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Learning How Scientists Work: Experiential Research Projects to Promote Cell Biology Learning and Scientific Process Skills

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Facilitating not only the mastery of sophisticated subject matter, but also the development of process skills is an ongoing challenge in teaching any introductory undergraduate course. To accomplish this goal in a sophomore-level introductory cell biology course, I require students to work in groups and complete several mock experiential research projects that imitate the professional activities of the scientific community. I designed these projects as a way to promote process skill development within content-rich pedagogy and to connect text-based and laboratory-based learning with the world of contemporary research. First, students become familiar with one primary article from a leading peer-reviewed journal, which they discuss by means of PowerPoint-based journal clubs and journalism reports highlighting public relevance. Second, relying mostly on primary articles, they investigate the molecular basis of a disease, compose reviews for an in-house journal, and present seminars in a public symposium. Last, students author primary articles detailing investigative experiments conducted in the lab. This curriculum has been successful in both quarter-based and semester-based institutions. Student attitudes toward their learning were assessed quantitatively with course surveys. Students consistently reported that these projects significantly lowered barriers to primary literature, improved research-associated skills, strengthened traditional pedagogy, and helped accomplish course objectives. Such approaches are widely suited for instructors seeking to integrate process with content in their courses.

Keywords: undergraduate, science education, experiential learning, mock symposia, primary literature comprehension, project based, assessment, survey.

INTRODUCTION

During the past two decades, one of the important debates in U.S. education has focused on the relative merits of emphasizing process skill development versus content-based teaching in undergraduate pedagogy (McNeal and D'Avanzo, 1997; Leonard, 2000; Zoller, 2000). Such discussions have spurred widespread support for innovations in college teaching, providing added impetus for ongoing models of curricular reform, including student-active teaching (McNeal and D'Avanzo, 1997; Silberman, 1996), cooperative learning (Novak and Gowin, 1984; Brody, 1995; Millis and Cottell, 1997; Lord, 2001), collaborative learning (Bruffee, 1993), and experiential learning (Cantor, 1995). All these models address process skill development (which includes developing skills in critical thinking, quantitative reasoning, oral and written communication, interpersonal relationships, social responsibility, and collaboration). However, we have to ask whether work on process has come at the expense of time to work on content. Can we achieve both goals simultaneously without a trade-off?

Science curricula that integrate more research and research-like experiences into undergraduate teaching have especially seen increased support from the National Science Foundation (NSF; 1996), the Howard Hughes Medical Institute (see science education grant programs online at www.hhmi.org/grants), and others (National Research Council, 1997; Rothman and Narum, 1999). Such support has led to increased engagement of students in project-based research experiments and other creative firsthand investigative exercises in lieu of "cookbook" experiments (Sundberg and Moncada, 1994; Stukus and Lennox, 1995; Chaplin *et al.*, 1997; Glasson and McKenzie, 1998; Grant and Vatnick, 1998; Henderson and Buising, 2001; Guziewicz *et al.*, 2002); Ledbetter and Lippert, 2002; Odom and Grossel, 2002). Although undertaking firsthand science is vital to helping beginning students learn, enjoy, and later work in science, other ways of familiarizing students with the fast-paced world of contemporary research may be just as relevant.

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Science is communicated within the scientific community through primary literature that uses a highly technical language. This language is a learning barrier for even the brightest beginning students. If we can provide effective ways for beginning students to develop the oral and written vocabulary needed to comprehend and communicate this jargon-filled primary literature, they will likely better engage in contemporary research, feel part of the scientific community, and appreciate the research behind textbook information. In fact, the ability to comprehend primary literature improves critical thinking skills (Janick-Buckner, 1997; Fortner, 1999; Hermann, 1999; Henderson and Buising, 2000; Muench, 2000) and the understanding of scientific discourse and research behind textbook knowledge (Houde, 2000) in advanced undergraduate students. Can similar approaches also help students in introductory-level courses? Furthermore, can such approaches be designed to facilitate both the mastery of sophisticated subject matter and the development of process skills?

In this article, first, I describe the pedagogy I developed to infuse strong content and diverse process skills into an introductory cell biology course taught at the sophomore level. Second, I elaborate on five classroom activities designed to promote process skill development within content-rich pedagogy and to connect text-based and laboratory-based learning with the world of contemporary research. Together, they require sophomore students to comprehend, communicate, and author primary research articles in cell and molecular biology. Third, I describe a course survey designed to assess student attitudes toward learning outcomes associated with these five projects. Last, I state and discuss several survey findings that strongly suggest that projects and the pedagogy build process skills and reinforce cell biology learning in students.

PEDAGOGICAL DESIGN

Current trends in science education support the hypothesis that engagement of students in specific research projects that allow them to act out activities that science professionals routinely perform will 1) promote student interest in and mastery of sophisticated science content, 2) help students develop scientific process skills, and 3) help students gain closer familiarity with scientific culture. I tested this hypothesis by designing several research projects in both beginning and advanced undergraduate-level science courses. I call these projects "mock experiential" because these diverse role-playing experiences help the student link classroom learning with the practice of science in the scientific community. Here, I describe my use of such projects in a cell biology course taught six times at Kalamazoo College (Michigan) and more recently at Lake Forest College (Illinois), which has allowed me to evaluate the transferability of my pedagogy and to compare learning outcomes and student attitudes between two student populations. Both schools are small liberal arts colleges that have a history of encouraging undergraduate science research.

