Challenge faculty to transform STEM learning

Focus on core ideas, crosscutting concepts, and scientific practices

By **Melanie M. Cooper*, Marcos D. Caballero, Diane Ebert-May, Cori L. Fata-Hartley, Sarah E. Jardeleza, Joseph S. Krajcik, James T. Laverty, Rebecca L. Matz, Lynmarie A. Posey, Sonia M. Underwood**

Models for higher education in science, technology, engineering, and mathematics (STEM) are under pressure around the world. Although most STEM faculty and practicing scientists have learned successfully in a traditional format, they are the exception, not the norm, in their success. Education should support a diverse population of students in a world where using knowledge, not merely memorizing it, is becoming ever more important. In the United States, which by many measures is a world leader in higher education, the President's Council of Advisors on Science and Technology (PCAST) recommended sweeping changes to the first 2 years of college, which are critical for recruitment and retention of STEM students (*1*). Although reform efforts call for evidence-based pedagogical approaches, supportive learning environments, and changes to faculty teaching culture and reward systems, one important aspect needs more attention: changing expectations about what students should learn, particularly in college-level introductory STEM courses. This demands that faculty seriously discuss, within and across disciplines, how they approach their curricula.

EDUCATION

Compared with lecture-only courses, active-learning pedagogies (e.g., the use of personal response "clicker" systems or peer instruction) can improve retention and course grades, particularly for underprepared and underrepresented students (*2*). But conversation must extend beyond interactive classrooms to how to support students to develop and use deep, transferrable knowledge. Even after successful completion of several college-level science courses, there are huge challenges to understanding and using scientific knowledge (*3*). *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (*4*) provides the most up-to-date, research-based strategies for promoting deep learning and is well aligned with other international initiatives. These strategies were developed for K-12 (primary and secondary education), but we believe the approach is valid for the first 2 years of college.

Michigan State University, East Lansing, MI 48824 USA.
**Correspondence to: mmc@msu.edu*

CORE IDEAS, CROSSCUTTING CONCEPTS. Disciplinary experts have a great deal of knowledge—organized and contextualized around important concepts (*5*). Students should develop knowledge around these "disciplinary core ideas" rather than try to assemble understanding from many disparate ideas and activities. Core ideas should be advanced over time through carefully developed progressions of learning activities and assessments that provide students and instructors with feedback about student understanding (*6*). This is at odds with most introductory science courses that attempt to provide an overview of the discipline. Ideas and concepts are often compartmentalized by chapter, which obscures connections within and across courses and makes it difficult for students to correlate facts, ideas, and exercises (*1*).

PHOTO: SKYNESHER/ISTOCKPHOTO

Several initiatives have developed around a model for organizing ideas in a discipline. *Vision and Change*... (*7*) identified core ideas in biological sciences. Reforms of Advanced Placement courses in the United States and Canada, which offer college-level courses to secondary students, were built around "big ideas" in biology, chemistry, and physics (*8*). Although efforts must be informed by national-level initiatives and the research literature, we believe that core ideas must be negotiated locally by faculty in each discipline in order to build ownership and buy-in.

For example, core ideas that emerged from cross-disciplinary discussions at our institution, Michigan State University (MSU), include "evolution" for biology, "structure and properties" for chemistry, and "interactions cause changes in motion" for physics. Focusing on core ideas within each discipline allows reduction of the amount of material that many agree has become overwhelming (the "mile-wide, inch-deep" problem). Faculty agreement on what is centrally important moves the conversation from what to eliminate to what supports core ideas.

There are also ideas that span disciplines—"crosscutting concepts," such as cause and effect, conservation of energy and matter, and systems thinking. Energy itself is a core idea in each discipline, yet we rarely note the different ways disciplines treat energy, leaving students often unable to apply what they have learned in one discipline to another. If each discipline were to agree on a coherent approach, it would allow students to construct understanding and to apply that knowledge across disciplines.

