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CREATE a Revolution in Undergraduates' Understanding of Science: Teach through Close Analysis of Scientific Literature

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The teaching of science to undergraduates aligns poorly with the practice of science, leading many students to conclude that research is boring and researchers themselves are antisocial geniuses. Creativity, a key driver of scientific progress, is underemphasized or ignored altogether in many classrooms, as teaching focuses on the complex integrated concepts and voluminous amounts of information typical of STEM curricula. Faculty, largely untrained in science education per se, teach largely as they were taught, through lectures based in textbooks. This situation could change, and students' understanding of research practice could be fostered relatively easily, if faculty began teaching classes focused on the journal articles they read in their professional lives. In this essay, I outline a novel scaffolded approach to guiding students in a) deciphering the complexities of scientific literature and b) the process of gaining new understanding of who scientists are, what they do, how they do it, and why.

"Activity without understanding seems to be a regular feature of classroom life for science students in American schools."[1]

"Argument and debate are common in science, yet they are virtually absent from science education."[2]

"All too often biology education appears to be defined by trivia – an impression that can alienate students from what is an inherently highly personal and intellectually fascinating subject."[3]

Science professors want students to learn how to think deeply and critically about key concepts; retain understanding developed in class; and sharpen analytical abilities that can be applied in novel situations. Yet

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what many science courses actually require from students – mere recall – does not promote the development of these skills. An undergraduate can complete multiple science courses by passing exams, yet have only a fragmented understanding of science. As a result, too many students lack the ability to apply creatively what was learned; for example, to relate physical and chemical principles to biological systems.[4] In upper-level electives, which should build on foundational knowledge acquired in prerequisite classes, teachers find themselves reteaching fundamentals that students previously "learned" in prerequisite courses, but did not understand or retain. Current approaches to undergraduate STEM education are failing many students, and have been for years.

The National Research Council compendium *How People Learn* proposed at the dawn of the twenty-first century that "to develop competence in an area of inquiry, students must: (a) have a deep foundation of factual knowledge, (b) understand facts and ideas in the context of a conceptual framework, and (c) organize knowledge in ways that facilitate retrieval and application."[5] Multiple lines of evidence support the argument that college science teaching errs by overemphasizing factual knowledge (via extreme content coverage) while neglecting the more complex issues of building conceptual frameworks. Students need to spend more time focused on synthesizing, extending, and applying what they have learned. Further, current teaching practices virtually ignore scientific creativity, a key driver of scientific advancement.

The nature of science is similarly neglected. Faculty members' deep knowledge of how scientific research is done is rarely communicated in the classroom, and opportunities for developing students' reasoning and argumentation skills are largely missed, as instructors and students alike confront the ballooning quantities of information. Despite years of efforts at reform supported by organizations including the National Science Foundation, the Howard Hughes Medical Institute, and the American Association for the Advancement of Science, the typical science course is still a lecture, and though faculty members may recognize the importance of higher-order cognitive skills, many test primarily for recall of details.[6]

Multiple attempts to reform college science teaching are in progress, with many focused on increasing student engagement.[7] These are often conveyed through publications, workshops for college professors, instructors, or postdoctoral fellows, and, in some cases, the addition of pedagogical training to graduate curricula. Ideally, changes in faculty members' (and future faculty members') understanding of best practices for teaching and learning will trickle down to the benefit of college students. This process, however, will be slow. Even faculty members who are motivated to hone their skills by attending teaching workshops find it difficult to shift their classroom practices substantially.[8] When this training technique has been analyzed, only limited data support its efficacy.[9]

Many reform proposals seek more engaging ways for professors to convey material from college textbooks. We need a revolution in undergraduate science education: with teaching primarily based not on textbooks but on primary literature, and classroom focus on depth rather than breadth. Of course, core factual content is necessary, but it should not dominate what students learn. Just as one does not need native fluency in Spanish in order to travel successfully in Madrid, students do not need encyclopedic knowledge of scientific facts in order to engage in scientific discourse.

In this model, "fundamentals" courses will be present, but streamlined. Broad-coverage textbooks will serve as references rather than as the backbones of syllabi, and students will learn to read, analyze, and understand primary literature, and go on to review, intelligently criticize, and propose follow-up studies for published research reports. In this process, they will be able to define for themselves what they "need to know" and look up key content to fill in gaps, without losing focus on the broader picture of the logic of a study. They will see how the experiments or descriptive studies reported in a given paper led to interpretable evidence. In an unconventional but immensely valuable step, students will gain insight into issues not reflected in published success stories through an email Q&A encounter with authors. Class sessions will resemble lab meetings that range over the nature of science, scientific creativity, the logic of study design, and the motivations of researchers, in addition to the findings and conclusions of individual papers. Such activities will help students develop a deeper understanding of the subject at hand, coupled with transferable analytical skills.

There are many ways to teach using scientific literature. These include methods for using individual data panels from a paper as the focus of class discussion and providing closely annotated online versions of papers with prompts and suggested activities for teachers and students.[10] Primary literature–focused approaches have been adapted for large-enrollment undergraduate and graduate courses.[11] My focus here is primary literature analysis through the CREATE strategy (Consider, Read, Elucidate hypotheses or questions, Analyze and interpret data, Think of the next research study, Engage with the authors), which I began developing in collaboration with geneticist Leslie Stevens in 2003.[12] We felt that focusing on primary literature would: 1) leverage professors' deep understanding of the research process; 2) reveal to students how knowledge develops in science while consolidating their conceptual understanding of, in the initial iterations, biology; and

3) provide insight into the nature of research careers and the people who choose them.