Cell biology is a sophomore-level course required for the biology major at both colleges. At semester-based Lake Forest, it is the fourth course in an introductory sequence of four biology courses and is taught once a year. It carries 1 course credit (32 semester course credits are required for graduation), and it meets each week for two 80-min lecture sessions and one 4-h laboratory session. Students must take, in addition to the other three introductory biology courses, two courses in general chemistry as prerequisites. At quarter-based Kalamazoo, this course is one of three introductory core courses in biology and is taught twice a year. It carries 1 course credit (36 quarter course credits are required for graduation), and it meets each week for three 75-min lecture sessions and one 3.5-h laboratory session. Kalamazoo students take at least one course in organic chemistry in addition to two general chemistry courses, and although previous biology course work is not required, most students have previously taken the two other introductory biology courses. Class sizes at Kalamazoo varied between 9 and 48, whereas at Lake Forest, 22 students took the course in 2002 and 37 are enrolled for 2003.

Identifying Course Goals and Designing the Course

I identified six course goals meant to either impart content or build process (Figure 1A). To accomplish these goals, I use a tripartite strategy that combines lecture, laboratory, and mock experiential research projects (Figure 1B; the complete syllabus is available online at the course web site, which is listed in the Appendix). Even though this article focuses on the mock experiential research projects, I first summarize the more traditional aspects of my pedagogy for two reasons. First, the projects are purposefully intended to complement and strengthen, but not replace, the content and process skills that lectures and labs impart. Second, lecture and laboratory-based work together account for 75% of the student's grade (Figure 1C; this includes the lab report presented as Project 5 in the next section).

Conveying Content (Course Goals 1 and 2)

Most of the content of the course is conveyed through classroom lectures and discussions. As a primary textbook, I use almost all of *Essential Cell Biology* (Alberts *et al*., 1998). For 1 week near the beginning of the semester, students take instructional responsibility for discussing *The Double Helix* (Watson, 1998), two primary articles (Watson and Crick, 1953a, 1953b), and an essay reflecting on Rosalind Franklin (Piper, 1998). I provide content packets for every classroom session so that instead of taking notes, students listen, ask questions, and initiate discussions. To evaluate proficiency (50% of grade; Figure 1C), I give numerous quizzes and two exams (samples are available through the Teacher Resources web site listed in the Appendix). The projects described in the next Section also provide content by requiring students to research in considerable depth the topics learned in the classroom.

Building Process (Course Goals 3–6)

Process skills are imparted through five laboratory experiments during the first half of the course and five mock experiential research projects during the second half. Initially, I taught this course with the five projects interspersed and alternating with the five labs. Although such scheduling was successful, student feedback strongly indicated that students preferred that laboratory and project schedules be

A. Content-specific and process-specific goals

1. Understand why and how cells are the units of life and why you should care about cells
2. Appreciate that cells hold the key to both human health & human disease
3. Increase student engagement in the world of contemporary biology research
4. Increase student understanding of the scientific discovery process and how to think scientifically
5. Increase student ability to communicate science effectively both orally and in written form
6. Increase student ability to collaborate with peers and integrate individual talents

Content (goals 1–2)
Process (goals 3–6)

B. Tripartite Pedagogy

Lecture	Laboratory	Mock Experiential Research Projects
Readings	1. Basic Skills	1. Journal Club
1. Essential Cell Biology	2. Cellular Microscopy	2. Medical News Journalism
2. The Double Helix	3. Animal Cell Culture	3. Disease Review Article
	4. Enzyme kinetics	4. Disease Symposium Seminar
	5. DNA Technology	5. Lab Report Written as a Primary Article

C. Grading Scheme

Content (50%)	
Lecture	
Quizzes	15%
Midterm Exam	20%
Final Exam	15%
Process (50%)	
Laboratory	
Laboratory Notebook Assessment 1	7.5%
Laboratory Notebook Assessment 1	7.5%
Mock Experiential Research Projects	
1. Journal Club	5%
2. Medical News Journalism	5%
3. Disease Review Article	5%
4. Disease Symposium Seminar	5%
5. Laboratory Report as a Primary Article	10%
Resource Use and Collaborative Preparation	5%
TOTAL (100%)	**100%**

Figure 1. Integrating process with content in pedagogical design. (A) Course goals: Two content-specific and four process-specific course goals are shared with students on the first day of class. (B) Tripartite pedagogy: Content is imparted through classroom lectures and discussion and requires reading two books and three papers. Process is integrated with content through five laboratories and five mock experiential research projects. (C) Grading scheme: Content and process skill evaluations each make up 50% of the students grade.

separated, with labs scheduled earlier and projects later, because the projects required extensive preparatory groundwork. Students perform experiments from five laboratory modules (Figure 1B), which are fairly standard in current curricula.

