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Teaching Cell and Molecular Biology for Gender Equity

Jill C. Sible, Dayna E. Wilhelm, and Muriel Lederman

Department of Biological Sciences, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061

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Science, technology, engineering, and math (STEM) fields, including cell biology, are characterized by the "leaky pipeline" syndrome in which, over time, women leave the discipline. The pipeline itself and the pond into which it empties may not be neutral. Explicating invisible norms, attitudes, and practices by integrating social studies of science into science education may be the necessary first step in helping female students persist in STEM disciplines. In 2003 and 2004, a sophomore Cell and Molecular Biology course at Virginia Tech (Blacksburg, VA) was taught integrating social studies of science with standard material. The course was successfully implemented, teaching students factual content while increasing awareness of the cultures of science and their self-confidence in engaging with the subject. Course evaluation data indicated that females in particular perceived greater gains in logical thinking and problem-solving abilities than females in a traditional cell biology course. Consistent with K–12 studies, males in this class were likely to view scientists as male only, whereas females viewed scientists as male and female. This pilot project demonstrates that social studies can be integrated successfully in a cell biology course. Longitudinal studies of this cohort of students will indicate whether this approach contributes to the retention of women in the field.

INTRODUCTION

The number of women and members of certain ethnic minorities who are practicing scientists at the postgraduate level in most science, technology, engineering, and mathematics (STEM) fields, including cell biology, remains far below the proportions of these individuals in society at large. The proportion of women completing undergraduate degrees in the biological sciences in 2001 was 57% (National Science Foundation, 2004), yet these women are not persisting through graduate school and as professionals in the field. In the same year, women earned only 46% of the doctoral degrees in the biological sciences and made up just 38% of the postdoctoral fellows in the biological sciences, 40% of the postdoctoral fellows in cell biology, and 30% of the workforce in life science-related fields (National Science Foundation, 2004).

This trend also begins earlier, during undergraduate years, and persists through doctoral training. At Virginia Tech (Blacksburg, VA), an engineering- and technology-focused Research I institution at which we are appointed, females do not persist within the College of Science or the Biological Sciences department to the same extent as males (Virginia Tech Institutional Research Web site; http://www.irpa.vt.edu). Within the college, retention of undergraduate white, non-Hispanic students (the majority) was 52% for females and 59% for males, and the retention of black, non-Hispanics was low for both females (40%) and males (36%). In biological sciences, with some fluctuation, the proportion of females is approximately two-thirds at the undergraduate level, one-half at the master's level, and one-third at the doctoral level. Within the entire College of Science, which includes programs in biochemistry, biological sciences, chemistry, economics, geosciences, mathematics, physics, psychology, and statistics, the percentage of females is lower overall but with the same consistent decline from undergraduate through postgraduate programs.

These data suggest that efforts at recruitment of females into STEM at the K–12 and undergraduate levels may have succeeded, but retention of females has not been adequately addressed: This progressive loss has been termed the "leaky pipeline" syndrome (Vetter, 1984). A critical, unresolved next step toward increasing the participation of women as professional scientists may be identification of those factors responsible for their leaving the field. Many practical and obvious issues, such as the coincidence of late training/early careers with the childbearing years, have been raised, and

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Address correspondence to: Jill C. Sible (siblej@vt.edu).

they may indeed contribute to the attrition of females in cell biology and other STEM disciplines. Efforts to mitigate this problem include stopping the tenure clock (for both parents) for the birth or adoption of a child and the creation of work-site child-care centers.

However, other less obvious factors also may contribute to the disproportionate loss of women during their education and early careers. Feminist theory, as one of a group of disciplines that challenges "the view that science represents a uniquely valid approach to knowledge, disconnected from social institutions, their politics and wider cultural beliefs and values" (Lemke, 2001), examines scientific epistemology and the structure of scientific institutions. Based on this analysis, scholars conclude that the current norms of science are constructed to select for those who have historically defined and presently predominate as practitioners in the disciplines, primarily white males. The homogeneity of practitioners may have restricted ideas within and about science, leading to a science that reflects the gender and racial ideologies of societies (Brickhouse, 2001). At the Scientific Revolution, these natural philosophers created a deterministic view of nature along with a mechanistic and masculinized epistemology and internal scientific culture. In the process, the perception of Nature as female/hermaphroditic was destroyed, and the conjunction of humans and the natural world was severed, allowing humankind to exploit nature for its benefit (Merchant, 1980; Keller, 1985, 1992; Shapin, 1996; Bordo, 1999).

The basis of the leaky pipeline syndrome is that the pipeline and the pond into which it empties (e.g., academic and industrial science) are gender neutral, that is, they have no influence on retention so that increasing recruitment will be sufficient to raise involvement. It is assumed that women will be comfortable in the masculine culture in which they are immersed as students and practitioners of science. Instead, the science they find is described as hyperrational and ahistoric (Fausto-Sterling, 1991); mathematics is divorced from any internal or external culture (Henrion, 1997), and computer science is boring, lonesome, and isolating (American Association of University Women, 2000). Little attention is paid to "how the structure of institutions or the current practices of science need to change before women can comfortably join the ranks of scientists" (Schiebinger, 1999, p. 64).

Seymour and Hewitt (1997) found that women students feel psychologically alienated from the realities of science and engineering pedagogies. "The system . . . does not relate to the (different) way in which they were taught to learn, nor to the models of adult womanhood which their socialization encouraged them to emulate" (Seymour and Hewitt, 1997). They find instead the norms of science promulgated through science education in ways that are usually transparent to instructors and to students alike. Various pedagogical strategies have been formulated to overcome aspects of science that could be discriminatory in subtle ways. These strategies include informal science education (Lee and Roth, 2002), postmodern approaches (Weaver *et al*., 2001), supplementing introductory courses with material on the process of doing science (Allen and Baker, 2001), the foregrounding (Taylor *et al*., 2002) and challenging (Mayberry, 1999) of social constructivism, and the search for a political philosophy of science education, one that is "as much oriented toward social justice, critical democracy, empowerment, action-taking and investing in our future's intellectual capacity as it is about constructing conceptual understands of the world" (Kyle, 2001).