In the past fifteen years, we and collaborators have evaluated the effectiveness of this teaching and learning strategy using an array of cognitive and affective assessments of a variety of student populations, across courses taught by faculty at diverse two- and four-year institutions. The original CREATE course was designed as an elective for upper-level students. Based on student feedback, we developed an additional CREATE course for first-year students; this freshman population included both future STEM and non-STEM majors. The core tenets of the CREATE strategy are the same in both courses and both use primary literature, although the readings differ. In the upper-level "Analysis of Scientific Literature" CREATE course, papers (such as from *Science*, *Neuron*, or *Developmental Biology*) are chosen to capitalize on upper-level students' (theoretical) core understanding of STEM topics from previous courses. The first-year "Introduction to Scientific Thinking" CREATE course uses literature on topics (such as animal behavior, infant cognition, or distracted driving) that do not require a foundational physics or chemistry background. Here, a newspaper or Internet report is often used to introduce the subject before diving into the primary literature. The first-year version of CREATE thus builds on the foundation of students' high school backgrounds. While many of these students have not yet chosen their major field of study, like upper-level CREATE students, they make significant gains, for example in critical thinking, self-efficacy, and expert-like scientific thinking, as well as in epistemological maturation.[13] Thus, for students who take a single general education science course in college purely to fulfill a requirement, a CREATE course would be substantially more beneficial than a mile-wide, inch-deep overview of general biological topics, much like the high school biology courses that likely inspired some students to avoid STEM in college.[14]

CREATE courses are built using modules: sets of papers that were either written in sequence by one lab or by multiple labs attacking the same challenge. CREATE instructors typically choose module topics that are within their own expertise, and the CREATE website provides sample modules and "road maps" for how to teach them.[15] CREATE instructors do not teach by telling students about the papers, but coach the class to discover why and how a given study was done and to think deeply about how (and sometimes if) the data drive particular conclusions. Classes are run much like lab meetings: students are guided in a stepwise process of decoding and deconstructing/reconstructing research studies (see Table 1). Substantial amounts of class time are spent on discussion and interpretation of data, with students challenged to analyze the data as if it were from their own research. For this constructivist

Table 1
Steps of the CREATE Process

Step	Activities
Consider	• Concept map introduction • Review main concepts • Relate old and new knowledge • Define knowledge gaps for review
Read	• Look up vocabulary, paraphrase key sentences • Annotate figures • Represent table data in graphical form • Sketch "what went on in the lab or field" for each experiment
Elucidate hypotheses or research questions	• Retitle each figure in your own words • Use the sketch of the study to derive question being asked or hypothesis being addressed
Analyze and interpret data	• Use templates as a framework for interpreting data • Learn to cope with jargon of scientific writing • Determine the organization/logic of each experiment • Discuss data in class • Write bullet points for your own discussion • Write your own title for the paper
Think of the next experiment	• Design and sketch two different follow-up studies for a given paper • Pitch your experiment to a student grant panel • Compare/debate/defend various proposed experiments
Engage with authors or experts	• Students brainstorm questions to ask • Faculty member edits list, sends single survey once to each author or expert • Students annotate, reflect on, and discuss responses

Source: Adapted from Sally G. Hoskins and Leslie M. Stevens, "Learning our L.I.M.I.T.S.: Less Is More In Teaching Science," *Advances in Physiology Education* 33 (1) (2009).

process to succeed, students must be very well prepared for each class session. Passivity is not an option. We recognized that students were unaccustomed to prepping intensely for class and devised methods to address this challenge.

Before class, students complete a variety of homework assignments that require employing a combination of pedagogical tools, including concept mapping, sketching, and paraphrasing key sentences (see Table 2). Students build their own textbooks throughout the term by compiling homework material and annotated research papers along with background information they sought out to fill self-discovered gaps in their knowledge. These portfolios are brought to every class and may be consulted during open-book exams. While upper-level CREATE classes have foundational prerequisites, we find that students have difficulty retrieving and applying knowledge from such courses; thus, it is key for them to begin to assess what they do and do not know and fill in where needed. In class, the instructor leads a discussion of each figure and table of the paper, examining what was done in the lab or field to generate these data. This is an important step often skipped in traditionally taught courses; many students are accustomed to analyzing results without considering how they were generated. This process is time-consuming but valuable. After completing the data analysis of a given paper, students propose and debate potential follow-up studies, experiencing the creativity and open-ended nature of scientific exploration.

Important for their potential to evoke revolutionary change in science pedagogy, CREATE teaching strategies can be easily learned and applied, since they capitalize on skills that college faculty members already possess though rarely employ in the classroom. As one faculty colleague noted, "I used to spend the 48 hours before any class running around making PowerPoints. Now my prep is my last ten years' research experience in this field." CREATE faculty need not be active researchers; those who have engaged in research for their graduate degrees also have deep knowledge of this art, which is rarely brought to class. The CREATE website provides guidance for those whose research experience is limited.