Briefly, Lab 1 (basic skills) introduces students to cells with bacterial and yeast culturing and determination of their growth requirements. Students are given guidelines for keeping detailed lab notebooks, and they become familiar with instruments used in the next four labs, such as phase contrast microscopes, the multi-imaging documentation system, incubators, centrifuges, and spectrophotometers. Lab 2 (cellular microscopy) engages students in several staining techniques and in sizing and describing several cell specimens from each of the five kingdoms of life, by using bright-field and phase contrast microscopy. Labs 3 through 5 can be sculpted minimally as single-session labs or expanded into multiweek projects. In Lab 3 (DNA technology), students isolate plasmid DNA from bacteria and quantify DNA concentration and size, and in expanded labs, they construct restriction maps of the plasmid by designing restriction enzyme digestion reactions, and they amplify specific genes from the plasmid by polymerase chain reaction. In Lab 4 (enzyme kinetics), students measure Michaelis–Menten kinetic parameters for alcohol dehydrogenase, and in expanded versions, they assess the actions of various types of inhibitors, pH, and temperature on enzyme kinetics. Lab 5 (animal cell culture) allows students to culture several animal cell lines and quantitatively assess abilities of cells to grow in different serum concentrations, and in expanded labs, they subculture cells and evaluate the effects of specific growth factors and chemical regulators. Each year, one of labs 3 through 5 (most often the DNA technology lab) is expanded into a multiweek lab (typically 3 weeks in semesters and 2 weeks in quarters); the others remain single sessions. In semesters, all laboratories are completed before midterms, whereas in quarters, the last lab is completed after midterms.

Evaluation of laboratory work involves two types of assessment (Figure 1C). First, I grade student laboratory notebooks twice for completeness, organization, data presentation and analysis, and strength of discussion. Second, and only for the multiweek lab, I require that students write one laboratory report, in the form of a primary research article written and formatted for *Cell*, later elaborated as the fifth mock experiential research project.

MOCK EXPERIENTIAL RESEARCH PROJECTS

Overall Design

The course includes five mock experiential research projects (Figure 1B), which represent specific activities typical of science professionals (graduate students, established scientists, and science journalists). Students complete these increasingly challenging projects in the following sequence: 1) Journal Club; 2) Medical News Journalism; 3) Disease Review Article; 4) Disease Symposium Seminar; and 5) Laboratory Report Written as a Primary Article. These projects are designed with the assumption that incoming sophomore students have minimal familiarity with grasping primary literature. Projects 1 and 2 stress comprehension and communication of one primary article. Projects 3 and 4 stress the ability to integrate and communicate information from several related primary articles. I focus these two projects on the cell biology of disease because of high premedicine interest among my students. I strive to balance this bias toward human biology by frequently providing optional primary readings in class that highlight plants and lower organisms as invaluable model systems in cell and molecular biology. Project 5 develops the ability to personally author a primary article based on laboratory experiments that students conduct in this course. If successfully completed, these projects are intended to bolster all process and content-specific course goals. To emphasize cooperative learning and collaboration (the last goal), I made four of the projects group based: Projects 1, 3, and 4 involve groups of 3–5 students. Project 5 is performed in pairs. Only Project 2 is individually completed.

Figure 2 depicts the suggested schedule for implementing projects in semesters or quarters. In either calendar, a syllabus workshop during the first week of the course introduces projects in substantial detail. Students are assigned or choose project topics by the second week so that maximum time is available to complete projects. The multiweek investigative lab is among the first labs completed so that Project 5 (which depends on data from this lab) can be implemented successfully. Mandatory meetings with the instructor to initiate project discussions are held early as a way to provide momentum. Early working bibliography deadlines also allow time for interlibrary loan requests and help students avoid time crunches closer to final project deadlines. Peer research communication skills workshops (detailed later) are held at least 3 weeks before final project due dates. All final projects, whether written papers or oral presentations, are scheduled after midterm exams and spaced at least 1 week apart when possible (more easily achieved in semesters). The oral presentations associated with Projects 1 and 4 are conveniently held during laboratory sessions.

Project-Specific Pedagogical Support

I provide two regular forms of out-of-classroom support that students consistently find useful. First, because bibliographical research is required for all projects, college reference librarians and I designed a web-based bibliographic research guide (to access it, visit the course web site listed in the Appendix) to help students throughout the semester search and acquire articles and books by using our library system and other resources. It also provides information on how to cite sources, states the college policy on plagiarism, and points to resources for various types of science writing.

Second, I actively employ peer-based supplemental instruction, a well-established teaching and learning support system used in many institutions (Mazur, 1997). For example, in spring 2002, I selected two academically superior students familiar with my pedagogy to be peer teachers. Such college-paid peer instructors undergo formal on-the-job training at Lake Forest College's Learning and Teaching Center. They attend all lectures and labs and hold weekly supplemental instruction sessions, which I do not attend. Attending peer sessions is not mandatory for students, in line with college policy; I also favor this policy because the student has responsibility for attending. These peer-guided "self-help" sessions are designed to reinforce key concepts taught in the lecture and the lab. Peer teachers also play active instructional roles in the laboratory, where I provide them with direct opportunities for instruction. Most relevant to the projects, peer teachers hold two workshops on research communication skills targeted to help students further master the projects. During these workshops, specific project requirements are detailed again to reinforce information provided initially in the syllabus workshop and on the written syllabus. Past examples of good and excellent papers and PowerPoint presentations are discussed. Project grading sheets are reviewed (Figure 3; See also the Teacher Resources web site in the Appendix) as a way to provide insight into what I most look for. I do not attend these workshops because I believe that peer teachers teach the ropes of success more confidently and freely in my absence. Although the workshops are optional, in the past more than 90% of Kalamazoo and Lake Forest students attended them, with at least one student from each group present.