We propose a strategy that would make the "rules" of science explicit while students are learning scientific information; examples of science courses that integrate disciplinary information and scientific cultures are the developmental biology courses of Scott Gilbert and Ann Fausto-Sterling (Gilbert and Fausto-Sterling, 2003) and a physics course developed by Karen Barad (Barad, 2000). Under this rubric, traditionally marginalized students will be empowered to make deliberate choices as to how to respond to these rules (Lederman, 2001, 2005). They may choose to accept the cultural norms that prevail, adapting their behavior as needed. They may choose to leave the field of science, but with a clear understanding of why they are leaving. Alternatively, they may choose to challenge those norms, with the goal of practicing science in a manner consistent with their own culture, ethics, and perceptions. Those students who make this last choice may face the greatest challenges, but they hold the promise of diversifying and transforming the practice of science in ways we can scarcely imagine.

During Spring 2003 and Spring 2004 semesters, pilot sections of an undergraduate, introductory cell and molecular biology course were taught at Virginia Tech. The objective of the project, funded by the National Science Foundation (HRD-0332843), was to develop and implement a curriculum that integrated the social studies of science with standard scientific information. The short-term goals of this strategy were student learning of the basic material of the field, student understanding of the sociocultural dimensions of science, and an increase in student perception that they can do molecular cell biology successfully. The long-term goal is to increase the persistence of women and other underrepresented groups in biology. In this report, the implementation of the objective in spring 2004 is detailed, and assessment of the effectiveness of the course materials is provided.

APPROACH

Selection of Students and Student Demographics

BIOL 2104, Cell and Molecular Biology, is a required sophomore-level course for all undergraduate biology majors at Virginia Tech. This course is also required or a free elective for several other life science majors on campus. Typical sections of BIOL 2104 range from 50 to 150 students, averaging 90 students per section. For the Spring 2004 semester, enrollment was capped at 50 students and was restricted to biology majors, although the instructor was able to force-add four students from other majors.

Demographic information for students enrolled in this course is presented in Table 1. The proportion of male and female students correlates well with overall values for biology majors at Virginia Tech. In 2003, biology majors were 64.9% female and 35.1% male (Virginia Tech Institutional Research Web site; http://www.irpa.vt.edu). For comparison, demographic information for a more traditional section of BIOL 2104 taught during the Fall 2003 semester is also included.

Table 1. Demographic information on students enrolled in BIOL 2104 (traditional section during Fall 2003 and experimental section during Spring 2004 semesters)

Semester	Total enrollment	Gender	Major	Class	Ethnicity	Nontraditional[a]
Fall 2003 (traditional)	149	98 F 51 M	103 Biology 37 Other life science 7 Other STEM 2 Non-STEM	6 Freshman 53 Sophomore 69 Junior 21 Senior 1 Grad	Unknown	Unknown
Spring 2004 (experimental)	47	30 F 17 M	42 Biology 4 Other life science 1 Unknown	1 Freshman 14 Sophomore 22 Junior 7 Senior 1 Grad 2 Unknown	7 Minorities	3

F, female; M, male.

[a] Nontraditional students are defined as those students older than the typical undergraduate and with full-time employment or child-raising experience.

Instructors

The two experimental sections of Cell and Molecular Biology were taught by two different instructors, both female. M.L., who taught the Spring 2003 section, has a scholarly background in both molecular biology and the social studies of science (with an emphasis in feminist pedagogy). M.L. was codeveloper of the original BIOL 2104 course, first taught during fall 1997. J.C.S., who taught the Spring 2004 section, is a cell biologist who had taught BIOL 2104 six times previously, beginning in 1999, in sections ranging in size from 30 to 150 students. Although not formally trained in feminist pedagogy, J.C.S. prepared for teaching this special section by reading relevant background materials in feminist pedagogy (e.g., Lederman and Bartsch, 2001) and by discussing them with M.L. During the Spring 2004 semester, D.E.W. was the graduate teaching assistant for the course. D.E.W. had just completed her B.S. in biology at Virginia Tech and had served as an undergraduate teaching assistant for a large section of BIOL 2104 (taught by J.C.S.) during the Fall 2003 semester. To eliminate differences due to different instructors, all of the data presented here are from the Spring 2004 semester with comparisons to the Fall 2003 traditional section, both taught by J.C.S.

Syllabus and Course Material

Overall, the scientific material was organized as it would be for a traditional introductory-level cell and molecular biology course, with social studies incorporated by way of writings and in-class discussions. The materials and analysis for the second section, taught in 2004, are presented here. The required text was *Essential Cell Biology* (Alberts *et al*., 2004). (The 2003 class used Cooper's *The Cell*; Cooper, 2000.) The syllabus for 2004, provided on the first day of class and posted on the course Web site, provided the following information regarding the learning goals and special nature of the course.

1. Understand and utilize information deemed basic by practicing molecular and cell biologists.
2. Describe how the practice of cell and molecular biology is influenced by society at large.
3. Recognize that science itself has a culture that influences its practice.
4. Engage with the idea that studies of science itself are as much a part of science as data gathering. You need not ultimately agree with this concept, but you should be able to defend your position rigorously.
5. Consider you own position in the society of science, where you are and where you would like to be.

This section of the Cell and Molecular Biology course is funded by the National Science Foundation and is a pilot offering for a new way of teaching science. This course integrates scientific knowledge with analyses of science that have been carried out by historians, sociologists, and philosophers of science, and by scholars in the field of science studies. In this section, we use the concept of "the cultures of science" as a tool to understand not only the basics of biology but also how these cultures influence the biology itself. It is our hope that students will adopt a critical stance to see the assumptions, concepts, and practices of science in new ways. Linkage to science studies will reinforce scientific content and science studies will make explicit how culture of science influences its theories and practice.

