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Selective Use of the Primary Literature Transforms the Classroom Into a Virtual Laboratory

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ABSTRACT

CREATE (*c*onsider, *r*ead, *e*lucidate hypotheses, *a*nalyze and interpret the data, and *t*hink of the next *e*xperiment) is a new method for teaching science and the nature of science through primary literature. CREATE uses a unique combination of novel pedagogical tools to guide undergraduates through analysis of journal articles, highlighting the evolution of scientific ideas by focusing on a module of four articles from the same laboratory. Students become fluent in the universal language of data analysis as they decipher the figures, interpret the findings, and propose and defend further experiments to test their own hypotheses about the system under study. At the end of the course students gain insight into the individual experiences of article authors by reading authors' responses to an e-mail questionnaire generated by CREATE students. Assessment data indicate that CREATE students gain in ability to read and critically analyze scientific data, as well as in their understanding of, and interest in, research and researchers. The CREATE approach demystifies the process of reading a scientific article and at the same time humanizes scientists. The positive response of students to this method suggests that it could make a significant contribution to retaining undergraduates as science majors.

DESPITE the stunning success of research science in the last half of the 20th century, there is a general consensus that the teaching of science to college students has not made parallel gains (Chickering and Gamson 1987; Felder 1987; American Association for the Advancement of Science 1989; Seymour and Hewett 1997; Glenn Commission 2000; McCray *et al.* 2003; National Research Council 2003; Handlesman *et al.* 2004; Alberts 2005; Cech and Kennedy 2005). Indeed, the vast increase in scientific knowledge has potentially contributed to this problem, because instructors feel compelled to teach their students an ever-growing body of facts, and students spend more time honing their memorization skills than they do learning how to understand and evaluate scientific data. The sense of discovery felt by the scientists involved in generating this new information is unfortunately rarely communicated to undergraduates. Textbooks, for example, typically present the growth of scientific knowledge as a gradual increase of information over time, ignoring the blind alleys, digressions, and unexpected findings that in fact characterize research science. Although laboratory courses are often proposed as a complement to lecture classes that rely on textbooks, students in lab classes too often test hypotheses developed by others, perform experiments for which the results are known, and fail to become intellectually invested in their results. Many undergraduate science majors do not have the opportunity to carry out individual laboratory research projects; even for those that do, the short-term nature of most such projects makes it difficult for students to visualize how their work fits into the overall scientific progress of the laboratory. As a consequence, many undergraduates have little sense of how scientific

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knowledge is generated, how research projects progress over time, or of how scientists think about and actually do research. These factors often combine to induce disappointed students to drop out of science majors (Seymour and Hewett 1997; Alberts 2005; Cech and Kennedy 2005), a problem that is exacerbated for minority students, who remain underrepresented at all levels of academic science (National Science Foundation 2002; American Council on Education 2003; Bok 2003, Atwell 2004; total enrollment by gender/race/ethnicity is at http://www.aamc.org/data/facts/2003/2003school.html).

As one approach to addressing these problems, we have developed CREATE (*c*onsider, *r*ead, *e*lucidate hypotheses, *a*nalyze and interpret data, and *t*hink of the next *e*xperiment), a teaching method that involves students in reading and analyzing the primary scientific literature while simultaneously exposing them to the intellectual excitement and challenges experienced by the scientists who carried out the work under discussion. In contrast to other approaches that use single or partial journal articles in the undergraduate classroom (Janick-Buckner 1997; Herman 1999; Muench 2000; Chowe and Drennan 2001; Klemm 2002; Herreid 2004), CREATE focuses on a sequence of articles that reports a single line of research from one laboratory as it developed over a period of years. In addition to promoting the development of skills that students need to understand and analyze scientific information, the CREATE approach introduces students to issues regarding the nature of science (Lederman 1992; Schwartz *et al.* 2004) and to the creative roles played by individuals in scientific research. CREATE is not meant to substitute for standard lecture classes and hands-on research projects, but rather to supplement and complement such classes. Consistent with the recommendations of recent reform documents (American Association for the Advancement of Science 1989; Bransford *et al.* 1999; Glenn Commmission 2000; National Research Council 1999, 2000, 2003), CREATE involves in-depth study of a single line of scientific research, which takes advantage of the narrative nature of science (Muench 2000; Kitchen *et al.* 2003). A CREATE module consists of four articles, published in sequence from the same lab, that are read and analyzed sequentially, providing insight into the evolution of ideas as a project develops over time.