CREATE pedagogical approaches align well with advice from science educators, though the strategy was developed without strong influence from education literature. Like most college faculty members, Dr. Stevens and I were largely unaware of that literature when we began crafting an approach that could take students beyond a paper's abstract when they "read" primary literature in science. Our subsequent research, including collaborations with scientists Kristy Kenyon, Alison Krufka, David Lopatto, and Stanley Lo, has documented that students in CREATE courses make significant gains in critical thinking, experimental design ability, content integration ability, self-efficacy,

Table 2
The CREATE Strategy Fosters Creativity, Synthesis, and Analytical Thinking

Pedagogical Tool	Value for Students
Concept mapping	• Explicitly relate old and new knowledge • Build metacognitive skills
Cartooning	• Learn to visualize how data were generated in the lab or in the field • Create a context for the data analysis
Annotating figures and transforming tables	• Write identifiers and clarifying notes directly onto figures • Represent data from tables graphically
Paraphrasing	• Rewrite key sentences of the paper in your own words • Learn to cope with jargon of scientific writing
Analyzing data using templates	• Determine the organization/logic of each experiment • Engage closely with data by triangulating between figures, tables, methods, and results • Interpret results critically; evaluate the roles of controls
Grant panel activity	• Practice creativity and synthetic thinking • Hone critical skills of analysis • Develop communication skills through deliberation and debate of the proposed experiments
Surveying paper authors by email	• Gain insight into the people behind the papers • Recognize that scientists are diverse, much like the students themselves • Change negative preconceptions of scientists and research careers

Source: Adapted from Sally G. Hoskins, Leslie M. Stevens, and Kristy L. Kenyon, *The CREATE Teaching Handbook*, unpublished.

and attitudes toward science.[16] Students also undergo significant epistemological maturation and show more sophisticated (scientist-like rather than novice-like) thinking after a single CREATE course.[17] These courses are straightforward to develop and inexpensive to offer (there is no wet-lab component).

In principle, CREATE courses could be easily added to college science curricula, but in practice, changing how college faculty members teach is a tall order.[18] Fifteen years of research on the CREATE strategy have produced substantial data supporting its efficacy, but faculty members do not typically design courses or classroom approaches with reference to science education literature.[19] Many are constrained by long-standing tradition; for example, around the "content" question. Professors may feel a responsibility to cover all the material of the voluminous textbooks typically assigned for college courses. Yet covering is not teaching. At CREATE faculty development workshops, it has been typical for participants from a wide range of two- and four-year colleges and universities to note with frustration that their upper-level students seem not to have a working understanding of key information covered in course prerequisites, and that first-year students do not remember the material covered in their high school science classes.

Given the explosive growth of science since the mid-twentieth century, even if students were to remember 100 percent of the facts from their foundational STEM courses, they would not be prepared adequately for future scientific, teaching, or biomedical careers, or to vote intelligently on science-based issues of public policy. As knowledge expands and new techniques are developed, professors teach material that was not discovered until well *after* their own college years, and those engaged in research use methods that did not exist when they were working on their Ph.D.s.[20] Remembering how to clone 1990s-style does not prepare one for CRISPR technology, but knowing how to read and understand primary literature arguably does. Remembering all the steps of mitosis (covered in middle school, high school, and virtually every undergraduate general education biology textbook) does not prepare students to take a stand on the question of vaccines. Whether or not students in CREATE courses continue in science, they will benefit from having the ability to evaluate scientific claims.

It is the nature of science to grow and change continually, yet traditional educational approaches imply that if students master a finite amount of content, they will be prepared to go forward. Scientists constantly push into the unknown, often developing new studies by brainstorming with colleagues and working to interpret and understand unexpected data. Students, in contrast, often perform teacher-designed experiments with predictable results, and fail to engage fully in the scientific process. That is, science as presented in typical classrooms only rarely reflects the practice of science. Many students taught in traditional ways 1) do not remember or understand deeply key content; 2) do not gain insight into the research process, the nature of science, or scientific creativity; 3) retain views of science and scientists based on negative stereotypes; 4) if STEM majors, change to a non-STEM field; or 5) if non-STEM majors, do not gain a real understanding of how research relates to societal goals.[21]

How did we reach this impasse between what we know science to be and how we teach it? Indisputably, faculty members play a key role in students' understanding of science. Yet unlike K–12 teachers, the vast majority of college instructors have limited – or no – training in the fundamentals of teaching and learning. Neither how people learn nor current research-based best classroom practices are a standard part of graduate or postgraduate curricula in science, much less in the lives of newly hired assistant professors. Lacking such guidance, many teach as they themselves were taught, modeling the behaviors of their own favorite college teachers, usually lecturers.

Teaching higher-order thinking skills has proven particularly challenging. Despite exhortations of decades of science education reform advocates, for example in the American Association for the Advancement of Science's science education reform report *Vision and Change*, the majority of college science courses are still taught in lecture format.[22] Regarding the consequences of lecture, biologist Philip Camill notes,

> Students exposed only to lecture information . . . are ill-prepared for graduate or professional school where they will be required to think independently, develop research programs, or react to novelty or uncertainty. More importantly, lectures and cookbook labs squelch student curiosity because they leave no room for students to take charge of their own learning.[23]

Today's science students are constantly exposed to PowerPoint versions of scientific processes that encourage a simplistic, linear, stepwise view, masking the often intriguingly tangled paths within research – plus the occasional serendipity – that lead to discoveries. As noted by higher education scholar Ian Kinchin, by the time a PowerPoint lecture has been prepared, the intellectual work of disentangling and making sense of the complexity of the topic at hand has all been done *for the student* before class, by the professor.[24] The student receives (and may simply memorize) a distortedly vectorial view of scientific discovery. Kinchin quotes John Dewey (definitely not discussing a PowerPoint in 1910): "Just because the order [of a lecture] is logical, it represents the survey of subject matter made by one who already understands it, not the path of progress followed by a mind that is learning. . . . The latter must be a series of tacks, zig-zag movements back and forth."[25]

Putting this cognitive gap aside for a moment, one might expect that experiencing the hands-on activities of physics, chemistry, and biology in semester-long introductory courses that include labs would naturally lead students to begin to think more like physicists, chemists, and biologists. In fact, there is evidence that student thinking becomes significantly *less* expert, thus more naive, over a semester in such courses.[26] This finding is a clear signal that there is a need to modify introductory STEM courses to introduce more cognitive challenges.