In spring 2002, I employed, in addition to peer teachers, a student to be a writing consultant. Three of the five projects (Projects 2, 3, and 5) include submitting papers, each requiring a distinct form of science writing. To help students meet the strong writing emphasis, I choose an academically outstanding senior biology major with superior writing skills to become a paid tutor at the college's Writing Center. I encourage students to have this consultant review drafts of all three papers. For students who need the most help with

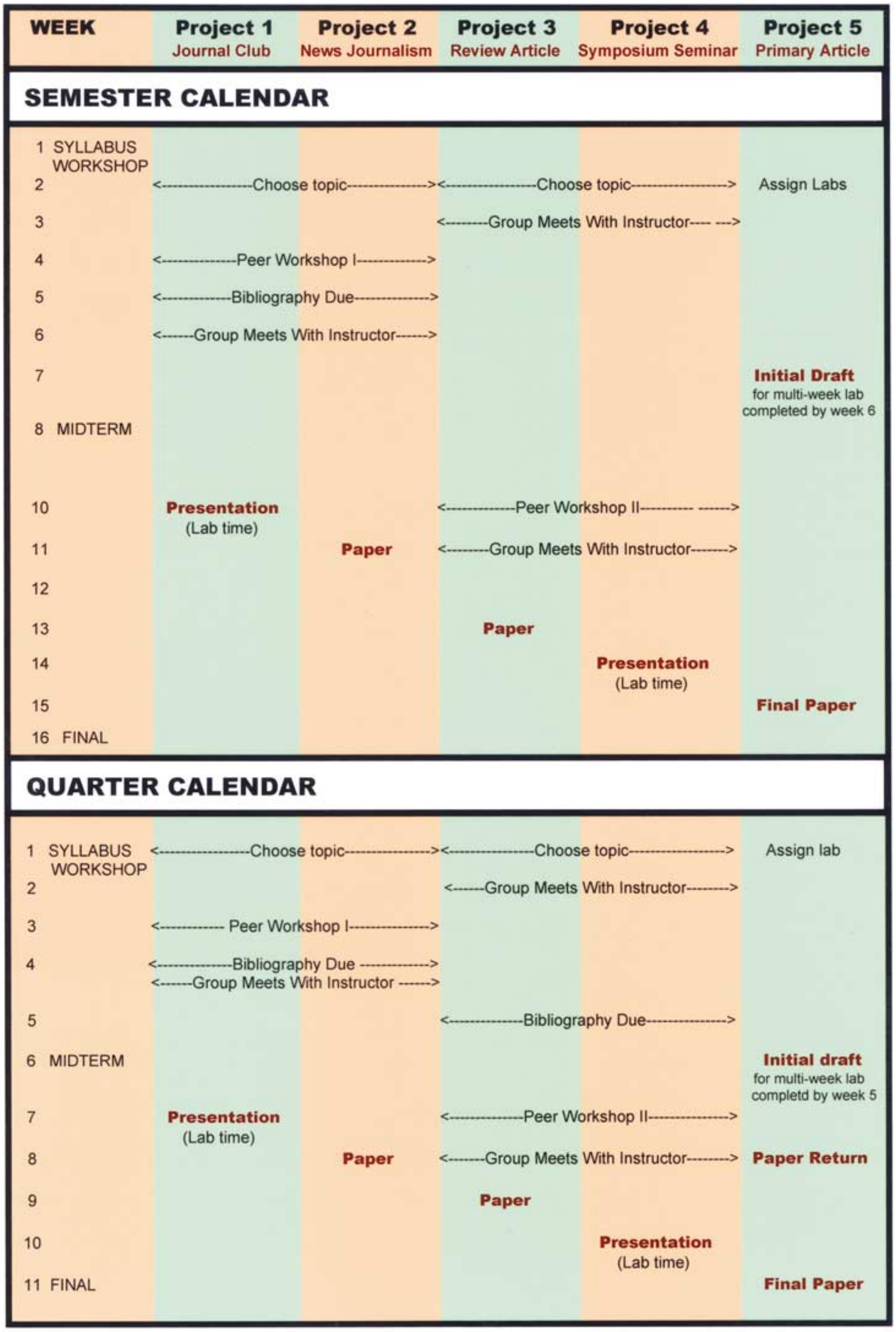

Figure 2. Suggested project schedule. These schedules are recommended for assigning the five projects during (A) a 16-week semester or (B) an 11-week quarter.

writing, I encourage additional visits. In spring 2002, all seven groups met with the writing consultant for the group writing efforts in Projects 3 and 5; however, only 17 of 22 students used the writing consultant for individually written Project 2. Four of the 5 students who did not consult submitted among the weakest papers for Project 2, although they were not my weakest students.

Rewards for Resource Use

Because I consider the process that students take in developing each project an important aspect of building their process skills, I instituted Resource Use and Collaborative Preparation points into the grading scheme for the projects (Figure 1C). Students earn these points by 1) attending the two peer workshops on research communication skills; 2)

BIO221 Cell & Molecular Biology **Group:** ______________
CELL BIO NEWS: The Journal Clubs ______________
Peer & Instructor Assessment ______________
____

Peer Assessor 1 Recommendation __________ **(/50)**
Peer Assessor 2 Recommendation __________ **(/50)**
Averaged Instructor Approved Score __________ **(/50)**

Contents of Presentation (35 points)

1. Introduction:____/8
___ Authors, title, and journal of papers presented
___ A Road map of where we are headed today
___ Background significance provided
___ Highlighted gap in knowledge