As outlined below, CREATE employs a unique combination of pedagogical tools and active classroom approaches that facilitate learning (Bransford *et al.* 1999; Siebert and McIntosh 2001; Chin *et al.* 2002; Zohar and Nemet 2002; Osborne *et al.* 2004). We had two overall goals. The first was to develop each student's ability to think like a scientist in terms of designing experiments, analyzing and interpreting data, and critically evaluating results as well as proposed follow-up experiments. Our second goal was to increase the students' interest in science and scientific research by providing them with insights into the experiences, both intellectual and personal, of working scientists. We tested the ability of CREATE to meet these goals in an elective course for juniors and seniors that required Genetics and Cell Biology as prerequisites. The 3-credit CREATE class met twice weekly for 75 min/class with a single instructor (S. G. Hoskins), and the class size ranged from 12 to 25 students in the three separate classes (51 students overall) that are discussed in this report. We focused on a module of four articles from the laboratory of Christine Holt (Cambridge, UK) (Nakagawa *et al.* 2000; Mann *et al.* 2002, 2003; Williams *et al.* 2003) that analyze the role of ephrin/eph-mediated signal transduction in axon guidance during optic nerve development. Our assessments indicate improvements both in the ability of CREATE students to think scientifically and in their confidence in their abilities. Importantly, CREATE students also developed a new appreciation for science and for scientists as individuals.

THE CREATE METHOD

In our previous experience, when students were assigned to read research articles, they often read only the abstract, introduction, and discussion, merely glanced at the figures and tables, and accepted the authors' conclusions without developing a thorough understanding of the experimental results on which they were based. To avoid this problem, we do not initially provide CREATE students with the articles' titles, abstracts, discussion/conclusion sections, or the authors' names. Using the specific exercises outlined below, we challenge the students to understand the methods, explain the experimental designs, and interpret the data as if they had made these findings themselves. Class discussion focuses on figure-by-figure data analysis and interpretation, with the professor acting as "lab head" and discussion leader, guiding students through evaluation of experiments and in synthesis and application of scientific concepts—higher-level cognitive activities known to facilitate understanding (Bloom *et al.* 1956). Mini-lectures of 10–15 min are occasionally used to review essential background material, but most class time is spent in whole-class or small-group discussion. After analyzing each article, the students generate their own proposals for what the next experiment would be if they were carrying out the research themselves. They then discuss and debate their ideas with other students in an exercise meant to model the peer review that real science undergoes. As the CREATE process repeats with each module article, students experience how an actual research project develops over time. To enhance the students' understanding of the personal experience of scientists carrying out research, students communicate with some of the article authors by e-mail, in which they pose their own questions about researchers' motivations and experiences. Sequential steps of the CREATE process are summarized below:

Consider: We explain to the students that, as they read each article, our goal is for them to work through the data as if they had generated it themselves. To facilitate this, they are given each section (Introduction, Results and Methods, Discussion) sequentially and they are not provided with the title and abstract of the article nor with the names of the authors. Although some students may try to circumvent this process by using the Internet to obtain the complete article prematurely, we did not find this to be a problem in our CREATE classes. Even if students do "look ahead," it does not significantly interfere with their learning experience because most of the CREATE activities require the students to think for themselves.

The students are introduced to the principles of concept mapping (Good *et al.* 1990; Novak 1990, 2003; Allen and Tanner 2003). They are then assigned to read the Introduction section of the first article and to construct a concept map of it by defining key terms and creating appropriate diagrammatic linkages between them. Such maps highlight the range of issues that the article addresses and alert students to concepts that they need to review in preparation for reading and analyzing the article. This exercise empowers the students to take charge of their own learning (Novak and Gowin 1984; Brooks and Brooks 1993).