PRACTICES AND LEARNING. Although many reform efforts have focused on "inquiry"—an idea with different connotations depending on context and audience (*9*)—the *Framework* describes eight "scientific and engineering practices" that can be thought of as disaggregated components of inquiry, e.g., developing and using models and engaging in arguments from evidence. Descriptions of these practices make it more likely that they will be incorporated into teaching and learning. Such descriptions will aid design of assessments that require students to use content knowledge (core ideas) in the same ways scientists do (by engaging in scientific practices). These practices can actively engage students in using their knowledge to predict, model, and explain phenomena—which one might argue is the primary goal of science.

Instead of developing or assessing core ideas, crosscutting concepts, and scientific practices separately, they should be integrated into "three-dimensional learning" (*10*). Emphasizing and integrating the three dimensions will necessarily change our approach to instruction. Providing students with opportunities to develop models, construct explanations, and engage in arguments using evidence requires that courses become more student-centered. Assessments must measure not only what students know but also how they use their knowledge. Although some transformation efforts have measured reforms' success by using multiple choice assessments [e.g. concept inventories (*11*)], these do not address how students use knowledge in the ways we have discussed here.

At MSU we are developing evidence-based approaches to assessment and instruction that incorporate the three dimensions (*10*, *12*). Although constructing and scoring these items is more difficult and time-consuming than traditional questions, assessments must change, or students will not learn to use scientific practices and core ideas to make sense of phenomena.

The pace of change in higher education can be glacially slow. Increasing numbers of students will enter college whose learning has been informed by the *Framework*. Higher education should capitalize on their carefully scaffolded knowledge. It would be a disservice to throw these students back into typical introductory courses that focus on memorizing facts and algorithmic calculations. ■

REFERENCES AND NOTES

1. PCAST, "Engage to excel: Producing one million additional college graduates with degrees in science, technology, engineering, and mathematics" (White House, Washington, DC, 2012); http://1.usa.gov/1OwzsBh.
2. S. Freeman *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **111**, 8410 (2014).
3. National Research Council, *Discipline-Based Education Research: Understanding and Improving Learning in Undergraduate Science and Engineering* (National Academies Press, Washington, DC, 2012).
4. National Research Council, *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (National Academies Press, Washington, DC, 2012).
5. National Research Council, *How People Learn: Brain, Mind, Experience, and School* (National Academies Press, Washington, DC, 1999).
6. J. S. Krajcik, L. M. Sutherland, K. Drago, J. Merritt, in *Making It Tangible: Learning Outcomes in Science Education*, S. Bernholt, K. Neumann, P. Nentwig, Eds. (Waxmann, Münster, 2012), pp. 261–284.
7. AAAS, *Vision and Change in Undergraduate Biology Education: A Call to Action* (AAAS, Washington, DC, 2011).
8. W. B. Wood, *Science* **325**, 1627 (2009).
9. M. Windschitl, *J. Res. Sci. Teach.* **41**, 481 (2004).
10. National Research Council, *Developing Assessments for the Next Generation Science Standards* (National Academies Press, Washington, DC, 2014).
11. R. R. Hake, *Am. J. Phys.* **66**, 64 (1998).
12. National Research Council, *Knowing What Students Know: The Science and Design of Educational Assessment* (National Academies Press, Washington, DC, 2001).

ACKNOWLEDGMENTS

This project was supported by the Association of American Universities' Undergraduate STEM Education Initiative, funded by the Helmsley Charitable Trust, and by the Office of the Provost of Michigan State University.