Additional Comments:

2. Hypothesis & Specific Aims:____/3
___ Testable statement presented
___ Main goals to test hypothesis elaborated

Additional Comments:

3. Methods:____/8
___ All techniques mentioned
___ Kept most technique explanations short and sweet
___ Elaborated on three cell/molecular biology techniques in significant detail
___ Used easy to understand graphics

Additional Comments:

4. Results:____/10
___ For each result, posed specific question, mentioned technique and showed data
___ Explained graph, picture, table simply & clearly; highlighted control experiments
___ Got main point of each result across
___ Logically connected results and developed an emerging story

Additional Comments:

5. Discussion: ____/8
___ Results interpreted
___ Significance of results explained & compared with other published findings
___ Presented biological model that highlighted the new findings
___ Suggested new experiments to test new hypotheses
___Criticisms

Additional Comments:

Summary Evaluation (15 points)

Peer Education: ____/5
___ Written and visual quality of handout to peers in audience
___ Addressed the main concepts so that peers could connect to lecture & lab

Technological & bibliographical proficiency:____/5
___ Quality of graphics, font, color
___ Slide layout and organization
___ Proper referencing of material

Group Dynamics: ___/5
___ Engaging participation (demonstrated enthusiasm and creativity)
___ Equal participation
___ Audience Involvement
___ Preparedness (no cue cards, confident eye contact, flowing dialogue)

Additional Comments:

Overall group or individual comments:

Figure 3. Using peer teachers and sharing expected outcomes during project development. During one of two peer workshops on research-communication skills held at least 3 weeks before project deadlines, peer teachers discuss with students grading sheets for each project. Shown here is the grading sheet for Project 1, the Journal Club. Such discussions allow students to clearly understand the exact outcomes expected by the instructor, which helps students produce high-quality efforts. All such grading sheets emphasize assessment of scientific content and scientific process. As explained in the text, peer teachers and the writing consultant assist me in grading most projects, but I reserve sole responsibility for assigning the final student grade.

having the writing consultant critique drafts of the three written assignments for Projects 2, 3, and 5; 3) attending mandatory group meetings with the instructor to discuss research progress; 4) meeting project bibliography deadlines; and 5) practicing their two talks for Projects 1 and 4 in front of peers.

The Projects

The five projects, as they were used most recently in spring 2002, are described next.

Project 1: Journal Club. In the first project, students role-play a group of graduate students who must present research papers for a routine research journal club. The underlying goal is for students to develop skills to grasp one primary article and communicate it orally to a scientifically literate audience. Each group picks one paper from several published in *Cell*, *Science*, and *Nature* that I preselect. No two groups select the same paper. Each paper elaborates on topics covered in lecture and lab and has clear general relevance. For example, in spring 2002, one student group chose Gotz *et al.*'s (2001) "Formation of Neurofibrillary Tangles in P301L Tau Transgenic Mice Induced by Aβ42 Fibrils," which was relevant to the protein-folding and apoptosis topics covered in lecture and the DNA technology and microscopy labs. Likewise, Alzheimer's disease research is of high public interest. For more examples of paper selections, see Figure 4.

Groups give 45-min PowerPoint presentations, followed by 15-min open discussions. Groups meet with me at least 3–4 weeks before their presentation, when we read the paper together, paragraph by paragraph, and figure by figure. Prior to meeting with me, they are expected to have read the paper thoroughly. Students know that at this stage, despite multiple readings, they are not expected to understand more than one-fourth of the paper. They are required to bring a

Xiaojuan M, et al (2000). Regulation of Cell Fate Decision of Undifferentiated Spermatogonia by GDNF. Science 287, 1489-1493.
LECTURE/LAB CONCEPT: protein function, gene expression, cell signaling, cell differentiation, DNA technology

Migliaccio E, *et al* (1999). The $p66^{Shc}$ Adaptor Protein Controls Oxidative Stress Response and Life Span in Mammals. Nature 402, 309-313.
LECTURE/LAB CONCEPT: protein function, cell cycle control, aging, cell signaling, DNA technology

Yan R, *et al* (1999). Membrane-anchored aspartyl protease with Alzheimer's disease β-secretase activity. Nature 402, 533-537.
LECTURE/LAB CONCEPT: protein folding, enzyme function, DNA technology, cell culture

Wang J, *et al* (1999). Inherited Human Caspase 10 Mutations Underlie Defective Lymphocyte and Dendritic Cell Apoptosis in Auto-iimmune Lymphoproliferative Syndrome Type II. Cell 98, 47–58.
LECTURE/LAB CONCEPT: apoptosis, gene expression, differentiation, mutation, cancer

Min K, *et al* (1999). Preventing Neurodegeneration in the Drosophila Mutant *bubblegum*. Science 284, 1985-1988.
LECTURE/LAB CONCEPT: apoptosis, mutation, organelle function, membrane transport, DNA technology, model systems

Miyado K, *et al* (2000). Requirement of CD9 on the Egg Plasma Membrane for Fertilization. Science 287, 321-324.
LECTURE/LAB CONCEPT: protein-protein interactions, extracellular signaling, meiosis, DNA technology, microscopy

Holmbeck K, *et al* (1999) MT1-MMP-Deficient Mice Develop Dwarfism, Osteopenia, Arthritis, and Connective Tissue Disease due to Inadequate Collagen Turnover. Cell 99, 81–92.
LECTURE/LAB CONCEPT: protein function, mutation, gene regulation, diffrentiation, DNA technology, model systems

