.e., the science concepts and practices just prior to Advanced Placement courses or university-level coursework).

Interestingly, the essential concept knowledge for biology described in the Next Generation Science Standards, AP biology curriculum, and College Board Standards for College Success are nearly identical, although the emphasis differs. Although NGSS broadly addresses science, technology, engineering, and mathematics (STEM) disciplines, not just biology, all three of these publications organize biology concepts into broad headings, such as cell structure or evolution, which are either identical

or clearly overlap with the five *Vision and Change* concept categories that will be discussed in detail later. The documents also provide knowledge statements (called either essential knowledge or enduring understandings) under these broader headings and articulate performance expectations or learning outcomes that are more detailed than the broader essential knowledge statements. The reported essential biology competencies, also referred to as skills and practices, are also congruent among these reports for K–12 and are presented as practices blended with concepts (in NGSS in particular). They are further supported in the literature by validated assessments aimed to measure them (Dillashaw and Okey 1980). The level at which the learning outcomes and skills are described in these documents is strikingly similar to, or in some cases even higher than, those described for undergraduate students (Coil, Wenderoth, Cunningham, and Dirks 2010; Gormally, Brickman, and Lutz 2013). Although some overlap in essential concepts and competencies is expected across educational levels, future work should be done to examine the different cognitive levels at which students should be expected to work in high school versus undergraduate biology courses.

Concepts and Competencies for Undergraduates

Compared with K–12, there have been fewer long-term national efforts in higher education aimed at standardizing essential concepts and competencies for biology students. However, in the last several years progress at the college level has been stimulated by *Vision and Change*. Most important, the work around *Vision and Change* has involved broad participation of faculty. For example, in developing the BioCore guide, Brownell et al. (2014) surveyed hundreds of biologists and biology education researchers for their input in developing a more detailed framework of the concepts outlined in *Vision and Change*. The BioCore Guide is a framework for departments to more easily implement the *Vision and Change*

goals. Additionally, the Partnership in Undergraduate Life Science Education (PULSE) fellows have created the PULSE Vision and Change rubrics that are meant to assess if departments are successfully implementing *Vision and Change* in their curricula.

After students graduate with an undergraduate degree in biology, the GRE subject test in biology and the Major Field Test (MFT) in biology, among others, may be used to assess whether students are ready for more advanced work. The topics selected for these tests serve as a proxy for what the testing organizations and their constituents believe is important for biology students to learn in their undergraduate work. The publicly available descriptions of the biology MFT and GRE, which are intended to measure the performance levels of students graduating from college, articulate nearly identical concept or knowledge statements to those outlined in the expectations for high school students. Again, more work should be done to better clarify the cognitive levels at which students are expected to work along the continuum of K–12 to undergraduate education.

Progress has been made to define essential concepts for undergraduate biology majors, but very little has been done to articulate the competencies, skills, and practices biology students should learn. Several groups have surveyed life science faculty to identify the skills all students should master by the time they graduate with an undergraduate degree in biology (Coil et al. 2010; Dasgupta, Anderson, and Pelaez 2014), whereas another group has created an assessment tool for measuring general scientific literacy skills in the context of biology (Gormally, Brickman, and Lutz 2013). For students graduating with a biology degree, *Scientific Foundations for Future Physicians* (AAMC and HHMI 2009) has presented a thorough list of skills that should be developed by those wanting to enter the medical profession. Not surprisingly, the skills identified by the aforementioned groups also overlap with many of the core competencies in *Vision and Change* and the documents described for K–12 education. However,

given the ever-changing nature of biology and the importance of developing biology students' skills, it is evident that much more work needs to be done in this area.

In addition to the aforementioned efforts initiated by *Vision and Change*, many others have worked to better define the concepts students need to know in subdisciplines of biology and the skills that introductory students should learn in biology. The many concept inventories (also known as concept assessments) in biology will be discussed further in the current assessments section of this paper. Here, we would simply like to note that the authors of these concept inventories had to identify core concepts to be tested in the concept areas targeted (e.g., molecular and cell biology, genetics, evolution, developmental biology, microbiology, physiology, introductory biology, and plant biology). Collectively, such work has helped to lay the foundation for identifying the essential concepts for the biology major since many inventories address overlapping concepts. For example, questions about evolution or information flow are found on many of these tests.