As shown in Figure 1, the scientific content covered in the course was basic and standard. The course began with an introduction to cell biology, including the most popular tools and model organisms. Then, fundamental biochemistry of nucleic acids and proteins was reviewed, followed by several classes dedicated to the central dogma (DNA → RNA → protein). The second quarter focused on molecular biology with an emphasis on techniques and the discoveries resulting from the implementation of new technologies. The third quarter was dedicated to classic topics in cell biology with an emphasis on the function of different cellular compartments and organelles. In the last section of the course, a review article entitled "The Hallmarks of Cancer" (Hanahan

BIOL 2104 CRN 90731

Class	Date	Topic	Relevant text	Writing assignments
1	Tues, Jan 20	Welcome, introductions, overview, in class writing assignment	1-5, 11-26	#1 in class
2	Thur, Jan 22	Tools in cell and molecular biology - microscopy and biochemistry	5-11, 60-61, 160-161	
3	Tues, Jan 27	Model organisms in cell and molecular biology/**discussion-which, why and how many?**	27-34 + handout	#2 due today
4	Thur, Jan 29	Building blocks of cell biology-nucleic acids, amino acids, enzymes	169-187, 119-142	
5	Tues, Feb 3	continued/ **discussion-biology is chemistry is physics is math?**	91-102	
6	Thur, Feb 5	DNA replication, transcription, translation, protein processing	195-208, 229-258	
7	Tues, Feb 10	continued		
8	Thur, Feb 12	continued/**discussion - representations**		#3 due today
9	Tues, Feb 17	EXAM 1		
10	Thur, Feb 19	The early molecular biologists - /**discussion - data and credit**	handout	#4 due today
11	Tues, Feb 24	Molecular biology techniques I	327-364	
12	Thur, Feb 26	Moleclar biology techniques II		
13	Tues, Mar 2	The human genome project/**discussion - private vs. public effort, implications of HGP**	handout	#5 in class
14	Thur, Mar 4	SPRING BREAK		
		HGP continued/**discussion - metaphors in HGP**		#6 due today
15	Tues, Mar 16	Scientists and the scientific conference- dayna -**discussion-What are these people like?**		#7 due today
16	Thur, Mar18	EXAM 2		
17	Tues, Mar 23	Membranes/the plasma membrane	365-410	
18	Thur, Mar 25	The nucleus	handout	
19	Tues, Mar 30	Endomembrane domain (ER/Golgi)	497-531	
20	Thur, Apr 1	Mitochondria and chloroplasts	453-477	
21	Tues, Apr 6	Cytoskeleton	573-600	
22	Thur, Apr 8	**discussion - Representation exercise**		#8 due today
23	Tues, Apr 13	EXAM 3		
24	Thur, Apr 15	Hallmarks of Cancer	handout	
25	Tues, Apr 20	Self-sufficiency in growth and anti-growth signals	533-540, 552, 612-625	#9 in class
26	Thur, Apr 22	continued		
27	Tues, Apr 27	Angiogenesis and metastasis/**discussion-thalidomide- the politics of a cancer drug**	703-714	
28	Thur, Apr 29	Telomeres and stem cells/**discussion - poltitics and ethics of human stem cell research**	721-726	#10 due today
29	Tues, May 4	Genomic instability and apoptosis	625-628	#11 due today
30	Sat, May 8	EXAM 4 7:45-9:45 AM		

Figure 1. Class topics, readings, and highlighted discussions for the Spring 2004 section of BIOL 2104.

and Weinberg, 2000) was used as a conceptual framework for the topics of cell signaling, cell cycle, cell death, and cancer. J.C.S. had used this material for BIOL 2104 several times before teaching this class. For comparison, the course topics covered in the more traditional Fall 2003 section of the course is presented in Supplemental Material 1.

The more novel aspect of this course was the social studies content, which was interspersed, and whenever possible, integrated, with the standard scientific material. The primary mechanisms for introducing the social content were scheduled class discussions (bold text in Figure 1) and both in-class and out-of-class writing assignments. In the Spring 2003 experimental section taught by M.L., additional readings on the social studies of science were assigned to the students. The reading list appears in Supplemental Material 2. J.C.S. did not make use of these readings but would do so as an improvement for future classes. Instead, she provided context and coaching for the writing assignments as part of class discussions.

Class Discussions

The goal of the class discussions was to introduce a generally accepted topic or concept in molecular cell biology and then to encourage students to question, probe, and challenge the topic by asking questions such as, "Why was the topic considered to be important? How was it presented in the textbook or other scientific literature and why?" "Who was responsible for a particular discovery?" and "Were there alternative approaches, conclusions, etc.?" The intention was to make students aware that scientific knowledge is constructed, a product of the scientist and the cultures (both internal and external) in which he or she practices the discipline (Fleck, 1935; Kuhn, 1962; Keller, 1985; Shapin and Schaffer, 1985; Latour, 1987; Hubbard, 1990; Barnes *et al*., 1996; Shapin, 1996). Typically, the discussions occurred in small groups, which then reconvened as a class with each group invited to report highlights from its discussion.

The first in-class discussion concerned the widely accepted use of a subset of organisms in molecular cell biology. Students were first introduced to the concept of a model organism and given information regarding the most popular of these organisms (e.g., *Escherichia coli*, *Saccharomyces cerevisiae*, *Drosophila melanogaster*, *Arabadopsis thaliana*, and *Mus musculus*) and their putative advantages (e.g., small genome size, low cost to maintain, and short generation time). Afterward, the concept of focusing the majority of federally funded research on a small number of species was challenged. A commentary by Bolker and Raff (1997) was presented, exposing students to the opinion that model organisms are often more convenient than representative, and focusing too exclusively on a small number of species not only hinders scientific progress but also may perpetuate fallacies. Students were then asked to comment on the decision by the National Cancer Institute (Bethesda, MD) to fund a subset of seven nonmammalian model organisms for cancer-related research. Their reactions ranged from the perspective that cancer research should only be funded for mammalian studies to the view that seven is far too few models for any meaningful scientific progress.

As another example of a class discussion, after two traditional lectures in which the fundamental biochemistry of nucleic acids and proteins was presented as a foundation of cell biology, students working in small groups were asked to organize the terms "biology," "chemistry," "mathematics," and "physics" diagrammatically, however they saw appropriate. Some groups produced the traditional hierarchy where biology is beneath chemistry, which is lower than physics, which is under mathematics, whereas others had more novel representations. One group produced a Venn-style diagram resembling a flower with each field overlapping the others, none larger or dominating another, but all interconnected. Through this exercise, students seemed to appreciate that there was a standard, although rarely explicit, organization of the scientific disciplines, but that this approach was not necessarily the only way or best way to consider large amounts of scientific information.