Data collected over decades indicate that many STEM-interested students leave these majors due to disappointing experiences in introductory courses.[27] Intriguingly, the attrition is apparently not because students doubt their intellectual abilities, but rather largely because they are bored or overwhelmed by the material and the competitive atmosphere. Students who persist have a hard time gaining and retaining an integrated understanding of course material or a real understanding of how research is done, or how science advances. Thus, traditional teaching of science, a route often followed by faculty members because they survived it and/or because other job pressures mean they don't have time to experiment with anything that might be better, can have far-reaching negative consequences.

Participation in undergraduate research experiences can be pivotal for college students, inspiring some to choose research careers.[28] However, if previous coursework has reinforced a distorted idea about science (such as "science is boring"; "everything is known already"; or "it's all in my textbook waiting to be memorized"), students may avoid research opportunities. Students who must work to support themselves may not have time for extracurricular research. Distortions about "who" becomes a scientist are also relevant. Popular culture conveys an image of scientists as loner geeks/geniuses, potentially alienating anyone who is gregarious and does not have a straight-A transcript from even considering hands-on research.

Editorials in science journals urge reform, yet the encyclopedic nature of many twenty-first-century textbooks makes it difficult for students to understand what science "is," much less that biology, for example, has a primary literature of its own. By significantly underrepresenting scientific processes in their illustrations, traditional textbooks for introductory biology have made it difficult for students to recognize that the books' facts and concepts were derived from carefully designed research studies.[29] Some textbooks, however, are grounded firmly in literature, for example, citing some four thousand authors over twenty chapters.[30] These help students recognize that there are researchers behind the conclusions, but still, individual research studies are compressed drastically, making it difficult for students to reconstruct the scientific thinking underlying the conclusions presented. The development of new textbooks focused in part on published data is a promising step, but there are still large aspects of the research process missing from textbooks: for example, the reality that scientists learn a great deal from experiments that fail as well as from those that succeed, and that they constantly revise their working models in the face of unexpected results.[31]

As scientists, we should look at the data and draw the obvious conclusion. Major change in STEM education at the college level is needed, and the sooner the better. Given the emphasis on grants and publications in tenure packages, however, the current situation is unlikely to change in a top-down, administration-driven way. The post hoc efforts of including teaching workshops in graduate training or using teaching assistantships (such as lab instructorships) as opportunities for pedagogical development, while positive, do little to prepare graduate students for the real rigors of designing and teaching classes. What this implies about how universities value teaching and learning compared with the many other activities in which their faculties are expected to engage is an issue for a different essay.

Refocusing science pedagogy largely on primary literature would leverage preexisting skills of faculty members and has the potential to benefit students and teachers alike, but this will require a major shift in teaching and learning methodologies. Primary literature is a key medium of science research that is usually ignored altogether in the undergraduate STEM classroom. When literature is used, it is often approached superficially, as when a student "presents" a twenty-five-page paper in five minutes, recapping the abstract and concluding paragraph, and tacitly accepting all the findings, then sitting down to watch classmates perform the same ritual. In literature and history, among other subjects, primary sources form the skeleton of many course syllabi. This can be equally powerful in undergraduate science classes, as learning to decipher primary scientific literature can help build sophisticated reading and critical analysis skills while simultaneously illustrating how new knowledge is generated, evaluated, and built upon. To gain perspective on how biological research is done, in order to really understand where the textbook information comes from, students need fluency and experience in the language of the field, as well as some sense of what it is like to be a working scientist. To gain critical thinking skills, students must engage in, and practice with, activities involving analysis, synthesis, and higher-order reasoning.[32] To learn to evaluate societal issues influenced by science, students must read beyond content-rich introductory science textbooks focused on "science basics," and learn to decode the studies whose outcomes lead to new understanding in science. Higher-order thinking can be promoted in a cost-effective way through the close analysis of primary literature.

An important aspect of the CREATE process involves challenging students to tackle the question of how to follow up a given study. After fully analyzing a given paper, students individually design their own "next experiments" or follow-up research studies (recognizing that not all research involves experimentation), and then vet each other's proposals in an anonymous grant-review exercise (no one knows who designed which study). In our experience, this is the first time in a science course, whether in middle school, high school, or college, that students have been asked to exercise creativity and design a research study based on their own original idea. In the process, students recognize that research is rarely "finished," even though papers come to definite conclusions. The process also illustrates that a given published paper could be followed up in multiple ways and that choices are made based on the most recent data and not predestined from the start of a research study.

Depending on class size, there may be four to six student panels that deliberate by looking at the logic of the designs proposed by their peers, considering how a study flows from the work just analyzed, and factoring in the originality of the proposal and the potential impact of the work proposed. Logic- and evidence-based thinking can be done by students at any level, because it is not dependent on any particular body of background information beyond what was studied in class. The fact that the CREATE approach successfully builds both upper-level and first-year students' critical thinking skills and self-efficacy argues that the traditional approach – that the "first years of a STEM major are for the basics; then we'll get to the higher-order thinking in later years" – is needlessly limiting.[33] Students at all levels enjoy the freedom to create follow-up studies and to argue collegially about which are best, using evidence to back up their claims and thereby hone critical analytic skills. The faculty member may guide individual panels' discussions with prompts, and research-active faculty may also provide insight from personal experiences on such panels.