Finally, although not directly related to articulating core general concepts and competencies for biology, an additional resource is important to mention here. This new resource is CourseSource, a Web-based journal for publishing teaching tools and learning outcomes statements (http://coursesource.org). The learning outcomes for Course Source were constructed in collaboration with professional societies in biology subdisciplines (e.g., Society for Developmental Biology, American Society for Biochemistry and Molecular Biology, American Society for Microbiology, Botanical Society of America, American Society of Plant Biologists, American Society of Cell Biology, and Genetics Society of America). Faculty can use both the outcomes and the published teaching tools to help improve pedagogy. This resource may prove helpful for establishing core sets of learning outcomes, especially at the course level.

Methods for Creating a List of Essential Concepts and Competencies for Biology

Many biology educators have attempted over the past ten years to articulate what is essential for students of biology to learn at both the K–12 and undergraduate levels. The documents that exist for K–12, such as the Next Generation Science Standards and the AP biology curriculum, are exceptionally detailed. Those that have been created specifically for university-level learning tend to be more general if they are describing the content of the biology major and more detailed if describing the content of a particular course. Because the discipline of biology is comprised of many diverse subdisciplines, the principle challenge in articulating essential concepts and competencies for biology as a complete discipline is to assemble a list that is broad enough to accommodate learning outcomes in multiple subdisciplines without being overly detailed.

NOTE: This chapter includes a number of bonus online appendices which can be found on the publisher's website. To access Appendices A-D, go to www.wiley.com/go/arumimproving.

Concepts

One way to understand the general concepts valued by biology faculty is to explore how biology departments communicate their expectations of biology majors. We collected examples of departmental-level learning goals and outcomes from a variety of biology department websites, ranging from community colleges to R1 institutions. The goals shared for departmental majors were typically extremely broad and described both general competencies and general topic areas (For more detailed information, see Appendix A on the publisher's website; accessing instructions are provided above). No departmental website had detailed lists of learning goals

intended to capture specific concept-related learning outcomes of the whole major. Those that had detailed lists of learning outcomes (or goals) had them only for individual courses. Thus, it seems the approach of most departments has been not to articulate detailed outcomes for the major but rather to communicate in broad strokes the basic idea of what it means to be a biology major.

On the other hand, publications that have been generated to communicate the goals of K–12 instruction in biology are highly detail oriented. The AP biology curriculum, College Board Standards for College Success, and NGSS provide extensive lists of learning goals and outcomes. The essential concepts described in these documents are nearly identical, just worded slightly differently. In addition, at the topic or highest level of organization, the concepts overlap almost entirely with the five broad concept topics described in *Vision and Change*.

We also examined the concepts described for the MFT and the GRE in biology since we imagined the designers of these assessments would have articulated goals that overlap closely with faculty goals for students graduating with a degree in biology. Rather than providing clear learning outcomes, however, the MFT and GRE test descriptions feature lists of general topics, the percent of the test devoted to each topic area, and a list of the subtopics addressed in each area. The general topics and subtopics addressed by these two assessments are nearly identical to those outlined for AP biology.

Since a great deal of work has already been done in generating learning outcomes that communicate the essential concepts and competencies for the biology major, we have not written a completely new set of essential concepts and competencies here. Rather, we share in this document several compiled lists that we believe most accurately articulate these outcomes for undergraduate biology majors. First, we collected statements of biology concepts from the previously outlined sources and identified areas of

overlap. Although these documents use slightly different language to articulate the concept-related learning outcomes, the essential topics overlap almost entirely. Using information from all of these documents, we generated a detailed list of essential concepts for the biology major at each of three levels: broad topics, subtopics, and specific examples of learning outcomes. However, there were too many individual topics and associated learning outcomes articulated in previously published documents to realistically list for the current audience. To try to capture the many subtopics addressed in each of these larger topic areas, a selection of goals and learning outcomes that addressed the concepts most commonly taught at the undergraduate level were collated to illustrate each of the broader themes. (For details, see Appendix B on the publisher's website.) However, we ultimately deemed this list too lengthy as well and created a more streamlined set of outcomes instead (Table 6.1).