One theme that spanned several discussions was a consideration of the scientists who generate the data. The first context in which this topic was encountered was a class meeting called "the early molecular biologists" in which the work of a number of famous scientists, leading to the presently accepted view of the central dogma, was discussed accompanied by musical selections from the time period in which the discoveries were made. The point that almost all of the scientists credited with these breakthroughs in molecular biology were white, male, and primarily European was not ignored. James Watson was quoted from his own memoir, "The Double Helix" (Watson, 1980), to reveal the prevailing attitudes about female scientists such as Rosalind Franklin. Students were asked to give their opinions on this matter in Writing Assignment 4 (Figure 2), and many of them also raised the issue again on Exam 2 (Supplemental Material 3) when asked whether or not Watson, Crick, and Wilkins were deserving of a Nobel prize.

The discussion of scientists culminated after students completed Writing Assignment 7, in which they contacted a scientist they did not know by e-mail, and asked that scientist a question. We shared these experiences in class, which varied from very satisfying, in which students felt flattered that one or more scientists had replied, to frustrating, in which students received no responses despite multiple attempts at contact. The questions that the students asked ranged from very personal ("What is your favorite joke?" What are your hobbies?") to specific scientific questions. Several students used the opportunity to make contacts or ask questions regarding their own plans for graduate school. A few of the female students asked male and female scientists their opinions about the lack of credit given to Rosalind Franklin, and others wrote specifically to female scientists to ask what it was like to be a woman in cell and molecular biology. Although the questions and responses varied tremendously, the exercise as a whole seemed successful in reminding students that science is done by scientists, who bring their personalities, culture, and so on to the work that they do and in turn are affected by the culture of science in which they work.

BIOL 2104 Writing assignments

W1: What does an experiment in molecular cell biology involve? Please touch on the biological materials used, the instruments used, the sorts of questions asked and what makes the results obtained acceptable to other scientists. (This assignment was completed in-class on the first day of class and then was assigned again at the end of the semester (W11).)

W2: What properties should we look for in a model organism for molecular and cellular biology? Several years ago, the National Cancer Institute convened a panel that identified 7 non-mammalian model organisms to be targeted for funding for cancer research. What do you think about this idea?

W3: You have been provided with representations of the DNA replication fork from three different cell and molecular biology textbooks. Which representation do you prefer? Why? Create your own representation of the process using any medium you prefer.

W4: Brenda Maddox, in her book Rosalind Franklin: The Dark Lady of DNA, mentions the beginning of Watson's The Double Helix. Watson passes Willy Seeds of King's College, London, while climbing in the Swiss Alps. Seeds passes by without stopping to chat, other than to say "How's Honest Jim?" meant sarcastically. Do you think Watson and Crick were honest in their use of Franklin's data, considering how he obtained it? If not, what might they have done instead? What does this incident say about the practice of science?

W5: Draw a picture of a molecular cell biologist. (Students were asked to doodle during class.)

W6: During class, students worked in groups to identify all of the metaphors in an editorial on the human genome project. (HGP). Then they were asked to create their own metaphors for the HGP.

W7: E-mail a molecular cell biologist with a question you would like him/her to answer. The person you select can be anyone outside of VT whom you do not know personally. Please forward your question and response to Drs. Sible and Scheckler along answers to the following questions:
°Why did you choose that scientist?
°Why did you choose your particular question?
If the first person you write to doesn't respond, keep trying. Keep a record of the people you've attempted to contact who did not reply.

W8: Hans-Jorg Rheinberger has suggested that our representations of the natural world, e.g. in pictures and diagrams that describe the results of our experiments, are compared with each other, rather than with Nature. Do you think he is correct? What is the consequence of this for science?

W9: Please bring to class some information on an alterative treatment to cancer. You may use the World Wide Web as a resource. We will have an in-class discussion of your findings.

W10: We will have an in-class discussion of the ethics of stem cell research. Be prepared to participate.

W11: What does an experiment in molecular cell biology involve? Please touch on the biological materials used, the instruments used, the sorts of questions asked and what makes the results obtained acceptable to other scientists.

Figure 2. Writing/drawing assignments for BIOL 2104 Spring 2004 section.

Writing Assignments

Students were given several writing and drawing assignments (some in class, some out of class) throughout the semester (Figure 2). The assignments provided the students with a more formal mechanism to engage with social issues in science and a means for us to assess the effect of this course on students' perceptions of science. Examples of student responses as well as the qualitative analysis for two of these assignments are presented under *Results/Assessment*.

Writing assignments were graded on a scale of 0–10 points, and the top 10 grades for each student were added together (for up to 100 points). These assignments counted 20% toward the final grade for the course. Generally, students earned very high scores for this work (average 96.5%; range 56–100%), because they were evaluated on the thoughtfulness of the response and how well positions were supported, rather than on a perceived correct answer. Additionally, several of the assignments were experiential in nature (e.g., participation of an in-class discussion on stem cell ethics), and students earned an automatic 10 points for any level of participation. Although these assignments probably "inflated" the grades for the course, the instructor considered this just reward for students' participation in this experimental section and for the amount of writing required. Typically, 2000-level classes in biology at Virginia Tech require little or no writing, and although students are required to complete two or more "writing-intensive" courses, this course did not qualify as one of the two courses.

Examinations

In addition to the writing assignments described above, evaluation of student learning was based on four examinations. The first three were given in class, and the fourth exam was a take-home essay exam. The material covered in the examinations was both factual/typical and opinion/social in nature as illustrated by the first examination, shown in Figure 3. The other three exams are provided in Supplemental Material 3.

The short-answer format of the exam was selected based on several considerations. To be consistent with the goals and philosophy of this course, students needed to be able to put their own "voices" into the responses, and the examination questions needed to allow for elements of subjectivity. Thus, a multiple-choice format was inappropriate, although multiple choice is the testing format to which students at Virginia Tech are most accustomed during their introductory and 2000-level biology courses. Longer essay questions were not used (except for the take-home exam 4; Supplemental Material 3) based on practical considerations of grading time. Although this class was relatively small (<50 students), the instructor and teaching assistant were already committed to extensive grading time for the writing assignments and for the extra-credit options (see below). Therefore, short-answer questions seemed to provide the most acceptable balance between personal response and efficiency in grading.