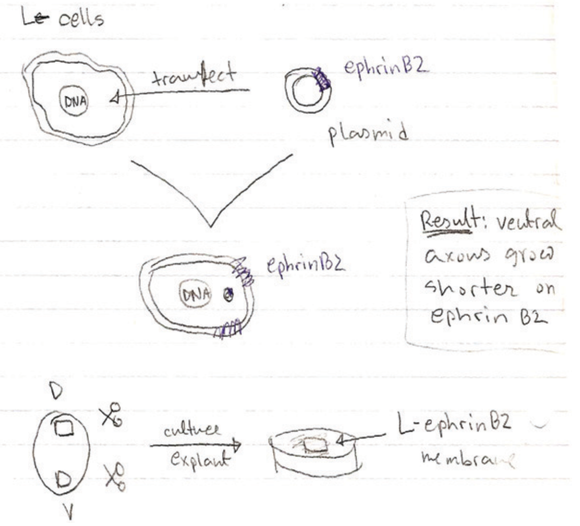

Figure 1.—Sample student cartoon. To link the information given in the Methods sections with the data represented in figures and tables of the Results, students make sketches to illustrate the experiments that were performed. The student cartoon above illustrates an experiment in which mouse L cells were transfected with frog ephrinB2 and then frog retinal explants were challenged to extend axons on membrane carpets made from the L cells. Creating these visual representations facilitates understanding of the hands-on lab work that led to the results reported.

Read: Students read the Methods and Results sections of the article. Then they are instructed to go through the Results section figure by figure and, using the information in the Methods section, "work backwards" from the data presented in each figure (or table) to determine how the results were obtained, that is, what experiment was performed. Students (1) diagram each experiment in a cartoon format that illustrates the methods used, (2) annotate the figures by adding clarifying labels, and (3) write their own descriptive titles for each cartoon and each figure. We emphasize that the cartoons are meant to depict what was physically done in each experiment (see Figure 1 for an example of a CREATE student's cartoon), not to show what the results were or to restate what the authors said about the experiment. We require the students to draw a sketch for this step, rather than a flow chart. We find that creating a visual representation of what was done in each experiment is critical for the students' ability to interpret the resulting data. In the annotation step, the students use the information from the figure legend to instructively label each panel in the figure. They note which panels serve as controls and which are experimental and also categorize the type of experiment depicted, *e.g.*, "dose-response histogram." To carry out this step, students must look closely at the figures and their legends to determine exactly what is represented in each panel. Finally, writing their own titles for the figures as well as their cartoons gives the students a sense of ownership of the material and can help them to distill the essential information. For example, one student rewrote "Ephrin-B overexpression at the chiasm induces precocious ipsilateral projections in the early tadpole" as "Early Ephrin-B drives axons ipsilaterally."

Each of these activities promotes the development of conceptual linkages between what was actually done in each experiment and the data that were obtained. These methods encourage visualization and abstraction as well as integrative and synthetic thinking, all of which facilitate learning (Bloom *et al.* 1956; Kozma and Russell 1997; Foertsch 2000, Zull 2002; Yuretich 2004). These steps—the cartooning, annotation, and retitling—are done by students as homework in preparation for class. Thus, students arrive in class familiar with the article and ready to participate actively in class discussion.

Elucidate the hypotheses: Research articles typically involve numerous individual experiments, each of which plays a role in the final conclusions. Introductions to articles, however, tend to emphasize one major finding, and the Materials and Methods sections often describe the methods without linking them to individual figures or tables. The students triangulate between their cartoons, annotated figures, and rewritten figure/table titles to dissect the "anatomy" of the study by identifying each individual experiment and defining the specific hypothesis that it tested or the question that it addressed. The student-generated hypotheses or questions are written above the figure or table to which they apply.