To build the list of essential concepts shown in Table 6.1, we chose to focus on two recently published sources specifically addressing university-level biology: one that summarized the core concepts for biology majors (*Vision and Change*) and another that articulated in more detail the overarching principles within the *Vision and Change* core concepts (BioCore Guide). As mentioned previously, the *Vision and Change* document arose from a significant effort over five years and included contributions from many biologists who weighed in on essential biology concepts for undergraduates. Therefore, we present these five core concepts as the highest level of organization for biology concept knowledge. However, although *Vision and Change* outlines what faculty agree are the core concepts at a broad level, it does not include specific subtopic knowledge statements or learning outcomes. The BioCore guide (Brownell et al. 2014) provides more detail under each of the *Vision and Change* topic headings, so we used, with slight editing, the so-called overarching principles

of the BioCore guide to further articulate *Vision and Change's* broad topics and finally included sample learning outcomes for each overarching principle. These example learning outcomes were gathered from the more detailed concept statements presented in BioCore, from other sources such as those presented in papers describing the creation of concept inventories (e.g., Couch et al. 2015), and where necessary, were written de novo.

Competencies

As discussed previously, understandings of essential biology competencies are congruent among several well-recognized reports (AP biology curriculum, College Board Standards for College Success, Next Generation Science Standards, *Vision and Change*, and *Scientific Foundations for Future Physicians*) and research publications (Coil et al. 2010; Dillashaw and Okey 1980; Gormally, Brickman, and Lutz 2013). We used these to identify nine main categories of competencies and two categories that bridge concepts and competencies. When reports or publications contained an overlapping competency (which occurred frequently), we used the reference that best articulated the competency or modified the statement for clarity. We parsed statements of competencies that were verbose or in paragraph form into several more clearly measurable outcomes. Some references included laboratory practice or the use of instrumentation related to competencies acquisition; for these competencies, we edited the text such that the learning outcome was more generalizable to any biology class setting. We then reviewed and removed redundant phrasing or learning outcomes and ultimately created an exhaustive list of representative competencies for biology (see Appendix C on the publisher's website). Although this exercise of pulling together detailed articulations of competencies was instructive (primarily because of the extensive overlap among all sources), the list was too detailed to be useful. Thus, we

further refined the list using the seven competencies presented in the AP biology curriculum into six competencies that best reflect college-level biology competencies (competencies 3 and 6 were rephrased into a single competency: engage in scientific inquiry and experimental design). The AP biology competencies were the most completely articulated of the lists we examined and over-lapped nearly completely with the MCL faculty panelists' opin-ions of essential competencies for undergraduate biology majors. We also added an additional set of knowledge statements that falls under the category of nature of science (see Appendix D on the publisher's website).

Essential Concepts and Competencies for the Biology Major

Using the process described above, we were able to generate a distilled list of essential concepts and competencies for biology (Tables 6.1 and 6.2). The committee members overseeing this work unanimously agreed that biology instruction should focus on the experimental nature of biology and that, as emphasized in the NGSS literature, concepts and competencies are inextri-cably linked. To illustrate this link, we generated a matrix pro-viding examples of how both concepts and competencies can be articulated together in meaningful learning outcomes. Rather than articulating this integration for all of the competencies, we selected the three competencies the group deemed most critical to teach and assess—experimental design, data analysis, and the interdisciplinary nature of science—and paired them with the five essential concepts (Table 6.3). The order of concepts is not meant to be hierarchical, and each box in the matrix is merely a possible exemplar. No one example is intended to be exhaustive or definitive.

Table 6.1 Essential Concepts for Biology

Essential Concept	Definition	Example Learning Outcomes
Evolution: *The diversity of life evolved over time by processes of mutation, selection, and genetic change*	• All living organisms share a common ancestor. • Species evolve over time, and new species can arise, when allele frequencies change due to mutation, natural selection, gene flow, and genetic drift.	• Explain how a specific mutation arose in a population that has undergone a change in its environment and exhibits different traits from its ancestors. • Predict the impact of different factors on the genetic composition of a newly isolated population compared with its parent population.
Information Flow: *The growth and behavior of organisms are activated through the expression of genetic information in context*	• Organisms inherit genetic and epigenetic information that influences the location, timing, and intensity of gene expression. • Cells/organs/organisms have multiple mechanisms to perceive and respond to changing environmental conditions.	• Determine how mutations at different locations within a gene could alter the amino acid sequence and function of the resulting protein. • Predict the contribution of environment versus genetics on the phenotype for a specific trait among individuals in a particular population.
Structure and Function: *Basic units of structure define the function of all living things*	• A structure's physical and chemical characteristics influence its interactions with other structures and therefore its function. • Natural selection leads to the evolution of structures that tend to increase fitness within the context of evolutionary, developmental, and environmental constraints.	• Compare how the properties of water affect the three-dimensional structures and stabilities of macromolecules, macromolecular assemblies, and lipid membranes. • Compare how competition, mutualism, and other interactions are mediated by different organisms' morphological, physiological, and behavioral traits.