Furthermore, the short-answer style permitted the integration of both fact- and opinion-based questions (e.g., Figure 3, question 9) and enabled us to assess whether students exposed to this type of course were learning standard scientific information (e.g., primary, secondary, tertiary, and quaternary structure of a protein) and whether they could apply an opinion (Is knowledge of a protein's structure necessary to study its function?) to that information. For each exam question, the instructor developed a grading rubric with specific point values for each component of the question. An example of the range of answers and points awarded for a typical question is provided in Supplemental Material 4.

Extra Credit

After each of the first three examinations, students were allowed to participate in an extensive extra-credit project, in which they performed a self-analysis of their approach to the examination and a rigorous assessment of every point lost on the exam. This extra-credit assignment was not a new feature of this course but rather had been developed several years earlier by the instructor (J.C.S.) in collaboration with

1) Why do you think that RNA was the genetic material in the first, primitive cells? (3pts)
Why do you think that DNA ultimately evolved to be the genetic material? (3 pts)

2) Eukaryotes control "gene expression" at multiple steps along the central dogma, whereas in prokaryotes, almost all control exists at the initiation of transcription. Provide a rationale for this difference. (3pts)
Name two other steps where the expression of a eukaryotic gene might be regulated. (3 pts)

3) Refer to the 4 polypeptides shown below. Indicate the correct choice for each question. (6pts)
A) phenylalanine-arginine-glutamic acid-valine-methionine
B) methionine-phenylalanine-valine-glycine
C) valine-threonine-proline-glutamine-cysteine-lysine

Which has a net positive charge?
Which could be found at the beginning of a protein?
Which could be phosphorylated?
Which is most likely to be found at a kink or bend in a protein?
Which could contains an amino acid that forms a disulfide bond?
Which is most likely to be associated with the lipid interior of the plasma membrane?

4) We know that there are 64 codons, 20 amino acids, and 34 tRNAs.
For each of the following alternatives, could a functional, accurate genetic code be produced? Why or why not? (do not concern yourself with stop codons) (6pts)

64 codons, 64 amino acids, 34 tRNAs
34 codons, 64 amino acids, 64 tRNAs
34 codons, 10 amino acids, 34 tRNAs

5) You are interested in studying the molecular mechanism of fetal alcohol syndrome (raise your hand if you've not heard of this disorder). Which of the following model organisms would you choose? Why? *Arabadopsis thaliana*, *Saccharomyces cerevisiae*, *Mus musculus*, *Drosophila melanogaster* (6 pts)

6) Briefly, describe the experiment performed by Messelson and Stahl, which proved that DNA replication was semiconservative. (5pts)
Do you agree with James Watson that this experiment is "beautiful" and "elegant"? Why or why not? (2pts)

7) When the scientist Okazaki discovered his famous fragments on the lagging strand of replicating DNA, he helped to resolve a major puzzle regarding the mechanism by which DNA polymerase simultaneously replicates both strands of DNA. What is the puzzle that his discovery helped to resolve? (6 pts)

8) Genetic studies of the Ashkenazi Jews have led to the conclusion that certain mutations of the BRCA1 gene correlate highly with the incidence of breast cancer. Why do you think scientists and clinicians have chosen a single ethnic group as their "model organism" for this work? Are there any disadvantages to their choice? (6 pts)

9) Define primary, secondary, tertiary and quaternary structure of a protein. (4 pts)
Is it necessary to know a protein's structure in order to study its function? Why or why not? (2 pts)

10) How could one experimentally distinguish between a promoter and an enhancer element on a gene? (6 pts)

11) If stretched end to end, the DNA in a single chromosome would reach across the room. Describe briefly the types of compaction that enable 46 human chromosomes to fit into each of our cells. (6 pts)

12) Describe the reaction catalyzed by each of the following. Name an enzyme that catalyzes the opposite reaction. (6 pts)
a) kinase
b) DNA ligase

13) You have just cloned and sequenced some DNA from yeast. You believe that this DNA contains a gene that encodes a protein. Based on the sequence, how would you predict where the open reading frame begins and ends? (Remember, yeast genes have no introns to worry about.) (6 pts)

14) Briefly, describe the role of each of the following types of RNA during translation (6 pts)
mRNA
rRNA
tRNA

15) DNA replication is always 5' to 3'. Explain what 5' to 3' means with respect to the nucleotide subunits. (5 pts)
What activity of DNA polymerase necessitates that replication is always 5' to 3' and not 3' to 5'? (2 pts)

16) Choose the specific type of microscopy or the biochemical tool you would choose to study ONE of the following. Briefly describe how you would proceed with the experiment. (8 pts)
a) the route by which the toxin ricin enters the cell.
OR
b) the rate at which the toxin phalloidin disrupts the swimming of a sperm flagellum.

Figure 3. BIOL 2104, exam 1. The examination was given in class during the regular 75-min period.

Patricia Bevan of the Biological Sciences Initiative at Virginia Tech. The assignment, detailed in Supplemental Material 5, is consistent with the philosophy that science (and science education) is socially constructed and that by encouraging students to deconstruct the material, in this case, the examination itself, they will achieve a higher and more personal level of learning. For this experimental section of BIOL 2104, all extra-credit assignments were read and graded by the teaching assistant (D.E.W.) who met with all students in small groups after the first extra-credit project was graded to discuss what they had learned from the exercise. Participation in the extra-credit assignments was high, with 41 (89%) of the students completing the extra credit for at least one exam and 45% completing extra credit for all three exams. Details of class participation are provided in Supplemental Material 5.

RESULTS/ASSESSMENT

Analysis of student writings and drawings provides valuable information regarding shorter-term effects of the course on students' perceptions of cell biology and their relationships with the discipline. Only a long-term follow-up survey of the students who participated in these special sections of BIOL 2104 will indicate whether the retention of females in the field was elevated and whether these students feel that the course influenced their decision to persist in science.