Experience has shown that these grant panels – all weighing the same contenders – often rank proposals differently. This situation surprises the student participants ("Experiment 6 was *obviously* the best! WHY did your panel pick experiment 12?!"), underscoring how peer reviewers bring their own preferences and opinions to the table and the reality that more than one excellent follow-up option exists. Education research supports the idea that projects like this, which lack a single "correct" answer, stimulate creativity.[34] After the grant panel, students are highly interested in the follow-up the authors actually carried out, newly aware that the choice was one of a number of viable options. The process of analyzing a full paper, designing follow-ups, and evaluating them repeats with each paper in a set of two-to-four articles. This strategy allows students to build their skills and illustrates both the conceptual flow of a given project over a two- to ten-year period and shows research itself to be a creative and open-ended process. Most of our data are derived from CREATE courses in biology; findings in other disciplines, including chemistry and psychology, while less extensive, are consistent with the biology findings.

The intensive focus on research design and data analysis in the CREATE classroom is complemented by a look at the people behind the papers. Late in the term, students generate a set of questions for authors of the papers they have analyzed. These are compiled by the instructor into a single survey that is emailed to each author, including principal investigators, postdocs, and graduate students. Responses reveal insider information about the studies along with insights into the researchers' lives and motivations. These more personal reflections help dispel negative perceptions held by many students regarding research life (that it is lonely, boring, and open only to straight-A geniuses, for example). In a given semester, all authors are sent the same set of questions. Researchers seem to enjoy the opportunity to respond to students' questions, and a response rate of more than 50 percent is typical. The spectrum of responses is broad, underscoring for students that "scientists" are a widely diverse group of individuals with unique ideas and backgrounds. These replies can provide revelatory insights to questions such as:

- In your opinion, is it necessary to be "a brilliant person" to be a research biologist?
- How do you balance career and family? (if applicable)
- Do you ever get bored? Or frustrated when experiments don't work? How do you deal with it?
- What would be your "dream discovery"?
- Have you encountered any ethical dilemmas along the way? How were they resolved?
- What happens when there are differences of opinion within the lab? Who decides?
- Are there any clinical applications of your work, and if so, what are they?

- How do you choose the next step in your research program? That is, out of all the potential "research directions" to choose next, how do you decide which to do?

Students annotate authors' responses, noting comments that particularly surprised or inspired them. Class discussion of the authors' comments illuminates a number of rarely discussed aspects of science, including how the "next step" is in fact chosen for a given project, how researchers respond to setbacks, and that many successful scientists were not, in fact straight-A students. Further, passion and persistence are more important than genius. Numerous aspects of the nature of science also are highlighted: that knowledge changes over time; that science is creative; and that rejected hypotheses are critically important on the road to achieving understanding.

After the first three upper-level CREATE classes, we conducted postcourse interviews of students to complement other cognitive and affective assessments. We learned that even after three years of college science, students (mostly graduating seniors) came into the class harboring quite negative opinions about science and scientists. Such misapprehensions can deter students from considering research careers. CREATE courses can refute such fallacies, and the email survey likely contributes substantially to this by emphasizing the highly personal aspects of biological research.[35]

What follows is a series of student comments made during post-CREATE course interviews. Their reflections illustrate four conclusions about the efficacy of the model.[36]

CREATE changes students' ideas about research:

> "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, because I had always thought everybody would go in the same direction."

> "I think the biggest, kind of like enlightenment for me 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."

> "I always thought...that people do research and they spend all their lives on this one topic, and then it doesn't go right, and then, Oh, their whole life's work is, you know, screwed up.... But that's not really the way it works. You keep changing, and moving, and stopping/starting, 180-degree turn, stopping/starting, maybe go

back to where you were originally and then move in a completely new direction, so it's just a process of discovery."

CREATE changes students' ideas about scientists:

"I thought [precourse] they were close-minded. They just had one specific thing in mind and then bam-bam-bam they proved it and that was it. 'This is my evidence: a, b, c, d, e, f, g. Forget it; can't refute it.' That's it. [Now] I think scientists, they are always asking questions, they always want to know more. They have an angle in mind, and hopefully they strive toward that point. But they may be deviated from that by new discoveries along the way. Then they may have to reshape. So I think that...they have to be open-minded in a way."

"I learned how scientists think. Before, I thought scientists were like, you know, 'machinery kind of people.'...Somehow now they are more human....It's kind of cool....I feel like they are more relatable."

"[Before, I thought] yeah, just geniuses. Straight As, 4.0s, they were like just knockin' it away....Before, I thought they didn't have any families; like 'This Was Their Life.' But now I'm like, no, they have families, they have careers, they have doctor's appointments; they have everything going on....You realize they're people, trying to balance life, family, career, everything, just like a normal person; and anybody in the world...you know, like they are not just geniuses, that everything comes simple to them....They just have a better understanding of a particular subject. But they are people."

CREATE changes students' ideas about who can be a scientist:

"Who can be involved in scientific work? It's not 'very rich people'; it's not the professors alone, it's not the students who are getting the As. But I think everybody is capable of being involved in scientific work, provided he gets the correct guidance. That's what I found out."

"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."

"Research, I thought, was just like, 'certain people' can do it; not everyone can be a scientist. Now I feel like if you train, if you get the right training and the right background knowledge . . . I could be a scientist if I wanted to. I could be a scientist. . . . Before I was like: I wasn't one of 'those people' that could do science, but now, reading the papers . . . I realized that I can be a scientist if I wanted to. If I really worked hard towards it."