Analyze and interpret the data: Students analyze each figure using CREATE analysis templates (supplemental Figure S1 at http://www.genetics.org/supplemental/), which build on the work done in the previous steps and guide them in determining which panels in a figure (or numbers in a table) should be compared directly. As they fill in the templates, students compare the control and experimental panels that they identified during figure annotation, relate the results to the hypothesis or question that the experiment addresses, and begin to draw conclusions. Students also explicitly relate the findings to the hypotheses previously elucidated, judge how convincing they find the data to be, and note any questions that they would like to ask the authors. Templates filled out as homework prepare students for active discussion of the outcomes of experiments. Templates are always used for article 1 of the module. Some students continue to use them for subsequent articles while others are able to generate their own analyses after their initial experience with the templates.

Class discussion of the articles focuses on data analysis, and the instructor runs the discussion much like a lab meeting. Some analysis is done in small groups, with students charged to work together and then to report their conclusions back to the class. When all of the figures have been analyzed and thoroughly discussed in class, students record their overall interpretations and conclusions as a list of bulleted points—points that they think would be worth including in a Discussion section. Only after completing their own lists are students provided with the actual Discussion section of the article. After reading it, they make a similar list of points based on the authors' conclusions. Comparing the two lists highlights the role of interpretation in science, showing that data may be interpreted from several different or even opposing viewpoints (Germann and Aram 1996). Finally, students make a summary concept map, this time using the articles' figures and tables as central concepts and creating linkages between them that indicate the logical flow of ideas in the article. After the intense and detailed analysis of individual experiments, this is an opportunity for the students to step back and weave the individual parts of the article into a "big picture."

Think of the next experiment: Each student imagines that he or she is an author of the article just analyzed and asks: What experiments should be done next? The students diagram two of their proposed experiments in cartoons that are discussed in class. To model the scientific peer-review process, the class collaboratively devises criteria for judging proposals and then divides into several three- or four-person "grant panels," each of which selects one of the student experiments to "fund." Often, different groups choose different "best" experiments. Such an outcome contrasts with some students' preexisting views of scientific research as a linear path with one obvious step after another. Grant panel discussions help students hone data interpretation and verbal logic skills (Vanzee and Minstrell 1997; Marbach-Ad and Sokolove 2000; Zohar and Nemet 2002) and foster an understanding of how science works by modeling the discussions and debates that are characteristic of research laboratories (Steitz 2003) and actual grant panels.

Final steps and reiteration of the CREATE process: After the CREATE methods are applied to the first article, the process is repeated with each additional module article, although in these cases there is the added excitement of discovering whether the experiments reported in the subsequent articles match any of the students' proposed experiments. For students who independently had the same idea as the authors, the experience reinforces the idea that they are learning to think like scientists. For students who have different "next experiments," the experience underscores the idea that real projects can move in many different directions. This realization contrasts with some students' previously held beliefs that science is very predictable and that scientists always know what their results will be (Table 1 and supplemental Table S1 at http://www.genetics.org/supplemental/). Analysis of the subsequent articles generally proceeds more rapidly because the students are now familiar with the experimental system as well as with the CREATE tools.

Interviews with scientist–authors: At the conclusion of the module, our *first* class of CREATE students prepared a survey of 12 questions (supplemental Table S2 at http://www.genetics.org/supplemental/) that was e-mailed to each author of the four articles, a group that included technicians, graduate students, postdoctoral fellows, and principal investigators. One author visited the class and was interviewed directly in a session that was videotaped. Subsequent CREATE student cohorts read the e-mail interviews and viewed the videotape generated by the first class; thus, authors were contacted only once. CREATE students' questions ranged from scientific ("How did you choose your research area?") and ethical concerns ("Have you ever encountered any ethical issues and how were they resolved?") to more personal issues ("Did you ever wake up and just want to give up? How did you deal with it?"). The range of responses from 10 different authors (50% response rate) to the same questions highlighted for students that scientists are individuals with different motivations and goals. Especially important for our students was the realization that their previous stereotypes of scientists as "antisocial" and as "geniuses" were inaccurate (Table 1 and supplemental Table S1 at http://www.genetics.org/supplemental/), which evoked comments such as: "I realized [for the first time] that scientists are people like me. . . . if I wanted to, if I worked at it . . . I could become a scientist" (supplemental Table S1 at http://www.genetics.org/supplemental/).

