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Perspectives

The Development of Curricular Guidelines for Introductory Microbiology that Focus on Understanding

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The number of students who leave majors in science, technology, engineering, and mathematics (STEM) due to a perception that courses are poorly taught is evidence that education reform in STEM is overdue. Despite decades of research that argues for student-centered teaching approaches, most introductory STEM courses are still taught in the large lecture format, focusing on rote memorization. While individual efforts in STEM educational reform are important, solutions will most certainly need to include institutional and cultural change. In biology, numerous national reports have called for educational reform to better prepare future scientists. We describe here a new, concept-based curriculum for Introductory Microbiology courses, designed to promote deep understanding of core concepts. Supported by the American Society for Microbiology (ASM) and based on the overarching concepts and competencies presented in the AAAS/NSF report *Vision and Change in Undergraduate Biology Education: A Call to Action*, we hope it will empower instructors to adapt student-centered approaches so that students in Introductory Microbiology courses can leave the course with a core set of enduring understandings of microbiology.

INTRODUCTION

One of the primary roles for introductory courses in the fields of science, technology, engineering, and mathematics (STEM) is to provide fundamental knowledge to students interested in the field so they can continue with their chosen major (27). Evidence is mounting that colleges and universities are not fulfilling this role for many students (34). There has been a marked decline in the number of students who major in STEM and continue on to graduate school or work in the field. STEM students leave because of a perception that the courses are poorly taught or not relevant, or that the professors care more about research than student learning (18). The vast majority of students who switched out of STEM fields cited poor teaching as a concern (28).

As the USA becomes less academically competitive in STEM fields, it seems as if students who stay in STEM disciplines are less prepared to solve the complex, multidisciplinary problems facing society today (21, 27). This decline in both the quantity and quality of STEM college graduates is particularly worrisome in light of current job growth projections for the US, where 17 of the 20 occupations with the fastest growth rate over the next decade fall within STEM disciplines (6).

What is wrong with how STEM classes are taught? Despite the fact that educational research has been questioning "traditional," passive, fact-based teaching methods for decades (34), most introductory STEM course are still taught in the large lecture format, focusing on rote memorization. There have been numerous reports issued in the last decade from national organizations, calling for changes in how STEM is taught (see, for example, 22, 24, 25). As scientists understand more about how we learn, the need for student-centered teaching approaches that focus on critical thinking skills, emphasize active learning, and allow for multidisciplinary investigation is becoming more apparent (15). STEM students learn more when teachers employ peer learning, collaborative projects, and active engagement (16).

There have been efforts to change how STEM is taught. There is a large and active scholarship on how to improve teaching STEM to undergraduates, and techniques have been developed by individual educators that are more engaging to students and more effective at helping them learn (see, for example, 10, 11, 13, 30). A reform movement in physics began decades ago, when educators became concerned that the emphasis on "plug and chug" problem-solving was not resulting in students understanding core concepts (17). Utilization of the Force Concept Inventory as an assessment of what students learn in traditional courses compared to those with informed teaching methods is credited with spurring dramatic change in how physics is taught (11). Concept inventories are being developed for use in other disciplines to generate evidence and motive similar change (20).

So why isn't reform now more widespread? Some faculty may not be aware of the current research in cognitive and learning theory that supports student-centered teaching (12). Some choose to invest their time and energy on research rather than develop new teaching strategies, as reward systems at most universities clearly incentivize

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research over teaching (32). A recent survey of university science faculty by Nature Publishing Group revealed that while most faculty thought education was as important as research, when given scenarios to choose between the two, their choices clearly showed that research had a higher priority (27). They concluded that research and teaching are considered by many to be a "zero-sum-game," as most faculty members believe they have to choose between the two.

While there is little disagreement that colleges and universities are not educating students in STEM as well as they should or could (27), there seems to be a lack of focus on what to do about it. Most STEM educational reform has been based on developing new teaching strategies, and has relied on publications and conferences to spread the word or on efforts to revamp single departments at individual institutions. Little effort has been spent on figuring out how to overcome the barriers that prevent the widespread use of the innovative tools that are already developed (9).

Solutions will most certainly need to include institutional and cultural change (4, 32). There must be a long-term commitment to intervene from many different groups, including college administrations, funding agencies, and the faculty (27). Other networks, such as professional societies, could also play a substantial role because they have national stature and many resources, and are respected sources of information for a wide range of faculty (10).