Students perceive their gains in CREATE courses to be transferable:

> "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! Just being able to sit down and focus and not get bogged down."
>
> "I think for any future class I take or even for my own personal interests, looking for information and really understanding what's out there is going to be a lot easier for me. And I'm not going to be as afraid to read a twenty-page paper."
>
> "I'm not as intimidated when I'm learning something new, because I feel like this whole semester we've been learning new things. So, it helped a lot. . . . Pretty much in other biology classes they just give you information and ask you to spit it back out . . . and this class was really neat because . . . it allows you to think of things on your own and use your own creativity, so that was good."

The CREATE strategy helps students develop a deep understanding of a module's papers, which provide insight into how knowledge in a research area deepens over time. Moreover, the method works on multiple levels. In upper-level CREATE courses, learning the specifics of methods (such as fluorescence-activated cell sorting, confocal microscopy, CRISPR/Cas9 technology, or immunoprecipitation) helps students see key principles of biology, chemistry, and physics put to use, and emphasizes the multidisciplinary nature of scientific research. In both the introductory and upper-level courses, dissecting the logic of the experiments and closely analyzing the data help students think like scientists. Class discussions, personal experiences related by the professor, the repeated experimental design and grant panel activity, and the author emails provide additional layers of insight into the nature of science and of scientists. The components of CREATE likely work synergistically to evoke the cognitive and affective outcomes documented to date.

Published papers are of course not transcripts of lab activities. Textbooks largely omit the research process, and primary literature arguably sanitizes it, presenting only the successful efforts. Experiments that led nowhere are (understandably) left out of published papers, and rejected hypotheses are not discussed (unless the point of the paper is to upend a previously held idea). The thought processes behind the studies are thus implied rather than stated. These important aspects of research projects are issues for the CREATE instructor to bring up in class. They are often also illuminated in the email surveys. In response to the question, "If your experiment does not turn out as expected, is this a problem? What do you do?" one author wrote, "I personally love it, because it means that it is time to check my premises and I thus may be getting closer to making a truly new discovery." A different author pointed out:

> This happens all the time – especially early in a project while exploring ideas – but is typically not a problem as long as things are working technically. One wants to always be open to different models and seek answers with exploratory hypotheses but an open mind. Something different than expected can in fact be exciting, because it can lead to deeper understanding. . . . Something was incomplete or wrong about a prior held view.

Students reported expecting a different answer: that researchers would be depressed or consider themselves failures. Instead, rejected hypotheses and confusing results were recast as unsurprising aspects of scientific investigation, and often a stimulus leading to development of better ideas. To a student question on whether the researcher had experienced "ethical dilemmas," the first respondent simply said "No." The second responded, "Yes, and if anyone tells you 'no,' they're lying!" Overall, the email interview activity provides abundant insight into both the research process and researchers themselves – insight difficult or impossible to achieve in traditionally taught science courses.

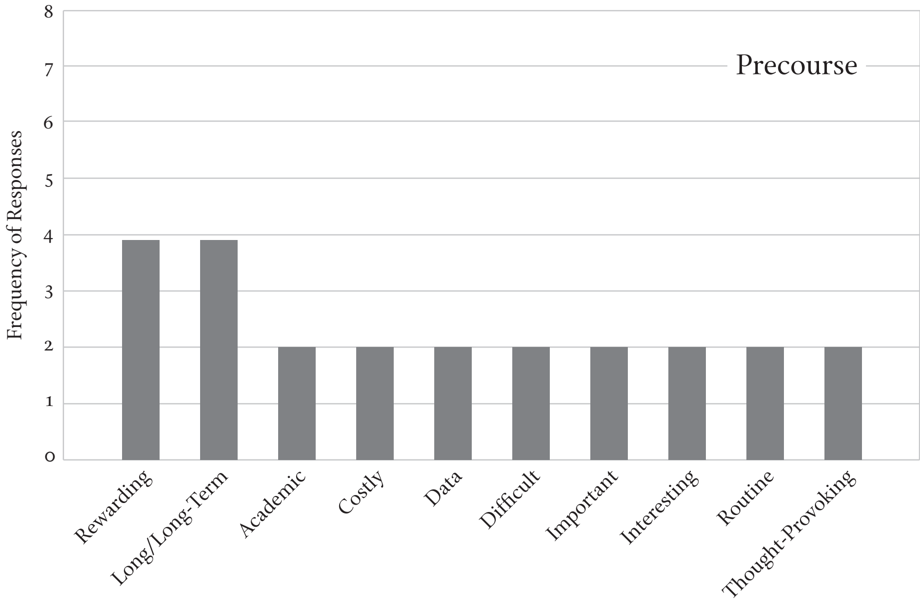
The topics of scientific creativity and science as understood by the general public deserve more comprehensive treatment than is possible here, but teaching and learning with the CREATE strategy has implications for both. Because traditional science courses overemphasize content at the expense of scientific reasoning, argumentation, and design, they render scientific creativity virtually invisible.[37] Unfortunately, creativity itself has proven problematic in education: work at the K–12 level has suggested that teachers may suppress student creativity rather than nurturing it; thus, a creative spark may end up being more of a burden than an asset for students.[38] In CREATE classrooms, students find that designing creative follow-up studies can lead to success in the friendly competition of the grant panel process, and they become increasingly aware of the creativity underlying scientific research in general.