Grades

A summary of the average examination points earned and ranges (without contributions from the writing assignments or the extra-credit option) is shown in Table 2. For comparison, grades for a larger section of BIOL 2104, taught the previous semester by the same instructor (J.C.S.) and teach assistant (D.E.W.) and incorporating some of the same disciplinary elements but not explicitly the social studies of science, are shown. Overall, the scores for the experimental section of the course were high, with a median grade of 85%. These scores indicate that students met the instructor's expectations in learning both the standard material and the sociocultural material. The higher exam scores in the experimental section compared with the traditional section for both males and females could be a function of many factors, including the changes in teaching style, the increased number of sociocultural questions, the change in text, and the smaller class size.

Comparison of First and Last Writing Assignments

As one mechanism to identify changes in students' perceptions of the field, qualitative analysis was performed of their first writing assignment (completed in class on the first day of class; Figure 2, W1) compared with their final writing assignment, which was the same set of questions, answered outside of class and due on the final day of class. Students were told not to spend more than 10 min on this assignment and to write the first things that came to mind. However, because the last assignment was completed out of class, some students may have dedicated more time and used additional resources than for the first assignment, which was performed in class. The writings for 19 students (14 female and 5 male), who had given informed consent, were analyzed. These students had all completed both the first and last writing assignment among those who had given permission to have their writings analyzed. Unfortunately, not all students completed the final assignment, because they had already earned a sufficiently high score for their writing assignments.

Qualitative analysis was performed on the student writings. Analysis was performed with a preset list of features expected to provide interesting data. This list included whether students raised sociocultural issues such as those concerning money, personal attributes of a scientist, value of an experiment, or an ethical issue. The instruments, questions, and materials used in molecular cell biology were identified in each writing and then grouped into categories. In addition, analysis was performed on interesting trends noted during the reading of the student writings, mainly the expression of uncertainty by many students in the first but not the second writing, the use and challenge of the term "hypothesis," and the discussion of model organisms. A summary of some findings from the analysis is shown in Table 3. The data are separated by gender, but because of the small number of males, no attempt was made to identify statistical differences based on gender. An example of two students' first and final writing assignments and how qualitative analysis was applied is provided in Supplemental Material 6.

Perhaps the most striking and unanticipated transformation seen in the students' writings was the assurance with which they approached the assignment. The first time, 58% of the students expressed some degree of uncertainty about their ability to answer the questions. In the final assignment, none of the students made such statements. This change, applying to both males and females, can be interpreted as an improvement in their self-confidence with respect to subject matter of molecular cell biology.

Another change provides an example of how students had learned a generally accepted practice in science and were able to "deconstruct" the topic by questioning the status quo. In the first assignment, only 16% of the students used the term "hypothesis" in their writing. In the final assignment, nearly one-half (47%) used hypothesis, indicating that the terminology and concept of hypothesis-driven science had been incorporated into their knowledge of cell biology. However, of those nine students who used the term hypothesis, five challenged the notion of hypothesis-driven science in some way. In the first assignment, none of the three

Table 2. Summary of average examination grades (range) without extra credit for students in the experimental section of BIOL 2104 (Spring 2004) and a more traditional section of the course (Fall 2003)

Semester	Class type	Class size	Total exam median scores (%)	Female exam median scores (%)	Male exam median scores (%)
Spring 2004	Experimental	47 (31 F, 16 M)	85 (60–97)	88 (60–97)	85 (64–96)
Fall 2003	Traditional	149 (99 F, 50 M)	80 (64–99)	81 (50–99)	79 (64–94)

F, female; M, male.

Table 3. Summary of analysis of student writings

	First assignment			Last assignment		
	Total	Female	Male	Total	Female	Male
Expressed uncertainty about ability to answer questions	11 (58)*	8 (57)	3 (60)	0 (0)*	0 (0)	0 (0)
Used the term 'hypothesis'	3 (16)*	2 (14)	1 (20)	9 (47)*	6 (43)	3 (60)
Challenged hypothesis-driven science	0 (0)*	0 (0)	0 (0)	5 (26)*	3 (21)	2 (40)
Discussed						
money or funding	2 (11)	1 (7)	1 (20)	5 (26)	3 (21)	2 (40)
a personal attribute of a scientist	3 (16)	2 (14)	1 (20)	2 (11)	1 (7)	1 (20)
the value of an experiment	4 (21)	3 (21)	1 (20)	6 (43)	4 (29)	2 (40)
ethics	4 (21)	2 (14)	2 (40)	3 (16)	1 (7)	2 (20)
Considered an acceptable experiment to be reproducible	11 (58)	9 (64)	2 (40)	10 (53)	8 (57)	2 (40)
As materials, named						
an organ or organism	7 (37)	6 (43)	1 (20)	8 (42)	8 (57)	0 (0)
a 'model organism'	0 (0)*	0 (0)	0 (0%)	6 (43%)*	6 (43%)	0 (0)
a cell or tissue	7 (37)	6 (43)	1 (20)	5 (26)	4 (29)	1 (20)
subcellular material	7 (37)	5 (36)	2 (40)	9 (64)	8 (57)	1 (20)
nucleic acid (DNA, RNA) or protein	1 (5)*	0 (0)	1 (20)	9 (64)*	8 (57)	1 (20)
As instruments, named						
a microscope	17 (89)	12 (86)	5 (100)	16 (84)	13 (93)	3 (60)
a molecular biology tool	4 (21)*	4 (9)	0 (0)	17 (89)*	12 (86)	5 (100)

Values in parentheses are percentages.

* Statistical difference ($p < .05$) by McNemar's test when comparing first and last responses for each student.

students who used the term hypothesis included a question or challenge.

As an example, in response to the first question: "What does an experiment in molecular cell biology involve?", one student (an African-American male junior biology major) wrote, "An experiment in molecular cell biology involves biological materials, spesial instruments and acceptable uses of experiment teqnices." (Spelling was not corrected; student has several documented learning disabilities.)

In the second assignment, in response to the same question, he wrote:

> "An experiment in molecular cell biology involves a clear defined question that a scientist wants to solve or enlighten the world, ad least that what I thought coming in to this class. However, after taking Biology 2104 I believe an experiment dose not have to be hypothesis driven rather it can be data driven or it may even be a simple desire to make things more efficient. Some examples of data driven experiments are microarrays, where mass amounts of data are collected then a question is derived from the comparison of the data, and the human genome project where the entire human DNA was sequenced with no clear question being asked in that instance as well."