Pathways and Transformations of Matter and Energy: *Biological systems grow and change by processes based upon chemical reactions and are governed by the laws of thermodynamics*	• Energy and matter cannot be created or destroyed but can be changed from one form to another. • Energy supports the maintenance, growth and reproduction of all organisms.	• Explain how free energy and entropy contribute to the folding of a protein comprised of polar and nonpolar amino acids. • Explain in energetic terms why reaction rate changes when the reaction is heated or when a specific enzyme is added.
Systems: *Living systems are interconnected and interacting*	• Biological molecules, genes, cells, tissues, organs, individuals, and ecosystems interact to form complex networks that exhibit emergent properties. A change in one component of the network can affect many other components. • Organisms have complex systems that integrate internal and external information, incorporate feedback control, and allow them to respond to changes in the environment.	• Make predictions about how organisms might use negative feedback mechanisms to maintain their internal environment. • Predict whether a biological or physical disturbance to an ecosystem will induce a change in the ecosystem depending on the complex set of interactions within the ecosystem.

Table 6.2 Essential Competencies for Biology

Essential Competency	Definition (Students Will Be Able To. . .)
Model	Construct, use, reexpress, and revise models and representations of natural and designed objects, systems, phenomena, and scientific ideas in the appropriate context and in formulating their explanation.
Apply Quantitative Reasoning	Reason about relationships between variables (e.g., data, representations, uncertainty, samples) through the lens of ratios, rates, percentages, probability, or proportional relationships when approaching or solving problems or when interpreting results or situations.
Engage in Argument from Evidence	Evaluate the claims, evidence, or reasoning behind currently accepted explanations or solutions to determine the merits of arguments.
Engage in Scientific Inquiry and Experimental Design	Design experiments with appropriate strategies, controls, and alternative approaches.
Analyze and Evaluate Data	Extract information from data and analyze it to discover patterns, critically evaluate conclusions, and generate predictions for subsequent experiments.
Appreciate and Apply the Interdisciplinary Nature of Science	Apply concepts from within biology subdisciplines and outside of biology to interpret biological phenomena.

Table 6.3 Matrix of Learning Outcomes That Blends Essential Concepts with Essential Competencies

	Essential Competencies		
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	Engage in Scientific Inquiry and Experimental Design	Analyze and Evaluate Data	Appreciate and Apply the Interdisciplinary Nature of Science
Essential Concepts Evolution	Design an experiment to measure changes in genetic makeup of a population over several generations.	Determine from graphical representations how the relative reproductive success of genetically distinct individuals affects the overall genetic composition of a population.	Apply the geological principles of cross-cutting and superposition to fossils in different strata to infer common ancestry.
Information Flow	Design a series of experiments to determine whether a mutation in a gene alters gene expression by affecting transcriptional, post-transcriptional, or post-translational regulation.	Interpret results from a Northern blot to predict what kinds of mutations could be responsible for altering gene expression and contributing to disease phenotypes.	Compare and contrast how different organisms respond to wavelengths of light and how this results in modulation of gene expression.

Table 6.3 *(Continued)*

		Essential Competencies		
		Engage in Scientific Inquiry and Experimental Design	Analyze and Evaluate Data	Appreciate and Apply the Interdisciplinary Nature of Science
Essential Concepts	**Structure and Function**	Design an experiment that would enable one to classify a newly discovered single-celled organism as eukaryote, bacteria, or archaea.	From their structures, predict which solutes will be able to diffuse spontaneously through a pure phospholipid bilayer membrane and which will require transport by membrane associated proteins.	From structures of amino acids, make predictions about where they would be found in a folded protein based on their chemical properties.
	Pathways and Transformations of Energy and Matter	Create a diagram that illustrates the flow of matter and energy during growth and cellular activities, and identify appropriate experimental analyses at different points to determine measurable outputs.	Given thermodynamic and kinetic data about a biochemical reaction, predict whether it will proceed spontaneously and the rate at which it will proceed.	Explain the transformations of energy between the plucking of a note on a guitar to the time a singer registers the note played.
	Systems	Design an experiment to identify the feedback points that operate in a system that exhibits homeostasis.	Using diagrammatic representations of feedback loops, make predictions of how organisms could use such mechanisms to maintain their internal environment.	Design a quantitative model that represents the exchange of molecules between an organism and its environment.

