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Learning our L.I.M.I.T.S.: less is more in teaching science

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Hoskins SG, Stevens LM. Learning our L.I.M.I.T.S.: less is more in teaching science. *Adv Physiol Educ* 33: 17–20, 2009; doi:10.1152/advan.90184.2008.—The rapid and accelerating pace of change in physiology and cell biology, along with the easy access to huge amounts of content, have altered the playing field for science students, yet most students are still mainly taught from textbooks. Of necessity, textbooks are usually broad in scope, cover topics much more superficially than do journal articles, and present the scientific process as a linear string of successful experiments, largely ignoring the reality of rejected hypotheses, unanticipated discoveries, or surprising findings that may shift paradigms. We suggest that a more narrow focus on scientific thinking, using a new method for reading a series of journal articles that track the evolution of a single project over a period of years, can more realistically convey the excitement and challenges of research science and perhaps stimulate some students to consider research careers for themselves. Our approach, termed "CREATE" (for Consider, Read, Elucidate hypotheses, Analyze data, and Think of the next Experiment), has proven successful at both demystifying the scientific literature and humanizing science/scientists in undergraduate biology courses (8), and we suggest that it could be profitably expanded to physiology courses.

primary literature; undergraduate; nature of science

WHEN WE TOOK undergraduate cell biology some 25 years ago, the 1-semester lecture course was packed with information. Cell structure, gene expression, membrane proteins–all these hot topics were covered in great detail. We finished the course confident we had learned a lot, or at least committed a great deal of cell biology to memory. But that was then. The past 3 decades have seen an explosion of biological discovery, with methodological breakthroughs allowing the analysis of cellular and genetic mechanisms in unprecedented detail. Twenty-first century biologists have a rapidly deepening understanding of the molecular basis of evolution, development, and disease, and the recent emergence of the field of genomics has set the stage for continued exponential progress in this century. Much of what we teach now was discovered long after we received our PhDs.

The semester, however, is still 14 wk long, and while some of the new findings have replaced the content that we learned in college, a fair amount of the "old" knowledge has held up. If we try to cover that material while adding highlights of the past few decades, we find ourselves packing some 40 wk worth of information into a single semester. We hope our readers will agree that teaching, and especially learning, that amount of material is impossible in a single course. Furthermore, an intense focus on transmitting content is completely at odds with the recommendations of science education reform panels, which encourage us to foster scientific thinking in the classroom (12–14, 16).

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This situation has serious consequences. Research published a decade ago showed that undergraduates drop out of Biology majors largely due to a sense of being "overwhelmed" by detailed and "boring" content (15), an unfortunate situation that persists today (6). Despite the growth in biomedical research in the United States, the fraction of American undergraduate students who undertake graduate training in biology is declining (10). College biology teaching clearly needs to change (1, 7, 11, 17). But how? Most professors have much more on their minds than science education. Tenure and promotion are largely tied to "productivity"–a measure of grant dollars and published research–while teaching expertise rarely factors into the equation. However, only a tiny proportion of first-time grant applications are funded, requiring time-consuming multiple submissions for virtually every grant awarded. Under these circumstances, why would faculty members change the way they teach, especially now that the Instructor's Version of the textbook comes with handy PowerPoint slides and test banks?

We suggest that by adopting a "less is more" philosophy and limiting the quantity of information they try to impart, physiology faculty members will improve both their own experience in the classroom and their students' understanding of physiology–the field, not just the facts. We used this philosophy in designing and evaluating a new upper-level biology course for undergraduates focused on journal articles rather than textbooks [see Ref. 8 for details of the approach and assessment data and Ref. 9 for more on adapting the "CREATE" (for Consider, Read, Elucidate the hypotheses, Analyze and interpret the data, and Think of the next Experiment) approach to the classroom]. Primary literature brings the reader inside the