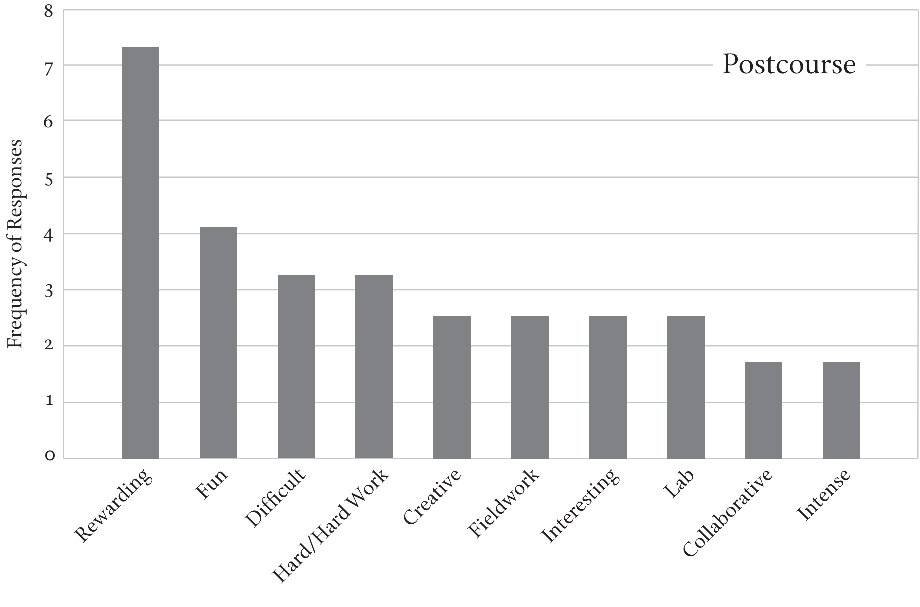
While every paper is, in principle, creative, papers also provide opportunities for professors to emphasize the everyday smaller-scale creativity inherent to research science. For example, one paper read in an upper-level CREATE biology elective examines how growth cones, the amoeba-like tips of growing nerve fibers, find their way in embryos. The paper opens with the authors growing pieces of retina in sterile dishes and discovering that the retinal growth cones collapse in response to treatment with a particular growth factor. The investigators next carry out an integrated set of substudies of this phenomenon defining dosages, time-courses, and specificities of the in vitro assay. The bulk of the paper's experiments then use the collapse assay to study the molecular basis of this aspect of axon guidance in the visual system.

Students had never considered the fact that if you discover a phenomenon like growth cone collapse, you need to characterize it experimentally before moving forward. The investigators had no handbook to check for methodology; proper dosages and timing needed to be determined empirically. Mulling over issues like this helps students develop a richer understanding of research design. In every CREATE course, students comment on their realization that science is creative, or "more creative than I thought." Data from multiple iterations of City College of New York CREATE classes on a Likert-style survey of student attitudes and beliefs show significant gains on a statement suggesting that science is creative – gains not seen in a comparison non-CREATE course.[39] Thus, even in the absence of wet-lab activities, CREATE students come to recognize that designing, carrying out, interpreting, troubleshooting, and extending research studies is an inherently creative process.

One of our anonymous assessment surveys included open-ended prompts asking students to write three to five words that they associated with "scientists" or with "research careers" (see Figure 1). In one study, the surveys were administered pre- and postcourse in a set of ten upper-level CREATE classes taught by faculty members in R1 institutions, public universities, and elite liberal arts colleges, all of whom had learned CREATE methods in National Science Foundation–sponsored workshops taught by Kristy Kenyon and myself. In pooled data from the ten CREATE courses, before the course, "creative" did not appear among the top ten words describing "research careers." After the course, however, "creative" appeared in the top ten for research careers (along with "fun" and "collaborative"), suggesting that the experience of a CREATE course shifts viewpoints to a more faithful reflection of reality, even in the absence of hands-on lab work. With regard to words associated with "scientists," "passionate" and "patient" were top-ten responses postcourse, but not precourse, and the frequency of mentions of "creative" increased postcourse, with "innovative" appearing as a new category (see Figure 2). These results suggest that over a CREATE term, students achieve a more nuanced (and accurate) understanding of and positive attitude toward researchers themselves. The no-cost email component can bring about significant changes in student perception and insight.[40]