In engineering and the physical sciences, professional societies have begun to get involved. In 1999, the American Physical Society, along with the American Association of Physics Teachers and the American Institute of Physics, formed the National Task Force in Physics Education, resulting in the SPIN-UP program that looked for common attributes among successful physics educational programs (11). Focusing more on attrition than pedagogy, the Task Force defined success as departments that awarded high numbers of bachelor's degrees in physics (25). In 2000, the Accreditation Board of Engineering and Technology (ABET) adopted new standards for engineering education that called for better communication and problem-solving skills (31). In 2005, the American Chemical Society revised its curricular guidelines to encourage pedagogical innovation (26). In these cases, the guidelines were not specific and change has been slow.

Within the field of biology, there is no central professional society. However, a number of significant national reports have called upon the educational and scientific community to more effectively prepare future biologists. *Beyond Bio 101* (19) emphasized the need for curricular revision that includes active learning and appropriate use of technology to engage students as working scientists. *BIO 2010: Transforming Undergraduate Education for Future Research Biologists* (23) advocated for teaching biology in the same manner as research is performed, and integrating the physical, mathematical, and information sciences. The Association of American Medical Colleges joined forces with the Howard Hughes Medical Institute (HHMI) to outline competencies that would guide educators in curriculum development for future physicians (5). Then in 2010, the American Association for the Advancement of Science and the National Science Foundation released the report *Vision and Change in Undergraduate Biology Education: A Call to Action* (1). It listed core, overarching concepts that students of biology should understand deeply. It also presented a set of competencies or skills that students should master, directed at understanding the process of science and at manipulating and interpreting the data.

Many educators recognize that the amount of information in the field of biology has expanded drastically in the last few decades. This has led to many Introductory Biology courses being taught "a mile wide and an inch deep." In response to these reports, many ideas for a unified curriculum in biology have been put forth (8, 14). However, these efforts have focused more on how to limit what is taught rather than how material is presented.

In 2004, The American Society for Microbiology (ASM) leadership joined with others from research universities, HHMI, and the National Research Council (NRC) to challenge the scientific community and research universities to engage in education reform (15). Through its Education Board and the Division on Microbiology Education, the ASM has long been committed to providing educational resources and support for faculty, including the ASM Conference for Undergraduate Educators, the MicrobeLibrary (2), and this journal (7). Its next efforts in support of educational reform are coming through curricular change.

The ASM Task Force on Curriculum Guidelines for Undergraduate Microbiology

To bring about a cultural change in how biology is taught, transformation must come from many sources. Faculty must be involved in the process. They must believe their efforts won't be in vain as the next "fad" in education comes along. Fifteen years ago, ASM first put forth curriculum guidelines for Introductory Microbiology courses for general biology/microbiology students and allied health students, as well as a Laboratory course (3). These have been widely respected by those teaching undergraduate microbiology. In light of the recommendations coming from the national reports, the Education Board of the American Society for Microbiology decided to revisit the microbiology curriculum guidelines as a strong statement of support for embracing ASM's recommendations for concept-based, student-centered learning.

Co-chaired by Sue Merkel (Cornell University, NY) and Jackie Reynolds (Richland College, TX) and including Billy Hung (Eastern Illinois University, IL), Amy Siegesmund (Pacific Lutheran University, WA), Ann Smith (University of Maryland, MD), and Heidi Smith (Front Range Community College, CO), the ASM Task Force on Curriculum Guidelines for Undergraduate Microbiology Education set out to engage educators of undergraduate microbiology at all levels to help develop a curriculum that was relevant to both Biology/Microbiology majors and allied health students.

Early on, we recognized and affirmed the five overarching concepts in biology presented in the "Vision and Change" report (1), with the addition of a sixth concept that speaks to the unique potential of microbiology in biotechnology.

The final list of overarching concepts put forth by the Task Force are:

- evolution
- cell structure and function
- metabolic pathways
- information flow and genetics
- microbial systems
- the impact of microorganisms

We further affirmed the process outlined by "Vision and Change": "that teaching must move toward active, outcome-oriented, inquiry-driven and relevant courses that define learning goals and align assessments to focus on conceptual understanding, not just on covering voluminous content (1)."

With the ultimate goal of having students develop a conceptual understanding of the central principles of microbiology, we adopted the framework outlined by Wiggins and McTighe called "Backwards Design" (33). In this framework, curricula are designed around learning goals and assessments such that students develop enduring understandings of essential concepts that are retained beyond the end of the semester. Only when goals are established and assessments are planned, do educators begin to think about how the teaching goals can be met. In adopting this framework, we hope to move course emphasis away from rote memorization of topics toward lasting understanding that can provide a foundation for further learning.