The student had incorporated the term hypothesis into his working vocabulary of molecular cell biology but in a sophisticated and critical context.

Because the course content placed emphasis on the social aspects of science, it was anticipated that in their final assignment, an increased number of students would raise a relevant social issue such as funding or some personality trait of a scientist. However, little change was discovered when comparing the two responses for discussion of social issues. Furthermore, the response to what makes an experiment acceptable was largely unchanged, with the majority of the students indicating that an acceptable experiment was one that could be or had been reproduced multiple times, rather than considering the value or ethics of an experiment. It seems that they understand well the conventions of fact-making within science, but they do not yet have the ability to challenge these conventions. Alternatively, despite the overt learning objectives of the course, students may not have considered social issues as appropriate subject matter for a graded response in a basic science class. Another change to improve future iterations of this course would be to ask students explicitly to discuss social issues.

Comparison of the two writing assignments also provided some data suggesting that students' perceptions of molecular cell biology had transformed from a perception that emphasized the cell to a perception that emphasized both cell and molecule. For the first assignment, students equally discussed organs/organisms, cells/tissues, and subcellular material. However, only a single student specifically named a biological molecule (DNA). In the final assignment, the discussion of organs/organisms, cells/tissues, and subcellular material remained balanced; however, all of the students who referred to subcellular material did so specifically, using the terms "DNA," "RNA," "protein," or a combination. Even at the level of the organism, students demonstrated more detail in discussion with six of the eight students who discussed an organism using the term "model organism," a term that was not part of their vocabulary in the first assignment. Likewise, in the first assignment, 89% students named the microscope as a piece of equipment used for experiments in molecular cell biology. Only 21% named any piece of molecular biology equipment, such as a gel electrophoresis apparatus or polymerase chain reaction machine. In the final assignment, 89% named a molecular biology instrument.

These changes may be typical for students taking introductory molecular cell biology courses and indicate that despite the emphasis on social aspects of science, students taking this course increased their knowledge of standard molecular cell biology content.

Although the data set is too small for statistical analysis, gender-specific differences in the types of molecular knowledge incorporated were observed. Whereas females increased their references to subcellular materials (e.g., organelles, DNA, and proteins) from 36 to 57% when comparing the first and last assignment as well as their mention of a specific molecule (from 0 to 57%), males did not (references to subcellular materials decreased from 40 to 20% and references to specific molecules were unchanged at 20%). In contrast, males showed the greater increase in reference to molecular biology tools (from 0 to 100%) compared with females (from 29 to 86%). This differential focus suggests that after this course, women connect more directly with the subject under study, overcoming a distance between observer and observed. This separation has been noted in feminist analyses as one epistemic change that occurred at the Scientific Revolution (see *Introduction*) that should be reversed (Merchant, 1980; Keller, 1985, 1992; Shapin, 1996; Bordo, 1999).

Analysis of Student Drawings

Among the most revealing student assignments was the simplest assignment. Approximately halfway through the semester, students were handed a blank piece of paper, and asked to draw a scientist. They were given no further instruction, even if they asked for instruction. The analysis, summarized in Table 4, indicates that the majority of male students (63%) depicted the scientist as male only, and none of the males depicted the scientist as female only. One male student depicted both a male and female scientist, and later indicated that the female scientist was meant to represent the instructor for the course (J.C.S.). She was drawn in her role as "teacher," in a classroom—not a laboratory or field setting. In contrast, 50% of the females depicted the scientist as female only and 38% drew only a male scientist. Thus, this simple exercise provided some of the most compelling evidence that males are more likely to view a scientist as a member of their own sex than are females.

Table 4. Summary of analysis of student drawings

	Total students	Female students	Male students
Scientist(s) depicted as			
female only	12 (38)	12 (50)*	0 (0)*
male only	14 (43)	9 (38)	5 (63)
both	2 (6)	1 (4)	1 (13)
indeterminate	4 (13)	2 (8)	2 (25)

The difference in female and male students who depicted any female scientist ('female only' + 'both') was not statistically significant ($p = .164$).

* Statistical difference ($p < .05$) by Fisher's exact test when comparing female students with male students.

DISCUSSION

Was This Project a Success?

We describe a pilot undergraduate cell and molecular biology course in which the social studies of science are integrated with standard course material. The rationale for the project was that making visible and challenging the norms of practicing science would provide individuals from underrepresented groups with a perspective and confidence that might promote retention of and a more positive experience for these individuals. This project focused on gender equity, a particularly interesting issue with respect to biology, because women are the majority who begin undergraduate training in this field, but their numbers decline steadily from the undergraduate through the postgraduate years. Thus, the biological sciences, including cell biology, provide a rich context in which to address the issue of the leaky pipeline during the undergraduate years.

The goals for this phase of the project were practical in nature: to integrate social sciences with cell biology such that 1) students still learned standard factual content, 2) students developed an understanding of the culture in which science is practiced, and 3) students gained self-confidence in their ability to do science. Our data suggest that these goals were met, encouraging continued implementation of courses like our course and additional and longer-term analysis of the effect on gender equity.

Are Students Learning Standard Factual Content?

Perhaps the most common concern about adding the social studies of science to a required cell biology course (or any science course) is that there simply is not enough time, and essential material will have to be discarded to make way for the "nonessential" new content. Although a legitimate concern, the instructors of this course have not experienced this problem. During the six previous times J.C.S. had taught BIOL 2104, a progressive decrease in the number of topics covered was noted, favoring a more in-depth, concept-oriented approach over a facts-based curriculum. The transition to this experimental section was not radical in terms of course content. Rather, the social content provided an opportunity for students to use new molecular biology terms in discussions of how the scientific information was obtained, its implications, and so on. Based on the responses to the more factual questions on the examinations, most students developed a solid understanding of the standard course material. We believe that the incorporation of social studies will deepen the appreciation of the concepts compared with standard course formats.