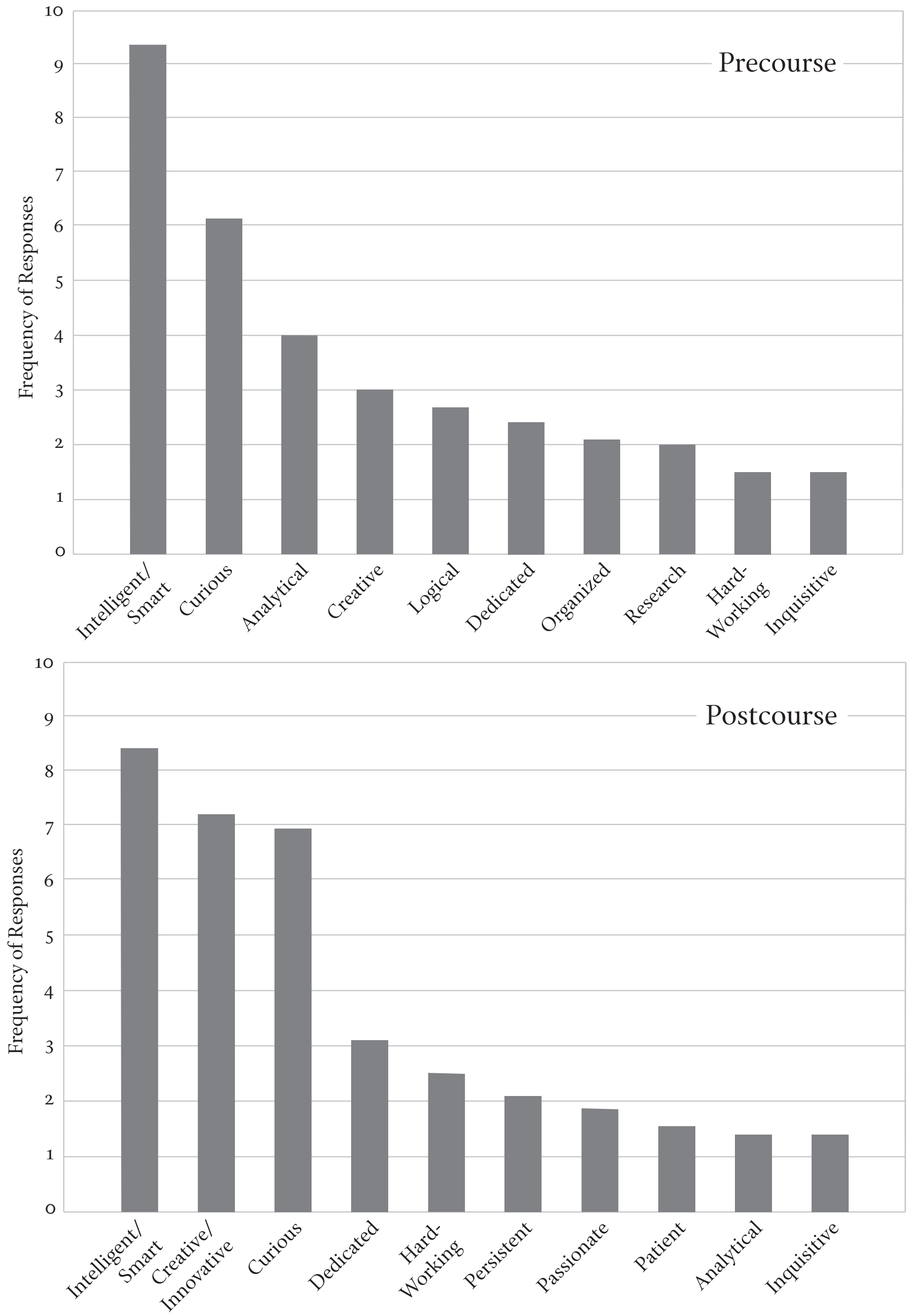
Figure 1
Top Ten Words Associated with "Research Careers" in CREATE Courses at Ten Four-Year Campuses, Pre- and Postcourse





Source (Figures 1 & 2): Sally G. Hoskins, unpublished data.

Figure 2
Top Ten Words Associated with "Scientists" in CREATE Courses at Ten Four-Year Campuses, Pre- and Postcourse



The first-year CREATE course could be adapted for general education science students, whose single biology course may be their only college science class. Teaching the nonmajors how scientists think, design research studies, evaluate data, and come up with new ideas, and guiding them in an email survey of selected scientists, could be a positive way to help them prepare to vote intelligently on science-related issues of public importance. As noted in *The Future of Undergraduate Education, The Future of America*: "Many of the country's founders...believed that the democratic experience had to be safeguarded and maintained and that the enduring success of a democratic government depended upon an educated citizenry."[41]

If biology students harbor negative preconceptions about science, one must assume that the nonscientifically educated public does as well. The situation is not helped by popular culture stereotypes of scientists as loner weirdos. Helping more students teach themselves to analyze data, creatively design follow-ups, and see their own questions answered by working scientists could help clarify the realities of science. Ideally all students will recognize that science does and should change; that new knowledge continuously challenges old; that scientists passionately pursue a quest for understanding; and that every time some "fact" is overturned by new data, it does not mean scientists "made a mistake." As our world becomes increasingly subject to biological challenges, for example those resulting from climate change, it is more important than ever that all citizens are science-literate. As a faculty-friendly approach with established cognitive and affective benefits for a wide range of students, CREATE courses could contribute significantly to this effort.

Some would use the evidence above to support the idea of adding single CREATE courses to traditional college curricula. The fact that both first-year and upper-level CREATE students make a variety of gains in a single-semester course suggests that this could be beneficial. But that may be only half of the revolution proposed in the title of this essay, and it would be insufficient. Imagine a STEM curriculum in which students delve deeply into the primary literature of not only one STEM discipline, but many, and in which students spend significant time thinking like geologists, astronomers, biochemists, or physicists, as well as biologists. CREATE courses immerse students in the language and logic of a particular discipline; physicists and biochemists encounter quite different challenges. Biochemists can do three different experiments in a week; in contrast, physicists working with the Large Hadron Collider may plan for years to carry out one study, and astronomers and paleontologists do not do classical-model experiments at all.

As projects become increasingly cross-disciplinary, we may eventually build a "fusion STEM" curriculum, but for now, colleges and universities design their programs around the departmental structure. I believe students could benefit substantially from reading deeply and closely in the language of *each* STEM discipline, and all STEM faculty could benefit from being able to bring their insider understanding of knowledge generation in that discipline to the classroom. Every STEM discipline is characterized by critical thinking, evidence-based analysis, and creativity; it would be very interesting to see how students might benefit from exposure to deep study in multiple areas of STEM through diverse CREATE courses. With regard to non-STEM students, it is essential to modify general education science courses so that they are not mere retreads of broad-coverage high school courses. The public must be able to read and evaluate scientific claims as they make critical decisions about their personal health and around issues of public policy. The present negative stereotypes about science and scientists can be dispelled and science literacy increased. While CREATE was originally developed for biology majors, development of a broad-based general education CREATE course based on the first-year "Introduction to Scientific Thinking" CREATE course and its widespread use in the United States could be the most important benefit of this evidence-based strategy.[42]

AUTHOR'S NOTE

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