Assessment: Many studies that describe methods for engaging undergraduate students with the primary scientific literature have been published (see, for example, Janick-Buckner 1997; Herman 1999; Muench 2000; Chowe and Drennan 2001; Mangurian *et al.* 2001; Klemm 2002; Herreid 2004). We did not directly compare the CREATE approach with these other methods because we did not design CREATE solely as a method for reading the primary literature. Instead, the CREATE approach uses a linked sequence of articles as a portal into the research laboratory such that the students experience many of the cognitive activities that scientists use in their daily work. CREATE students also had the opportunity to learn about the personal experiences of the scientists involved in the work. Our goal was to achieve a synergy between the intellectual and personal aspects of research science that would enhance students' interest in science as well as their abilities to read and understand scientific literature. For these reasons, we chose to use pre- and post-course testing, an established approach in science education, to determine whether the students made gains in these specific areas (Edwards and Fraser 1983; McMillan 1987; Ruiz-Primo and Shavelson 1996; Stoddart *et al.* 2000; Bissell and Lemons 2006; Bok 2006).

To determine whether there were improvements in the students' ability to critically read and interpret data, we administered *c*ritical *t*hinking *t*ests (CTTs; adapted from http://www.flaguide.org/) pre- and post-course. CTT questions required the use of general data analysis skills and were not specific to the CREATE module. To determine whether the CREATE approach facilitated the ability of students to understand and integrate concepts related to the module content, we carried out pre- and post-course assessments in which students constructed concept maps based on seed terms (Novak 2003). (Note that these assessment maps were distinct from previously described concept maps used as learning tools in the CREATE classroom.) Finally, to explore students' understanding of the nature of science and their attitudes toward science and scientists, we used oral interviews (Glaser and Strauss 1967; Novak 1998; Ary *et al.* 2002) and an online, anonymous Self-Assessed Learning Gains survey (http://www.wcer.wisc.edu/salgains/instructor/). The latter two assessments also provided information on the students' own perceptions of how their critical thinking and data analysis skills had changed and gave us feedback on students' reactions to the course format.

CREATE, in all three implementations, was demonstrated to improve students' critical thinking skills (Figure 2) and their ability to read/analyze scientific literature and understand complex content (Figure 2 and supplemental Figures S2 and S3 at http://www.genetics.org/supplemental/). Students taught using the CREATE method self-reported increased confidence in their reading and analysis abilities, as well as enhanced skills that transferred from the CREATE class to other science classes (supplemental Figure S4 at http://www.genetics.org/supplemental/). They also exhibited improved understanding of the nature of science, increased interest in science participation, enhanced personal engagement with science, and more positive views of science and scientists (Table 1; supplemental Figure S4 and supplemental Table S1 at http://www.genetics.org/supplemental/). Thus, CREATE students experienced gains in both their academic skills and their perception of the scientific enterprise.