Rudolph KL, *et al* (2000). Inhibition of Experimental Liver Cirrhosis in Mice by Telomerase Gene Delivery. Science 287: 1253-1258.
LECTURE/LAB CONCEPT: gene therapy, gene expression, aging, cancer, DNA technology, model systems

Figure 4. Sample primary Articles for Journal Club and Medical News Journalism Projects. As an example, in spring 2000, each student group focused on one article chosen from these primary papers for the first two mock experiential research projects (Journal Club and Medical News Journalism). All articles were recently published in leading journals: *Cell*, *Nature*, and *Science*. All have cell and molecular emphasis, connect to concepts taught in lecture and lab (concepts highlighted in red), and have easy-to-identify general relevance (many, but not all, papers are related to human diseases).

comprehensive list of words and phrases that they still do not understand despite some research on their part. At this meeting, in addition to discussing these terms, I help students understand the anatomy of a primary article, providing conceptual understanding of background and methods, clarifying hypotheses, interpreting data, and guiding relevant discussion. We also discuss papers to be used for Journal Club background, methods explanations, and discussion. We strive for a three-fourths understanding of the paper. Depending on the group, one or more additional meetings may be scheduled.

During the week preceding the presentation, students practice it at least once, often inviting advanced biology majors to these presentations for peer feedback. The journal clubs are made public so that noncourse students and faculty may attend. During the Journal Club presentation, presenting groups provide a two-page pamphlet that summarizes the main points of the paper and how it connects to cell biology, as a way to further demonstrate their ability to educate peers. Peer teachers evaluate each presentation on both content and process by using my grading sheet and recommend a grade.

Project 2: Medical News Journalism. In the second project, each student plays the role of a medical journalist assigned to convey an exciting new biomedical discovery recently published in a primary article for the readership of a popular publication such as *The New York Times* or *Time* magazine. The underlying goal is for students to learn skills to communicate the biological relevance of a primary article in simple, written language. Students write about the same primary research paper used for the Journal Club, so they are familiar with its content.

Students submit a 1200-word paper written in jargon-free language that captures the paper's biological relevance, describing results simply without compromising scientific content and discussing how the discovery advances biomedical knowledge. Because I preselect all articles for general relevance (Figure 4), students concentrate on getting to the heart of the science, without being hindered by technical details that are not necessary. Students also present a figure depicting a biological model at the cellular level that highlights the new discovery being reported. However, unlike in popular science journalism, students are required to cite primary articles, review articles, books, or other sources within the text (citing between 7 and 10 references is typical). Although this is an individual assignment, student groups are encouraged to collaborate on all aspects of research prior to writing the paper.

I provide examples of recent journalism articles that appear in the *Chicago Tribune* or *Time* magazine. I place *The Science Times Book of the Brain* (Wade, 1998) on library reserve because it is an excellent collection of articles written by noted science journalists. Peer teachers and I grade this project jointly by using a detailed grading sheet that evaluates papers on both scientific content and journalistic storytelling.

Project 3: Disease Review Article. In the third project, student groups role-play a team of scientists invited to author a review article on a human disease for a leading journal. The underlying goal is for students to develop the ability to comprehensively integrate cell and molecular research on a specific topic by synthesizing information from several primary research articles. Researching a human disease holds immediate interest for most students, especially if they choose the disease.

Students submit their research review articles for publication in an "in-house" review journal. I named this mock journal *Trends in Diseased Cells (TIDS)*, a name that was strongly influenced by the real reviews journal *Trends in Biochemical Sciences* and its sister publications (publisher: Elsevier Science). In coauthoring a 4000-word review article, students consult and cite at least 15 papers (at least half of which are primary articles). Key to this paper is a section on "current research" that elaborates on three to four heavily investigated areas of cell and molecular research on the disease, for each of which between 2 and 5 primary papers are summarized. Each paper includes two figures representing biological models for disease, often illustrating models for molecular mechanisms as supported by current research. Groups also submit abstracts pages simply combining the paper summary and a model from the paper, which are compiled into a second publication, *The Abstracts Book*. The department supports the costs of advertising and printing these publications.

I provide a list of diseases for which tremendous progress has been made at the molecular level in the past 5 yr, but students may pick others. Each group meets with me at least twice before the paper deadline. The first meeting (at the beginning of the semester) ensures that each group has sufficient preliminary leads to get started. I often lead them to an older review article and hint at the kinds of cell and molecular research themes that they might consider. Before the second meeting, students discuss their bibliographical collection, identify research topics for which they have the appropriate primary articles, and assign each group member one research theme for which he or she is responsible. By then, students have done their Journal Club projects, so most of them show reasonable familiarity with the papers. Often, this meeting simply serves to ensure that they are making correct interpretations and connecting research topics into a cohesive picture. Less often, I redirect some students who have either strayed in focus or still have trouble with paper comprehension (especially with the more technical papers). Peer teachers and I cograde this paper by using a grading sheet that evaluates both scientific content and review format; a composite score serves as the final project grade.