authors' laboratory by presenting the actual methods used and data generated. Making sense of these data is where much of the excitement of scientific discovery resides. Our CREATE approach brings this excitement to the classroom. We designed CREATE to demystify scientific literature and humanize science, with the goals of improving students' critical thinking ability, content understanding, attitudes toward science/scientists, and personal interest in the research process. Rather than relying on a textbook, CREATE uses guided analysis of a series of four journal articles, produced sequentially from a single laboratory, to highlight the evolution of a research project over a number of years. Students prepare for the class at home, using an assortment of pedagogical tools (Table 1), first to orient themselves in the topic area and define background subjects for review and then to break down the mass of information in the article, reassemble it into component experiments, and critically interpret the data illustrated. Applying the CREATE pedagogical tools in preparation for the class frees students to spend their classroom time on instructor-led in-depth discussion of the experimental findings and their implications. We find that CREATE students are empowered by rising to the intellectual challenge of deciphering the logic of each article and realizing, often for the first time, that they can "think like scientists." At the same time, CREATE instructors are able to run the class more like a laboratory meeting than a lecture, making use of their advanced training and reducing the amount of preclass preparation required.

In the CREATE classroom, less is more. We initially withhold article titles, abstracts, and discussion sections and provide only the introduction, methods, and results pages for *article 1* of the four-article series, challenging students to grapple directly with the data, analyzing and interpreting the findings as if they had been generated in the students' own laboratories. This intensive encounter with primary literature is the first time many students have been encouraged to delve beyond textbook summaries to the nuts and bolts of scientific discovery. After the first article has been fully analyzed in class, and before seeing what experiments were in fact done next by the team of researchers, each student designs two possible "next experiments" to carry out in the system. The class then compares the student-designed experiments and debates possible research directions for the project in an exercise that models the decision-making process typical of bona fide scientific grant panels. The analysis process repeats with each article in the series.

Many faculty members are reluctant to change what they do in the classroom (typically lecture) for fear that taking time for class discussion will result in less content being covered during the semester. We find that in regard to coverage of content, less is plenty in the CREATE classroom. To read and understand

Table 1. *Summary of CREATE tools*

CREATE Classroom Tool	Using the Tool Encourages Students to:
Concept mapping	● Relate old and new knowledge ● Define what they do and don't know about a topic ● Review to fill gaps in knowledge
Cartooning	● Visualize the experiments by representing "what went on in the laboratory" ● Link specific methods to specific data ● Triangulate information in methods/figure or table legends/narratives ● Construct a context for the data
Elucidating hypotheses	● Define, in their own words, the question being asked or hypothesis being tested in experiments related to each figure or table
Annotating figures	● Actively engage with data ● Determine the significance of each figure ● Closely read figure legends and narratives ● Prepare for in-class analysis of the data's significance
Analyzing data using templates	● Determine the logic of each experiment ● Define controls and determine their role ● Relate data presented to results derived ● Debate the significance of the data, defend their own ideas, and intelligently criticize the authors' interpretations
Designing a followup experiment	● Recognize research as a neverending process ● Exercise creativity in experimental design ● Consider that multiple options exist; science is not necessarily linear and predictable
Grant panel exercise	● Consider how research funding decisions are made ● Use critical analysis to rank student-designed experiments ● Develop verbal communication abilities by pitching/defending particular experiments ● Learn to work in small groups and reach a consensus
E-mail interviews of article authors	● See scientists as humans much like themselves, not stereotypes of pop culture ● Make personal connections to research/researchers ● Get their own questions answered ● Recognize the diversity of personalities that can all be "scientists"

CREATE stands for for Consider, Read, Elucidate hypotheses, Analyze data, and Think of the next Experiment. See Refs. 8 and 9 for additional information on how these tools are used in the CREATE classroom.