Essential Concepts and Competencies for the Introductory Biology Course

Articulating concept-related learning outcomes for introductory biology courses can be a daunting task in part because such courses are not at all uniform in the concepts they cover. Departments may offer an introductory course focused primarily on molecular and cell biology, ecology, or a general introductory biology, in which molecular and cell, ecology, genetics, and some physiology are all addressed. Some introductory courses are a single semester, whereas others are two semesters. Usually, the concepts covered in an introductory course reflect the overall specialization of the department—the department may be a general biology department, or it may be an ecology or molecular biology department. As a consequence of this diversity, it is unlikely that any one set of content outcomes would be adopted by all departments or all instructors of introductory biology. In fact, this diversity is likely one reason for the development of many new concept inventories that address components of introductory biology, for example: molecular and cell (Shi et al. 2010); genetics (Smith, Wood, and Knight 2008); meiosis (Kalas et al. 2013); natural selection (Anderson, Fisher, and Norman 2002); genetic drift (Price et al. 2014); and evo-devo (Perez et al. 2013). A similar issue exists for assessments designed to measure progression through or completion of the major. Aside from the standardized GRE and MFT, only one tool designed for college seniors is currently available (Couch et al. 2015), although others are in progress (e.g., the BioMAPS project). Since there is no typical introductory biology course, Table 6.4 shows an example set of essential concepts for a course that focuses on molecular and cell biology, an emphasis of many biology departments. This list could be modified for courses with slightly different emphases or expanded for courses that are more general.

Table 6.4 Concept Learning Outcomes for an Introductory Molecular and Cell Biology Course

Learning Outcomes (Students Will Be Able To. . .)
Outline the theory of evolution, citing evidence that supports it and properties of organisms that it explains.
Contrast the features that distinguish viruses, bacteria, archaea, and eukaryotic cells.
Recognize structures of the four major classes of building block molecules (monomers) that make up cellular macromolecules.
Compare how the properties of water affect the three-dimensional structures and stabilities of macromolecules, macromolecular assemblies, and lipid membranes.
Given the thermodynamic and kinetic characteristics of a biochemical reaction, predict whether it will proceed spontaneously and the rate at which it will proceed.
From their structures, predict which solutes will be able to diffuse spontaneously through a pure phospholipid bilayer membrane and which will require transport by membrane associated proteins.
Outline the flow of matter and energy in the processes by which organisms fuel growth and cellular activities, and explain how these processes conform to the laws of thermodynamics.
Using diagrams, demonstrate how the information in a gene is stored, replicated, and transmitted to daughter cells.
Describe how the information in a gene directs expression of a specific protein.

Although the biology concepts taught in introductory biology are diverse, the same six science competencies that we articulated in Table 6.2 are universally described by instructors as critical for students to learn in almost any kind of biology course, including introductory biology. Thus, we do not think there is value in writing an additional set of competencies just for introductory biology. We note, however, that students will likely achieve competencies at a lower level as they are completing introductory biology compared

with their level of competency when they are completing a major in biology.

A Note on Majors Versus Nonmajors

There are generally three kinds of introductory biology courses offered to undergraduates: those intended for biology majors only; those for nonmajors only; and those for the two populations combined. Many colleges and universities offer introductory biology courses that are taken both by majors and by other students who are fulfilling science distribution requirements, even when such a course is described as required for biology majors. This combination of majors and nonmajors presents a dilemma because such an introductory biology course may be the only science course the nonmajors take during their entire college experience. However, for those intending to major in biology, the introductory course is a foundation for the rest of the biology courses that follow. Thus, even though scientific literacy is often mentioned as a critical component of a student's undergraduate experience, no matter their major, nonmajors may not get the kind of specialized exposure that might be required for them to establish scientific literacy if they are taking courses designed specifically for nonmajors. This dilemma is worth considering as assessment tools for introductory biology are planned and developed.