As a first step, the Task Force engaged the ASM community in defining the fundamental concepts of microbiology. The concepts have been articulated in a number of "fundamental statements," each linked to one of the six overarching concepts. The fundamental statements identify the essential concepts of microbiology that students should truly understand. The fundamental statements were deliberately framed as declarative "statements" such that they explicitly present core principles of microbiology. It is important to note that these statements neither dictate specific course content, nor restrict instructors in teaching their course. Similarly, these statements are not meant to be memorized by students nor to be used as summaries of lectures. By focusing on core concepts instead of topical details, we aim to present curriculum guidelines that will withstand the continuing accumulation of new information in our field. As new organisms, new pathways, and new mechanisms are discovered, instructors will have an approach that continues to support a student's enduring understanding of fundamental concepts.

We further embraced the "Vision and Change" call for a curriculum that supports student development in competencies or skills, including: understanding the process of science, understanding the interdisciplinary nature of biology, competency in communication and collaboration, quantitative competency, and a basic ability to interpret data. To these, the Task Force added the expectation that a curriculum support the development of scientific and laboratory skills. We identified key competencies in scientific thinking and laboratory skills, as we believe these to be absolutely critical for any student of microbiology.

While the microbiology curriculum review process began with the Task Force, it has engaged the full microbiology education community. After formulating a draft set of fundamental statements for microbiology, we solicited feedback via an online survey. Over 165 educators responded to the online survey (95 self-identified as primarily teaching Biology or Microbiology majors, 72 as teaching allied Health Sciences majors). They were asked to rate the degree to which each fundamental statement described a critical concept in microbiology that all students should understand. In addition, participants could indicate whether or not they expected students to have prior knowledge of a given fundamental statement. Participants were also able to suggest ideas for additional statements.

A second draft was produced based on these survey results. We solicited feedback for the second draft at special break-out sessions at the 2011 Conference for Undergraduate Educators (ASMCUE). Participants were divided into small groups to provide critical feedback on the fundamental statements associated with one overarching concept, as well as on all the key scientific thinking and lab competencies. Over 140 educators participated (65 biology/microbiology, 50 allied health, 25 undeclared). Input from these sessions was used to rate and revise the fundamental statements (Table 1) and key scientific thinking and lab competencies (Table 2) that make up the recommended curriculum presented here.

The Task Force was cognizant of the need for our curriculum to address the demands for both general biology/microbiology and allied health students. From the composition of the Task Force through the feedback processes, we have been careful to ensure that the finished product will be relevant to goals of both types of courses. The feedback we received indicated that there is consensus on what fundamental knowledge our students should attain after completion of an Introductory Microbiology course, whether these students are Biology majors or allied Health Science majors. Consequently, we envision that each instructor will find the fundamental statements useful in developing particular course learning outcomes. For example, as faculty develop a curriculum to address the fundamental statement: "Mutations and horizontal gene transfer, and the immense variety of microenvironments have selected for a huge diversity of microorganisms," an instructor for general microbiology may choose to develop an activity that interprets this concept in terms of metabolic pathways and nutrient limitation, whereas an instructor for allied health students might instead focus on the spread of antibiotic resistance.

TABLE 1.
Overarching concepts and fundamental statements.

Evolution	• Cells, organelles (e.g., mitochondria and chloroplasts), and all major metabolic pathways evolved from early prokaryotic cells. • Mutations and horizontal gene transfer, with the immense variety of microenvironments, have selected for a huge diversity of microorganisms. • Human impact on the environment influences the evolution of microorganisms (e.g., emerging diseases and the selection of antibiotic resistance). • The traditional concept of species is not readily applicable to microbes due to asexual reproduction and the frequent occurrence of horizontal gene transfer. • The evolutionary relatedness of organisms is best reflected in phylogenetic trees.
Cell Structure and Function	• The structure and function of microorganisms have been revealed by the use of microscopy (including bright field, phase contrast, fluorescent, and electron). • Bacteria have unique cell structures that can be targets for antibiotics, immunity and phage infection. • Bacteria and Archaea have specialized structures (e.g., flagella, endospores, and pili) that often confer critical capabilities. • While microscopic eukaryotes (for example, fungi, protozoa and algae) carry out some of the same processes as bacteria, many of the cellular properties are fundamentally different. • The replication cycles of viruses (lytic and lysogenic) differ among viruses and are determined by their unique structures and genomes.
Metabolic Pathways	• Bacteria and Archaea exhibit extensive, and often unique, metabolic diversity (e.g., nitrogen fixation, methane production, anoxygenic photosynthesis). • The interactions of microorganisms among themselves and with their environment are determined by their metabolic abilities (e.g., quorum sensing, oxygen consumption, nitrogen transformations). • The survival and growth of any microorganism in a given environment depends on its metabolic characteristics. • The growth of microorganisms can be controlled by physical, chemical, mechanical, or biological means.
Information Flow and Genetics	• Genetic variations can impact microbial functions (e.g., in biofilm formation, pathogenicity and drug resistance). • Although the central dogma is universal in all cells, the processes of replication, transcription, and translation differ in Bacteria, Archaea, and Eukaryotes. • The regulation of gene expression is influenced by external and internal molecular cues and/or signals. • The synthesis of viral genetic material and proteins is dependent on host cells. • Cell genomes can be manipulated to alter cell function.
Microbial Systems	• Microorganisms are ubiquitous and live in diverse and dynamic ecosystems. • Most bacteria in nature live in biofilm communities. • Microorganisms and their environment interact with and modify each other. • Microorganisms, cellular and viral, can interact with both human and nonhuman hosts in beneficial, neutral or detrimental ways.
Impact of Microorganisms	• Microbes are essential for life as we know it and the processes that support life (e.g., in biogeochemical cycles and plant and/or animal microflora). • Microorganisms provide essential models that give us fundamental knowledge about life processes. • Humans utilize and harness microorganisms and their products. • Because the true diversity of microbial life is largely unknown, its effects and potential benefits have not been fully explored.