virtually any cell biology article, students must review aspects of gene expression, immunology, cell structure, and cell signaling. Thus, students assigned a series of four 20-page articles, rather than ten to fifteen 20-page chapters of a textbook, still integrate a great deal of content as a basis for intelligent discussion of the data. What is different about content coverage in the CREATE class is that it is contextual, directly related to a particular experimental situation. For example, understanding of methodology is reinforced by brief content reviews. A basic method like in situ hybridization with a digoxygenin-labeled probe detected via alkaline phosphatase histochemistry, used in many studies for mRNA localization, can trigger a quick review of probe production and binding (plasmids, RNA synthesis, and nucleotide specificity), bonds (covalent linkage of digoxygenin to a nucleotide and hydrogen bonding of probe and target nucleotides), antibody/antigen recognition (amino acid R groups, protein shape, and hydrogen/van der Waals/ionic bonds), the basis of specific binding, and enzyme/substrate interactions. Brief, narrowly focused reviews of content allow the instructor to rapidly determine students' depth of understanding of "the basics" (information they theoretically mastered in prerequisite courses but often don't fully understand), fill any conceptual gaps (e.g., what, exactly, makes antibodies "specific?"), and then return to the problem at hand: what do we learn from the patterns of gene expression revealed by the experiment illustrated in Fig. *X*?

Some in-class figure analysis focuses on canonical experimental designs seen in many studies. These include time-course experiments, dose-response curves, controls for antibody specificity, how "*n*" for a study is determined, and when or how to use statistical methods. As an example, one of our module articles contains a figure showing the characterization of a new bioassay for axonal growth cone collapse in response to a topical application of ephrin. In "old-style" teaching, we might have spent a mere 90 s on the entire figure, simply telling the students what dose was chosen, what time point was selected, and what controls were performed. In the CREATE classroom, in contrast, we challenge the students to dissect each aspect of the experiment and figure out how each of these parameters was determined. We consider why the collapse assay needed to be characterized empirically (i.e., you can't buy a commercial kit for analysis of a phenomenon you discovered yourself) and how, specifically, the authors designed, performed, and interpreted their dose response, time course, and antibody specificity tests. Taking time over this figure, which is merely a precursor to the bulk of the article's data, helps students see how novel phenomena are actually approached in laboratory situations. We do not expect students to remember the particulars of this experiment long term; rather, the next time they see a dose-response figure in a different article, we expect they will recognize and understand it. In this way, the CREATE method is constructivist (5), aiming at coaching students in building their own understanding of the approaches taken in a given series of experiments. In the CREATE classroom, more time is spent on activities at higher levels on the Bloom scale (analyzing, debating, and designing) than on the less cognitively challenging lower levels (naming, classifying, and defining) typical of many lectures (3, 4). With the ongoing explosion of information in 20th–21st century biology, we feel it important that students learn approaches that can be adapted to new information as it arises and develop a facility with data-analysis skills rather than focusing on memorizing or engaging only superficially with content that will rapidly age.

We evaluate students based on *1*) the concept maps, cartoons, figure annotations, and other homework assigned in preparation for class and collected in student notebook/portfolios, *2*) participation in class discussion and analysis of experiments, contributions to small-group work, and participation in grant panel debates, and *3*) performance on open-book/open-notes exams. As preclass homework, students construct concept maps and cartoon experiments to define for themselves "what went on in the laboratory" (as opposed to "what was found," i.e., the results presented in the figure), define hypotheses in their own words, and annotate figures. Students also draw conclusions from the data, summarizing their interpretations on template forms of our design. The templates prompt students to take the final step of defining control and experimental cases, determining which panels of figures or lanes on gels, for example, should be compared directly, and coming to their own conclusions about what the data mean. We give two open-book/open-notes exams and twice per semester collect and examine the notebook/portfolios in which students compile their data analyses, homework assignments, and experiments they designed. An example of a typical homework assignment would be asking students to take the data from a table in one of the articles and represent it in graphical form and then interpret the graph that they sketched. Exam grades, notebook grades, and class participation factor equally into the final grades.