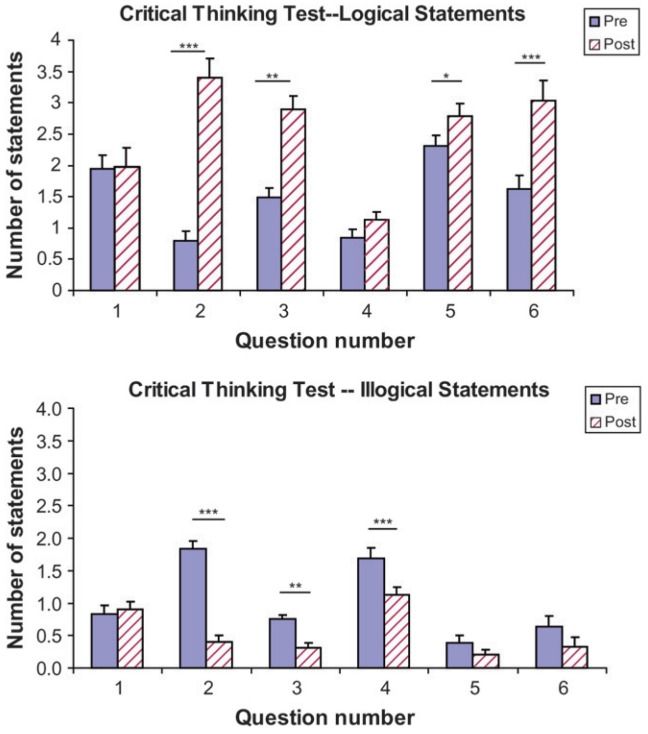

Figure 2.—Summary of results on CTT. Students who took CREATE classes demonstrated gains in their ability to critically analyze data and draw logical conclusions. CTTs requiring data interpretation were administered pre- and post-course. The CTT was a 30-min closed-book activity, designed on the basis of the Field-tested Learning Assessment Guide (http://www.flaguide.org/), in which students read and responded to six "story problems" requiring them to interpret data presented in charts or tables and explain why they did or did not agree with the conclusions stated in the problem. This test was not based on material covered in the CREATE modules. Horizontal bars with asterisks indicate questions on which significant increases in numbers of logical justifications (statements) or decreases in numbers of illogical justifications were seen post-course, compared to pre-course, in written responses to CTT questions ($^{***}P < 0.001$; $^{**}P < 0.02$; $^{*}P < 0.05$; paired *t*-test). These data suggest that students' critical thinking and data analysis abilities improved during the CREATE semester. For each question, we included only data for students who answered the same question in both pre- and post-tests; thus, the N is smaller for questions 4, 5, and 6. Error bars indicate standard error. Questions 1–3, $N = 48$; question 4, $N = 42$; question 5, $N = 34$; question 6, $N = 24$. Additional information regarding the CTT appears in the supplemental data at http://www.genetics.org/supplemental/.

TABLE 1

Post-course interviews: student comments about CREATE and its effect on their views of science and their own abilities

Class 1	Class 2	Class 3
	Reaction to the CREATE approach	
Before [the CREATE class] I used to read the entire paper and then go to the pictures. Now…it's figures first, then text…. I'm more of a detective now. I could, like, pinpoint certain words and look it up…. I could find the main part of the figure. And I wasn't able to do that before, I would just read, to read…. I would only get it [the overall point of the experiment or article] after I read the whole paper, and probably went through it with like, a professor or something, or in class? But now I think I'm good on my own. I could decipher what the message is, on my own. (S2)	I would recommend it to every student taking a science major or nonscience major, and I think this class should be a prerequisite in order to graduate with a science degree. I think it's a very strong class that expands all the students' minds. … And I think that this course will definitely help anyone who wants to pursue a career a science, whatever that might be, because it helps you really really understand what science is about. It's not just a textbook that you read and memorize things; you actually learn so much. (S1)	It's the most effective way of teaching that I've ever had, especially in a science course. Because in [real] science you're not really given exams, and you're not asked, like, to memorize things—you're asked to analyze and understand—and I think this class really focused on analyzing and understanding, as opposed to memorizing. (S3)
	Transfer of the CREATE approach to other classes	
I walked away with skills that are going to help me in every single class I take again, and even in life, really. I feel like I can take on my own taxes this year! [laughs] Just being able to sit down and focus and not get bogged down. (S6)	I had a paper for one of one of my other classes—called Muscle and Nerve—I had to do a review paper on a presentation I did. And [because of the CREATE class] I have never read through papers so quickly than I did those five papers, and I could actually sit there and say, "Oh, this makes sense; OK. This is dose response to creatine in embryonic umbilical cords. I'm like, oh, that was so great! I didn't think I would apply it so quickly … (S7)	I took microbiology—we read a paper then—if I read it again it would probably be totally different now, with this approach…. If I had to do it all over again, I'd probably want to take this course after the first two intro courses—because it allowed me to interpret information differently; "think outside the box" so to speak…. This pretty much required us to do all the work ourselves….It wasn't just a bunch of facts that we just had to accept. We had to actually question it. (S8)
	Understanding of how scientific research is carried out	
I expected: they had a theory, they proved that theory; that's it. [Now] I see it's more like a blind person placed in a room and trying to feel around as to what they think a structure may be; and even when they think a structure is "that" they're still not sure as to what it is, but they can kind of come up with what it is, based on the shape, and touching it, and comparing it to another structure that's next to it….(S4)	I thought [before] from lab to lab they had to *buy* each others' things; like if I needed a knockout mouse I would have to buy it? But it actually turned out to be a give and take, like "my stuff is your stuff"—I didn't know that. Another thing is…a lot of revision goes into these papers…. which shows you that it's not all cut and dried; it's not all clear; and that even top grade scientists can make mistakes…. It's like a circle; if those papers weren't passed around and read from one person to another, from one student to another, new ideas won't come up…. It's a network. It's a network of thoughts. (S10)	As far as research, I learned that one answer can lead to so many different things, and every person has their own ideas about where the ideas will lead. And I thought that was like the coolest thing—you know, you could have, like six different groups doing the same research, and get the same result; then go in different directions. And I thought that was interesting, because I [had] always thought everybody would go in the same direction. (S3)