10.1126/science.aab0933

MEDICINE

Personalization in practice

Dynamic computational modeling integrated with experimentation can enable precision medicine

By **Ravi Iyengar,[1] Russ B. Altman,[2] Olga Troyanskya,[3] Garret A. FitzGerald[4]**

Last month, an advisory committee released recommendations for recruiting at least 1 million individuals to participate in the U.S. National Institutes of Health's Precision Medicine Initiative. This bold approach to disease treatment and prevention seeks to account for an individual's genes, environment, and lifestyle to improve health outcomes. The ability to collect, integrate, analyze, and model relevant data streams is central to this effort. Moving beyond "just" massive data collection will require structured convergence among various disciplines. So, how should data be gathered? Here, computational modeling can be a useful guide. Modeling at the molecular, cellular, tissue, and organismal level will be essential to identify the molecular interactions that underlie progressive diseases and to generate a comprehensive and dynamic picture of the individual.

> ***"If you want me to play only the notes without any specific dynamics, I will never make one mistake."***
> **Vladimir Horowitz**

In 2011, precision medicine was described by the U.S. National Research Council as resting on a "new taxonomy for human disease based on molecular biology" (*1*), but implicit in this notion is the assumption that defining noncommunicable diseases on the basis of an individual's genomic and epigenomic determinants alone will enable the personalization of therapy. This has led to conflation of the terms "personalized" and "precision." The overlap is reasonable when the dominant driver of a disease is largely genomic, as in most cancers. However, for many other progressive conditions such as type 2 diabetes, psychiatric diseases, and heart failure, it is not clear whether genomic status is the major driver. All progressive diseases have genomic underpinnings, but it is the impact of diverse environmental influences—mostly unrecognized—on individual genomes that determines interindividual variation in disease progression and drug response (*2*). In short, we need to know the dynamics of an individual's physiology and pathophysiology.

Empowering the Precision Medicine Initiative requires a formalism to describe relationships between scales of organization and different time domains. This involves a convergence of measurements—from human cell culture experiments to studies in model organisms and clinical measurements in patients—and modeling to reflect unique and general aspects of each system and its relationship to human health and disease throughout the lifetime of an individual. There are several emerging powerful experimental and modeling technologies to do this. For example, induced pluripotent stem cells (iPSCs) enable cell type–specific measurements and provide the opportunity for in vitro experimentation with tissues at the level of an individual. Systems biology provides modeling formalisms to match key features of the molecular, cellular, tissue, and whole-organ physiologies for simulations. Here, Bayesian integration of heterogeneous data (*3*) can be a good starting point. Graph theory helps build networks that describe the local and regional geography of cells, organs, and organ systems. Dynamical modeling describes how this biological geography changes with environment, lifestyle, and age. Some of the dynamic modeling approaches are monomorphic (e.g., differential equation–based models), whereas some are more modular (linked simulations with different formalisms for different subsystems). Irrespective of the approaches used, modeling disease dynamics must start early, with incomplete data. Simulations can then drive the design of large-scale studies that are both clinical and laboratory-based.

[1]Department of Pharmacology and Systems Therapeutics, Systems Biology Center New York, Icahn School of Medicine at Mount Sinai, New York, NY 10029, USA. [2]Department of Bioengineering, Stanford University School of Medicine, Stanford, CA 94305, USA. [3]Department of Computer Science and Lewis-Sigler Institute of Integrative Genomics, Princeton University, Princeton, NJ 08544, USA, and Simons Center for Data Analysis, Simons Foundation, New York, NY 10010, USA. [4]Department of Systems Pharmacology and Translational Therapeutics, Perelman School of Medicine, University of Pennsylvania, Philadelphia, PA 19104, USA. E-mail: ravi.iyengar@mssm.edu; garret@exchange.upenn.edu

Challenge faculty to transform STEM learning
Melanie M. Cooper, Marcos D. Caballero, Diane Ebert-May, Cori L. Fata-Hartley, Sarah E. Jardeleza, Joseph S. Krajcik, James T. Laverty, Rebecca L. Matz, Lynmarie A. Posey and Sonia M. Underwood (October 15, 2015)
Science **350** (6258), 281-282. [doi: 10.1126/science.aab0933]

Editor's Summary