Project 4: Disease Symposium Seminar. The fourth project is intended to help students develop skills in orally presenting their review of a specific topic-based synthesis of information from several primary articles. I ask the groups to role-play the same team of disease experts, who are now invited to present a joint 45-min research seminar at a public research symposium entitled the "The Diseased Genome" (Figure 5A). This project is held toward the end of the semester's during laboratory sessions. Depending on the enrollment and the number of laboratory sessions, the symposium either lasts all day (as done at Kalamazoo during morning and afternoon labs) or progresses over 2 weekdays (as done at Lake Forest, where only afternoon labs are scheduled). Posters advertise the symposium around the campus community, inviting all to attend (Figure 5D). Many students invite friends and even families to "their scientific meeting." Peer teachers serve as symposium organizers and panel chairs. I purposefully maintain a low profile so that students feel strong ownership of their conference. All speakers receive copies of *TIDS* (Figure 5B). *The Abstracts Book* (Figure 5C) is distributed to all attendees. To make the symposium even more realistic, student presenters dress in professional attire, and a celebratory reception is held at the symposium end. Talks are videotaped and made available to students for later self-review.

I tell students to think of the seminar as the visual counterpart to their research review article. I also remind them that this talk is in some ways the opposite of the Journal Club: instead of dissecting one primary article, they now have to cohesively synthesize several primary articles. A few weeks before the symposium, either I give a talk about my research or, more often, I invite a noted cell and molecular biology scientist (someone known to give an outstanding research talk and with a keen interest in undergraduate science education) to present a professional research seminar geared toward undergraduates. This seminar serves as a model for students to emulate as they prepare their seminars, as much as it educates them on a cell biology topic and provides them with an opportunity to meet a well-known scientist.

Students typically present a 45-min PowerPoint seminar, but they often supplement it with other audiovisual support. In the past, students used overheads or the chalk board, or they performed theatrical skits depicting either a research lab setting, patients in a doctor's office, or how biological molecules interact in a signaling pathway. Others created physical props (e.g., French bread to represent a protein and bread knives to represent proteases) and audience-interactive exercises. Few creative boundaries are set except to require that presentation aids educate peers on a cell biology concept. Unlike in the other three projects, in this project the course students (and not peer teachers or the writing consultant) assess one another's work and recommend grades. Different subsets of six to eight students use my detailed grading sheet to anonymously evaluate presentations during the symposium. The highest and lowest scores are discarded, and the average of the remaining scores becomes the recommended grade.

Project 5: Lab Report Written as a Primary Article. Finally, after becoming conversant with grasping and communicating primary articles, students are required write their own primary article. Earlier in the semester, students worked in pairs to complete a multiweek experiment during regular lab sessions. The student pairs now coauthor a formal manuscript designed to mimic a primary research article to be submitted to a real peer-reviewed journal, such as *Cell*. In addition to discussing primary articles from the published journal as examples, peer teachers and I provide detailed instructions on content and format.

I require submission of the initial draft 1 week after completion of lab module, while details of the laboratory experiments are fresh in students' minds. Before student pairs submit their completed manuscript as an initial draft, I encourage them to have the writing consultant read their paper. After the initial submission, peer teachers and the writing consultant grade the papers and provide comments with particularly strict rigor. As such, initial grades are usually low and allow for significant improvements in the final draft. On purpose,