Keeping up with the notebook/portfolios by applying the CREATE tools to each article is the key to student success, as these at-home activities prepare students to think on their feet as they critically analyze the data in class. Working through the sequential CREATE steps demystifies the process of reading and analyzing an article, helping students achieve fluency in the universal language of data analysis. At the same time, well-prepared students free faculty members from the drudgery of describing every experimental detail, allowing the instructor to coach students in discussion of the significance of the findings, contributing insights and sidebar stories from their own research experiences.

Open-book tests reflect the reality that no working biologist we know walks into their laboratory and carries out a series of experiments based exclusively on memorized information without looking at any written material, logging on to a computer, or conversing with anyone. Research science is an open-book activity. The exam questions, often short-essay questions or requests for critical analysis of data, reflect issues previously discussed in class. Successful answers are ones that demonstrate that students have the data-decoding skills and analytical ability that lead to genuine understanding of the article's findings.

A unique feature of the CREATE approach is that it goes beyond data analysis to give students insight into the personalities and motivations of researchers. Late in the semester, students generate an e-mail survey for the articles' authors, posing questions aimed at providing a behind-the-scenes look at the people behind the papers. Students' questions range from personal (What made you decide to become a research scientist? How do you deal with rejection of a grant or paper?) to broader issues (Do you have to be a straight-A student to

become a researcher? What would be your "dream discovery?"). The range of responses received from authors (including graduate students, postdocs, and professors) reveal "scientists" to be a varied group of individuals with diverse attitudes and motivations, much like the students themselves. This aspect of CREATE humanizes science, helping to dispel students' preconceptions of scientists as antisocial geeks and of research as an activity open only to geniuses. In addition, the scientists who responded to our survey seemed to appreciate this "outreach" opportunity to share their experiences with our students.

Like the "use what you have" home decorating shows, where the style maven, without spending a dime, reconfigures your living room using furniture you already own, our approach allows Biology faculty members to capitalize on skills they already have but may only rarely bring to the undergraduate classroom. Biology professors know how to design research studies, evaluate scientific findings, and run laboratory meetings. The CREATE class takes advantage of these abilities, running as an active discussion in which methods are deciphered, results presented, and interpretations debated. Because students prepare on their own for class, the CREATE professor need not review every basic issue. Instead, the professor is freed to model "thinking like a scientist"–using sophisticated logic and data analysis skills developed over years of study–during every class. Faculty members using CREATE shift the challenge of learning to the students, who construct their own understanding as they work through the steps of the process.

Our approach aligns well with recommendations that students must take charge of their own learning (5, 16) as well as with the call for science teaching to focus on the research process (2, 7, 12–14, 16). CREATE faculty members do not "describe biology" through lecture but instead establish a classroom environment within which students discover biology for themselves. Students decode the biological research process through their own efforts, as they work to critically analyze, interpret, and understand data. Despite the relatively narrow content focus, students reported that they reviewed "all the biology and cell biology I ever learned" during the semester, said the CREATE approach helped them with scientific reading in general, and developed more positive attitudes about research/researchers (see Ref. 8 for student interview excerpts).

We suggest that the CREATE approach should be applicable to all areas of biology and encourage physiology faculty members to consider a parallel approach: limiting content, reading related articles in sequence, withholding summaries in favor of close analysis in class, and guiding students in getting their own questions answered through e-mail interviews of authors. Abandoning the lecture format may initially feel like stepping off of a cliff, but there are practical as well as cognitive advantages to emphasizing the analytical approaches typical of one's subject in the undergraduate classroom. Professors already know the logic of their discipline and how to "think like a biologist/physiologist/chemist/geologist." They have written and rewritten manuscripts, grants, and book chapters in response to criticism from colleagues, critically analyzed numerous articles, and given talks at conferences. Professors using CREATE spend class time posing challenging questions, moderating discussion, and guiding students in clarifying their explanations and defending their ideas. By limiting lecture in favor of active analysis, the CREATE instructor can devote class time to modeling the scholarly thinking characteristic of their field–something all of us already know how to do.

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