Current Assessments of Student Learning in Biology

Because high-quality, meaningful assessments are difficult and time-consuming to create, most standardized assessments used to measure biology concept knowledge have traditionally been multiple-choice exams focused on details rather than concepts, principally developed by organizations such as the College Board, Educational Testing Service (ETS), and Association of American Medical Colleges. These standardized assessments often come with a financial cost to the students who take them or the departments

that administer them. Unfortunately, this model has unintended consequences for underserved students who have significant financial burdens. Since many of these exams measure college readiness for biology or mastery of concepts and skills taught in biology and are used for entry into college science courses or graduate school, respectively, this model may eliminate many talented students from the discipline.

However, in the past eight years, many biology faculty have been working to develop well-tested and reliable assessment instruments designed to measure conceptual understanding of a diverse set of biology topics at the undergraduate level. These faculty-developed concept inventories (or assessments) differ from many prior individual department-level assessments because they have been rigorously developed to specifically test known student incorrect ideas (i.e., common misconceptions), and evaluated for reliability and evidence of validity. In this section we focus our discussion on both the standardized assessments created by large organizations, and on the more recently developed concept assessments, emphasizing those that have been used by colleges and universities across the country. We also highlight assessments that may serve as useful tools in the future or as foundational work for creating a more comprehensive assessment instrument.

Concept Assessments

The AP biology exam aims to measure the concept knowledge and skills of students who have taken a high school AP biology course, which is designed to be equivalent to an introductory biology course in college. The exam assesses many of the essential concepts and competencies that many efforts, including *Vision and Change*, have highlighted as important for biology students. It contains mostly multiple-choice questions that are machine scored and a substantial number of free-response questions that are scored with rubrics by educators; the free-response question scores are weighted and combined with the scores from the multiple-choice

section. Students who achieve a top score of 4 or 5 on the AP biology exam may be awarded college credit depending on the colleges or universities they attend.

The GRE subject test in biology has been administered since the early 1990s and is intended to measure test takers' potential for success with graduate-level study in biology. The strictly multiple-choice exam is based on concept categories but does contain a number of grouped sets of questions that are based on descriptions of laboratory and field situations, diagrams, or experimental results. Therefore, the exam does test a subset of the essential competencies we discussed in the previous section. The exam is often used by departments and programs to assess a student's ability for graduate work in biology.

The MFT in biology is an exam designed to assess graduating students' "mastery of concepts, principles and knowledge" in undergraduate-level biology (ETS 2014, 1). Similar to the GRE subject test in biology, but certainly not as comprehensive, the biology MFT assesses student learning of concepts. It also has question groups that are based on experimental design or analysis of data from lab or field scenarios. Similar to the biology GRE, some of the concept topics and skills are aligned with the essential concepts and competencies already outlined. The test consists of 150 multiple-choice questions. Though not widely used, some departments administer the biology MFT to gather data for the purposes of instructional improvement or to satisfy external data reporting requirements from accreditors or other agencies.

Biologists and biology education researchers have recently added to the assessments available by designing instruments that address either certain course topics or individual courses taken by biology majors. These assessments are sometimes referred to as concept inventories because they inventory what a student knows and is able to do shortly after instruction. Although most consist of all multiple-choice questions, several have incorporated two-tiered, multiple true–false, and free-response questions, or a mix of

these types along with multiple-choice questions. These inventories have been designed by faculty for faculty use and do not have any associated fees—they are typically published in journals or are made freely available online.[2] Some concept assessments are relatively broad and intended to be used at the beginning and end of a course to measure learning gains as a consequence of instruction. Thus, instruments like the Biology Concept Inventory (Garvin-Doxas and Klymkowsky 2008), the Introductory Molecular and Cell Biology Assessment (Shi et al. 2010), and the Genetics Concept Assessment (Smith, Wood, and Knight 2008) along with several others cover many topics and learning outcomes. Other instruments have been designed to address a smaller number of concepts in more detail, such as the Concept Inventory of Natural Selection (Anderson, Fisher, and Norman 2002), the Diffusion and Osmosis Diagnostic Test (Odom and Barrow 1995), the Host-Pathogens Interactions (Marbach-Ad et al. 2009), and a suite being developed at University of British Columbia (http://q4b.biology.ubc.ca/concept-inventories/).