(*continued*)

TABLE 1

(Continued)

Class 1	Class 2	Class 3
	Thinking like a scientist	
I think the biggest, kind of like enlightenment for me [laughs] is that you can have your own ideas . . . and you can come up with your own interpretation of things and not necessarily be "wrong." I think there is a lot more creativity behind science than most people are aware of. . . . Through this course, the creativity, for me it's been like "Wow I can really think about these things and not just take in this data and say "OK this is it; I can't question it." For me that was the biggest insight. It was like "I can question it and maybe come up with an alternate explanation. And it might be, it might not be, but at least I'm 'allowed' to do so; there's no big law against that." (S12)	You need to be skeptical in science—not just take the data for what they say it is. A lot of times [before], we study papers, we just look at the discussion and the title and take that for granted, and this class has taught us to be skeptical—to be scientists, and look at the data and try to analyze it for ourselves and see if we get the same conclusion that they got . . . from the data. (S6)	My scope of thinking has been widened. First, I have more ideas pulled together and I'm using my initiative much more. And I'm being innovative and I'm being very active; right on my feet thinking; and I have more interest in doing the work. My interest has been boosted up. It's very easy; it's made open for me to bring out the best out of me and then to join with others. The other thing too; in that class we learned to work together. We had different types of people in the groups, so we were learning something else. In addition to our individual capacities we were learning how to exchange ideas with others. (S2)
	Personal connection to science and scientists	
I believe scientists are people; they are like everyday people. Anyone can be a scientist. . . . Before I used to think that scientists were rigid people who wore lab coats and didn't talk to anyone [laughs] but from the class and from the responses we got from the e-mails I see that scientists are "people persons," everyday people; meaning they didn't have to be super-geniuses or really up in status to become a scientist; with connections or anything like that. (S1)	I definitely have changed my perspective of scientists. Before I thought being a scientist was a job where you were antisocial; cooped up in a lab, and that's it. And I always figured people who become scientists are not "people people," and I don't think that any more. (S11)	I got to see they're like everyone else. . . . Growing up, you think of scientists as geniuses like Einstein or whatever—but they have a job just like anyone else, and the concepts aren't that difficult . . . anyone could think of another experiment. You don't have to have a super-high IQ. It's just thinking up the work and being truthful with the data and not tweaking your results to match what you want it to be, but just coming up with a hypothesis, running the experiments, writing the data as you see it and trying to analyze it as best as possible. (S4)
	Increased interest in becoming a scientist	
I think I'm a little bit more confident that I could do it if I really wanted to go in that direction. I think the human aspect of it and the way that research is carried out by individuals, that whole experience has changed for me. I feel that if I wanted to do it I could. Like, there's somany people that help you along the way and get you started, and just the whole thought process, to think of experiments and to do them, is interesting to me. (S8)	I feel like this course . . . has made me become less intimidated. . . . because these people are just like you and I—you can sit here and wonder why the sky is blue—and you take your question and you put it to the test. . . . This course has definitely helped me with knowing that scientists are just people, just like you and I. Whatever work they're doing. . . . I can do it myself, you know? . . . I'm not a scientist, [but I'm] contemplating if I should be! . . . I'm starting to like research. What I love about it is the creative part of it. And I'm questioning. . . . can I still have that while being a medical doctor? This class has kind of changed my life in a way. (S3)	I myself could be a scientist now. Before I was like "[Only] some kinds of people can be scientists" and it has to be like these geniuses, who were, you know, like eight times smarter—I learned that it can be anybody. Anyone can be a scientist; it has to do with having a passion to do research, and just a drive, and not to get bogged down by failed experiments and things not going right, but just to go through a process, because there's a thinking process you have to go through, of elimination, and trying, and experimenting. (S5)