This conclusion is supported by data from the Student Perceptions of Instructions, or teaching evaluations. These questionnaires are standardized and required for all courses at Virginia Tech. The responses to questions concerning gains in the course, compared with the Fall 2003 section of BIOL 2104, also taught by J.C.S., are summarized in Table 5. Scores were unchanged for total students and males in the areas of knowledge and appreciation of the subject matter (2.7/3.0 and 2.6/3.0, respectively) and were modestly increased for females (from 2.6/3.0 to 2.8/3.0 for both categories). In the area of logical thinking and problem-solving ability, scores increased for total students (from 2.3/3.0 to

Table 5. Summary of responses to questions concerning gains in the course

	Spring 2004			Fall 2003		
	Total	Female	Male	Total	Female	Male
No. of responders	45	30	14	132	90	39
Rated gains in this course compared with similar courses						
knowledge of principles, theories, techniques, etc.	2.7	2.8	2.6	2.7	2.7	2.6
logical thinking and problem-solving ability	2.5	2.6*	2.4	2.3	2.3*	2.4
appreciation of the subject matter and discipline field	2.7	2.8	2.6	2.7	2.7	2.6

Some students included in the total rating did not indicate their sex on the form. Ratings were on a scale of 1–3, with 1, less than average; 2, average; and 3, more than average.
* Difference was significant ($p < .05$) by chi-square analysis.

2.5/3/0) and for females (from 2.3/3.0 to 2.6/3.0) but were unchanged for males (2.4/3.0). The change for females was statistically significant ($p < .02$). These data provide additional evidence that students made equal gains in the subject matter with social studies included and that gains in logical thinking and problem solving were improved for females.

Have Students Gained an Appreciation for the Culture of Science?

The writing assignments and class discussions, particularly those that focused on the people and personalities behind the science, seemed effective tools for creating an awareness that science is socially and culturally driven, that individuals or groups are excluded from full participation in science, and that the culture of science can change over time due to larger cultural influences (e.g., transition from individual, hypothesis-driven science, to large, data-driven science due to changes in computer technology).

However, one of the greatest challenges of teaching this course was convincing students that there was not a "right" answer to opinion questions. Just as cell and molecular biology is interpreted and influenced by the practitioners of science, so are the social studies of science. It was somewhat disappointing but perhaps not surprising that when students challenged the norms in the practice of science, they usually cited specific examples that were given in class (e.g., portraying the endomembrane domain as discrete organelles, the lack of credit given to Rosalind Franklin, and the overextrapolation of data from model organisms). This tendency is understandable, given the limited cell biology background that most of the students have upon entering this course. Occasionally, students would draw a reference from a related class (such as microbiology, which many take simultaneously with cell and molecular biology). One improvement to this course would be to develop methods by which the students investigate and critique an area of cell biology with less instruction (and therefore less influence) of the instructor. Including more outside readings, such as those used by M.L. in Spring 2003 semester and listed in Supplemental Material 2, as well as readings from authors with opposing opinions on relevant issues may also encourage students to voice a personal, independent perspective on social issues. Meanwhile, it becomes important that the instructor recognize the extent of his or her influence, just by being in a position of authority in front of the class. By discussing this situation explicitly, both student and teacher will have exposed another subtle but relevant bias in science education.

Did Students Improve Their Self-Confidence with the Subject?

Several lines of evidence indicate that as a group, students improved the confidence with which they approached the subject of cell biology. The first and last writing assignments, in particular, demonstrated that the majority of students approached the questions with hesitation initially, whereas all of them answered the questions directly and assuredly the second time. Certainly, improvement in student confidence with the subject is an expected outcome of any successful course, even a course without the social studies content. However, these students also demonstrated a willingness to challenge dogmas and venture opinions. One piece of evidence that females were affected particularly by this approach was their ranking of logical thinking and problem-solving skills gained in the course, which was statistically higher compared with females from the more traditional Fall 2003 class (Table 5).

There was also compelling anecdotal evidence (e.g., casual conversations and e-mails) that this course improved the self-confidence of several students, including some who felt marginalized from the field. During the semester, an African-American male student admitted that he was considering dropping out of school because his professors made him feel stupid. He persisted, and the next semester he stopped by to report that he was really enjoying his Genetics course. A nontraditional female student was taking the course as a requirement for the major, but she was really interested in ecology because she wanted to study the impacts of strip mining on the coal mining region where she grew up. After taking this course, she expressed an interest in pursuing cell biology and is now taking an independent study course to investigate carcinogenic effects of coal dust. As we follow these students long term, it will be interesting to discover whether this improved self-confidence with cell biology persists, and whether it has affected decisions about their career paths.

Were There Differences between Female and Male Students?

Despite the strong evidence for a leaky pipeline of females, assessment of the writing assignments to date has not revealed many distinctions between males and females in their perceptions of science. Certainly, the small numbers of participating males was an obstacle to this type of analysis. The "draw a scientist" did reveal the one clear distinction between males and females. Whereas females see scientists as males and females at this stage of their education, males see scientists as almost exclusively male. Other studies have indicated that this tendency to view scientists as male (especially by male students) begins by elementary school (Fort and Varney, 1989; Barman, 1996) and persists through high school (Gardner *et al*., 1989), Our findings raise the possibility that even at this relatively late stage of education, females are not viewed as "scientists." Thus, the incorporation of social studies of science in K–12 and undergraduate curricula may be a necessary step for both males and females to see a place for women in science.

How Can This Approach Be Applied to Other Classes?

The inclusion of social studies of science within a cell biology course should be broadly applicable. Implementation will be easier for smaller classes (<50 students, as described here), because these classes lend themselves better to discussion, and the grading of written assignments will be more manageable. However, some of the exercises described here could be applied even to large classes (>100), and indeed, several of the discussion topics (e.g., model organisms, stem cell ethics, and thalidomide) have been used successfully in sections of BIOL 2104 with up to 150 students. Even in a large lecture hall, students can break up into small groups and then reconvene as a class to report the highlights of their discussions. If written assignments or written examinations are used, then the amount of instructor time becomes proportional to the number of students. Thus, this approach will be much more readily implemented in small senior-level cell biology courses than in first- or second-year, large introductory courses. However, given the evidence that the pipeline leaks throughout the undergraduate years, then the extra effort applied to the introductory-level courses may be time well spent. Indeed, the only absolute requirements for incorporating the social studies of science into cell biology are a commitment to social justice in science education and a willingness to try a new pedagogical approach.

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