Recently, a group has begun to develop a suite of assessments intended to measure progression through the major. These assessments use the multiple true–false format and are not tied to any one course but rather consist of a suite of concepts that students would be exposed to throughout their career as biology majors. This project, Biology-Measuring Achievement and Progression in Science (BioMAPS), will ultimately produce a general biology assessment and tools for majors that are more physiology, ecology, and evolution focused. A molecular biology–focused assessment, the Molecular Biology Capstone Assessment, has already been published (Couch et al. 2015). The BioMAPS tools also attempt to more explicitly integrate competencies with concepts than do most previous concept assessments.

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[2] To view a list of existing concept inventories as of 2014, visit http://go.sdsu.edu/dus/ctl/cabs.aspx.

Published work on some of these faculty-developed concept assessments has helped to reveal or support previous reports of common student difficulties at both introductory and advanced levels (Couch et al. 2015; Smith and Knight 2012). Understanding these difficulties is essential for any further assessment development. However, although there are now many choices for faculty who are interested in measuring students' conceptual learning, no one instrument has been chosen to be the representative measurement tool.

Competency Assessments

Rigorously designed instruments that specifically measure the essential competencies, skills, and practices of undergraduate biology students remain woefully lacking. One of the first such instruments for measuring students' skills was the Test of Integrated Process Skills (TIPS) for Secondary Students (Dillashaw and Okey 1980). TIPS is an instrument designed to measure science students' abilities in data analysis and graphing. TIPS contains some biology-based examples. Up until the development of a biology-specific equivalent, TIPS was appropriate for assessing college freshmen who were biology majors (Dirks and Cunningham 2006). However, TIPS assesses only a narrow range of essential competencies and is incapable of measuring the true range of abilities among introductory biology students. A more recent assessment designed for undergraduate biology is the Test of Science Literacy Skills (Gormally et al. 2013), which focuses on scientific inquiry and working with and using data. This assessment is designed to measure basic scientific literacy, and thus while valuable for measuring general biology education students' literacy, it may not be challenging enough for biology majors. Two additional assessments, the Rubric for Experimental Design (Dasgupta et al. 2014) and the Experimental Design Assessment Test (Sirum and Humberg 2011), specifically assess students' knowledge of experimental design and are targeted to the level of biology majors. These more

recently developed tools are excellent resources, but biology faculty have had difficulty implementing them in large-scale biology classes because they are time consuming to administer and analyze. Thus, as is true of concept assessments, although several different instruments could be used to assess essential competencies, biology lacks a comprehensive, universally adopted set of assessments.

Future Assessments in Biology: Blending Competencies and Concepts

Assessing the essential conceptual knowledge and competencies of undergraduate biology students requires a diverse suite of tools capable of measuring a dynamic range of student abilities. Appropriate instruments would be able to distinguish novices from more advanced students both in the depth of their concept knowledge and their competency with biology skills. Although some assessments would measure concepts and competencies that all biology students should learn, others should be tailored to one of the many subdisciplines of biology to reflect their more specific concepts and skills. For example, a molecular biology major would need to know how to read the output from a DNA microarray experiment whereas an ecology major would need to know the difference between a point transect and a line transect and when to use them in field studies. Biology assessments should not only measure critical concepts and competencies, they should also be developed using the most commonly accepted principles of assessment design. Assessments should measure what they intend to measure and be equitable among groups taking the test. Test format, scoring, and interpretation of results are inextricably linked components of assessments. Given that assessment is a practice and a process that may impact curriculum and teaching, these different aspects of assessment require a great deal of attention when designing any instrument (NRC 2001). In this section we discuss assessments most suitable for measuring the core concepts and competencies of biology students.

Assessing biology competencies can be much more challenging than assessing concept knowledge, and test format can strongly impact what kinds of competencies can be measured. Being able to recognize the components of a good experiment is different than designing a novel experiment given a particular scenario. Thus, the creativity that goes into good experimental design is not easily measured with certain test formats, such as multiple-choice tests. The same can be true for other important skills in biology, such as model building and argumentation. Questions that require students to apply their knowledge and creative skills can measure students' ability to be flexible in how they approach interpreting and solving a problem: these questions cannot be multiple choice but rather should be open-ended.