Representative comments of CREATE students about the CREATE approach and its effect on their views of science and their own abilities. Interviews lasting ~20 min were conducted at the end of the semester and audiotaped. Interview questions examined students' overall reaction to the CREATE approach, whether the course had affected their ability to "think like a scientist," whether their views of science or scientists had changed over the course of the semester, whether their scientific reading skills had been affected, and whether their confidence in their ability to participate in science research had changed. We made transcripts of the interviews from the first class and used a constant comparison approach to categorize responses on the basis of broad themes that emerged in multiple interviews (Glaser and Strauss 1967; Novak 1998; Ary *et al.* 2002). We then analyzed interviews of subsequent cohorts on the basis of the similarity to or difference from the initially defined emergent categories (centered headings). The number following each quote corresponds to a distinct student (S) participant. Class 1: $n = 12$; class 2: $n = 13$; class 3: $n = 12$.

CONCLUSIONS

To our knowledge, CREATE is the only multiply assessed educational method shown to increase both understanding of *and* interest in scientific research among undergraduate students. In this regard it is also notable that 64% of our CREATE students were members of minority groups that are traditionally underrepresented among students progressing on to careers in science. We anticipate that the CREATE method will benefit students from a variety of backgrounds, however. Our data suggest that the CREATE approach could significantly alleviate the well-documented disengagement of many college students from science (Seymour and Hewett 1997; National Science Foundation 2002; Alberts 2005; Cech and Kennedy 2005). It is also important to note that the CREATE approach does not require any significant financial expenditure and therefore will be accessible to instructors at many different types of institutions.

We believe that the CREATE curriculum, which encourages students to think of themselves as scientists, will complement and enhance students' experience of traditional lecture-based science teaching and inquiry lab classes. Although CREATE was initially developed for use in an upper division elective course with relatively few students, we believe that elements of the CREATE method can be effectively adapted for use in lower division and larger science classes. The approach is adaptable to content in any area of science, and articles can be chosen to be accessible to students at a variety of levels. Earlier exposure to CREATE analytical approaches may help students to develop critical analysis skills early in their college careers so that they can benefit from them throughout their college coursework (Braxton *et al.* 2000). Correspondingly, the earlier that students develop an appreciation for the creative nature of scientific investigation and, in particular, recognize that they, too, could make an important contribution to science, the less likely it is that they will drop out of science majors.

In contrast to K–12 teachers, most instructors at the college level have not had formal training in how to teach effectively. Many faculty members in the sciences obtain academic positions and promotions on the basis of their research accomplishments. In this respect, we believe that the CREATE approach can benefit instructors as well as students because, rather than requiring instructors to learn a completely new teaching method, it encourages faculty members to use skills that many employ in their laboratories every day. The CREATE class is very similar to a lab meeting in which methods are described, results reported and analyzed, interpretations discussed, and future directions debated. In short, by using primary literature as a portal into the activities of working scientists, and by guiding class discussions rather than lecturing, instructors can create a virtual laboratory in which every student is a scientist.

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