Next steps: working towards a deep understanding

We hope that these fundamental statements will give educators the tools they need to change how their courses are taught. According to the outcome-based approach to curriculum design (33), the definition of learning goals, objectives, and outcomes is the first step. When articulated as "From this course, students will be able to explain and illustrate … ," the fundamental statements can serve as

TABLE 2.
Key competencies for scientific thinking and laboratory skills.

Scientific Thinking	
Ability to apply the process of science	Demonstrate an ability to formulate hypotheses and design experiments based on the scientific method. Analyze and interpret results from a variety of microbiological methods and apply these methods to analogous situations.
Ability to use quantitative reasoning	Use mathematical reasoning and graphing skills to solve problems in microbiology.
Ability to communicate and collaborate with other disciplines	Effectively communicate fundamental concepts of microbiology in written and oral format. Identify credible scientific sources and interpret and evaluate the information therein.
Ability to understand the relationship between science and society	Identify and discuss ethical issues in microbiology.
Laboratory Skills	
	Properly prepare and view specimens for examination using microscopy (bright field and, if possible, phase contrast).
	Use pure culture and selective techniques to enrich for and isolate microorganisms.
	Use appropriate methods to identify microorganisms (media-based, molecular, and serological).
	Estimate the number of microorganisms in a sample (using, for example, direct count, viable plate count, and spectrophotometric methods).
	Use appropriate microbiological and molecular lab equipment and methods.
	Practice safe microbiology, using appropriate protective and emergency procedures.
	Document and report on experimental protocols, results and conclusions.

course goals of an Introductory Microbiology course. Now that the fundamental statements have been established by the ASM education community, instructors can focus time and energy on developing appropriate approaches to achieve student learning instead of struggling to identify the basic concepts that define microbiology de novo.

To develop pedagogy around these fundamental statements, it is important to understand what students know about each concept. Faculty can begin to develop assessments that show what students understand throughout their microbiology course. Assessments such as concept inventories have been successful in revealing student understanding and thus motivating faculty curriculum reform (29). We hope educators will begin to develop concept inventories pertaining to these fundamental statements in microbiology.

As faculty begin interpreting the fundamental statements for a particular course (e.g., General Microbiology or Allied Health Microbiology), the ASM can provide peer-reviewed curricular activities and resources from the ASM MicrobeLibrary (2) that could be matched with many of the learning concepts within the fundamental statements. In addition, the MicrobeLibrary and this journal provide mechanisms through which new activities could be reviewed and distributed.

From the review of the ASM Curriculum Guidelines for Undergraduate Microbiology, we have generated 27 fundamental statements and 13 scientific and laboratory skills to guide microbiology educators as they design their courses. These statements, as affirmed by the ASM community, encompass the basic concepts that students should understand at the completion of a General Microbiology course. We hope this work will empower instructors to adapt student-centered pedagogical approaches so that students in Introductory Microbiology courses (be they Biology, Allied Health Science, or non-Science majors) can leave the course with a set of enduring understandings of microbiology.

While this is an important step in revitalizing higher education in STEM, individual efforts alone will not suffice if we wish to see systemic and sustainable changes. Not only do we need to provide tools, such as this revised curriculum, to enable educators to teach more effectively, we also need institutional and cultural change to enable educators to make the transition. National organizations can play a critical role in this by encouraging cultural change, recognizing and rewarding reform efforts, and continuing discussions about teaching outcomes and practices across all disciplines (32). We will only see sustained and meaningful improvements to STEM education when individual efforts are met with equally pervasive changes in the outlook of STEM education on an institutional and national level. We hope this revised curriculum will help to move us forward, more systemically and with more haste, toward true transformation in STEM undergraduate education.

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