On the other hand, some skills, such as interpreting graphs or making inferences from data, can be measured adequately with multiple-choice questions. Furthermore, not all assessments can be comprised of only open-ended responses due to the difficulty of collecting and analyzing data from such responses. Scoring multiple-choice tests takes far less time and resources compared to scoring open-ended tests. Also, because multiple-choice questions have only one correct answer, the scoring cannot be biased. On the other hand, open-ended questions, which are most often graded by hand, can lead to biases and mismatches between intended and actual measures (Baxter and Glaser 1998). Given that students come to college with a variety of life experiences that influence their thinking and learning, the answers they provide to questions requiring complex answers will be diverse and present challenges for analysis. Thus, because all assessment questions have caveats associated with them, comprehensive tests for measuring concepts and competencies in biology should be based on a variety of question formats (multiple-choice, multiple true–false, open-ended, and two-tiered) and the specific skill measured in each question should dictate which format is selected.

Assessments designed to measure concepts and competencies in biology should also be able to assess the progression of students from novice to master. Determining where a student is at several points along a learning continuum is more useful than just a snapshot of their abilities at any given time. Therefore assessments should be designed to capture a range of abilities within a class or a larger group of students. For example, a rubric designed to score an open-ended question would have a list of items that a student would have demonstrated if they had mastered the concept or skill tested. The same rubric would also show that a novice or intermediate student would have addressed only one or a few of the items, respectively, in their answer. Similarly, multiple-choice tests can be iteratively designed to provide different questions along a difficulty scale—students who progress along the scale are capable of answering more difficult questions about the same concept or skill as they move toward mastery. This is the premise of the adaptive nature of the GRE subject test in biology: When students correctly answer a question they are given a more difficult question, but if they get it wrong they are given an easier question; this continues until the end of the test and their final score is based on an overall ability score along a range of abilities. So as mentioned previously, the interpretation of test results is based on the scoring method and the overall test design. The complex link between concepts and skills in biology will require assessments that are capable of effectively measuring the intersection of these domains along ability continuums.

One potentially useful tool for understanding student thinking is computer-assisted analysis of student writing. Lexical analysis software (Weston et al. 2015) and machine learning programs (Nehm, Ha, and Mayfield 2012) have both recently been leveraged to help analyze student writing about essential biology concepts. If such tools can be perfected, assessment of student thinking will be more robust because creative lines of thought required for more cognitively challenging tasks could potentially be measured

rather than only the forced choices dictated by multiple-choice assessments.

A well-designed set of assessments for measuring student progression toward mastery of the essential concepts and competencies in biology is only one step toward improving learning in these areas. How the data are interpreted and used to improve instruction and curriculum is another critical component for enhancing student learning of biology. Good assessments can inform biology faculty about their teaching practices, but they will need support and development opportunities in order to implement the kinds of changes that will improve student learning.

Conclusion

In this paper, we have reviewed the current status of learning outcomes and assessment in undergraduate biology, focusing in particular on learning outcomes for biology majors and how they are currently being assessed. We have reviewed the outcomes articulated in the K–12 literature, which sets the stage for entering undergraduate biology students, and noted the similarities between concepts and competencies typically addressed in introductory biology and those which are typically addressed in high school biology courses. We have also described the current sets of learning outcomes that exist for undergraduate biology majors and the assessment tools, both standardized tests and faculty-developed concept assessments, that have been developed to assess students' achievement of these outcomes. In our research and discussions, we have agreed that biology is an experimental science and that it should be taught and learned with that idea in the forefront. Accordingly, future outcomes and assessments should emphasize the integration of concepts and competencies. To envision how this would manifest, we demonstrate how learning outcomes can be written such that concepts and competencies are articulated together.

All stakeholders in this endeavor should focus on teaching and assessment that merges the process of science with the concepts of biology. Although good assessments can inform biology faculty about their teaching practices, faculty will need support and development opportunities to implement changes that improve student learning. Thus, ultimately, administrators and faculty will benefit from collaborating to assess biology programs and curriculum, as well as pedagogy and student learning. Many faculty who have embraced the process of articulating learning outcomes and creating better assessment tools still emphasize learning detailed concepts at low cognitive levels and miss the opportunity to blend concepts and practices. Administrators can help improve teaching by providing the resources necessary to help instructors develop assessments that will better test science process skills such as reasoning, data analysis, problem solving, and experimental design in concert with essential concepts. Such collaboration between administrators and faculty will help make tangible the goal of advancing the depth of student learning by focusing instruction on merging concepts and competencies.

NOTE: On the publisher's website you'll find additional information, including more sample learning outcomes. To access this bonus online material, go to www.wiley.com/go/arumimproving.

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