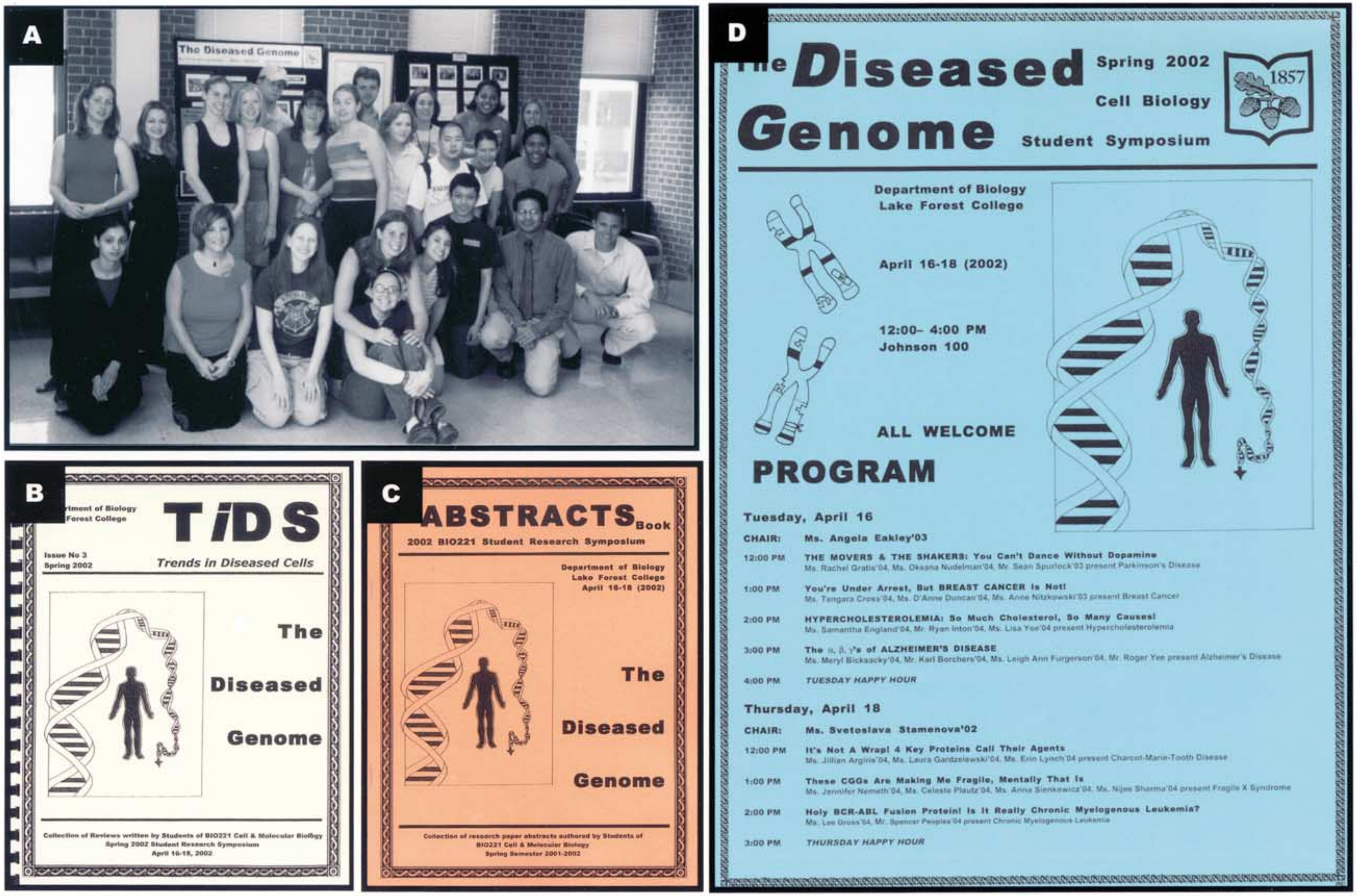

Figure 5. The 2002 Diseased Genome Symposium. (A) Twenty-two Lake Forest College students, one of two peer teachers, and the instructor pose in front of the registration desk on a symposium day. Seven student groups gave 45-min multimedia presentations in a professional conference setting conducted during two afternoon laboratory sessions the last week of the semester. (B) This 55-page in-house *Trends in Diseased Cells (TIDS)* journal, modeled after the life sciences reviews journal series published by Elsevier Science (*Trends in Biochemical Sciences* and sister journals), was distributed to all student presenters. (C) This second in-house publication, *The Abstracts Book*, was distributed to all symposium attendees. (D) Campuswide symposium publicity invited the college community to attend. Students from other courses, several faculty members, administrators, and family members of presenting students were among the audience during the symposium to demonstrate their support for students and to learn about the latest work in the field. To view abstracts and complete reviews written by student groups, visit the course web site listed in the Appendix.

Table 1. Perceived research communication skills and interests of students before and after taking Cell Biology at Lake Forest College, as determined by a precourse–postcourse survey

Survey statements	Lake Forest College		
	Mean perception[a]		Perception change (degree of significance)
	Precourse	Postcourse	
Communicating contemporary research			
S1. I can effectively communicate contemporary scientific research orally to my peers.	3.45	4.52	0.001
S2. I can effectively communicate contemporary scientific research in writing to my peers.	3.68	4.48	0.05
Primary literature comprehension and communication			
S3. I am knowledgeable about what a "primary research article" is and what its purpose is in the scientific world.	4.18	4.76	0.01
S4. I can effectively read and comprehend a primary research article for myself.	3.55	4.10	ns
S5. I can effectively communicate findings of a primary research article to my science peers.	3.68	4.43	0.01
S6. I can effectively communicate findings of a primary research article to my nonscience peers.	3.41	4.38	0.001
S7. I can effectively integrate and synthesize information from several related primary research articles.	3.64	4.43	0.01
S8. I am knowledgeable on how scientists communicate scientific information with each other and with the public.	2.41	4.19	0.001
S9. I am knowledgeable on the state of current research in the field of cellular and molecular biology.	3.23	4.14	0.01
S10. I have the skills to read primary research articles in scientific fields other than cell and molecular biology.	4.18	4.24	ns
Interest in scientific and health professions			
S11. I am interested in doing an undergraduate research internship and/or senior thesis in a scientific field.	4.64	4.47	ns
S12. I am contemplating a future career that involves scientific research or health professions.	4.05	4.77	ns
Relevance of primary literature to classroom learning			
S13. It is important that I am familiar with primary research and that I connect what I learn from understanding primary research to lecture and laboratory-based instruction.	4.86	4.67	ns

[a]Scale: 1 = Strongly disagree; 2 = somewhat disagree; 3 = neutral or no opinion; 4 = somewhat agree; 5 = strongly agree.

I provide at least 3 additional weeks for students to make revisions. Meanwhile, students are deeply engaged in the first four projects. This additional time and familiarity gained with primary literature allows students to best address peer-reviewer comments and produce superior final drafts. The incentive for revised final submission is purposely substantial: as many as 30 points (three letter grades) can be made up on this project on the basis of the quality of revised efforts. The writing consultant and peer teachers recommend the final grade.

SURVEY

Design

The survey was designed with two purposes. First, precourse–postcourse component assesses student perceptions of their own research-related process skills development before and after they take this cell biology course. Second, an additional postcourse component assesses student perceptions as a way to determine the relevance of the five projects in developing specific research skills, accomplishing course goals, and strengthening content-based pedagogy.

For the precourse–postcourse assessment, 13 statements (S1–S13; Tables 1–3) were rated on the first day and the last day of class with a Likert-type scale, from which students selected one of five choices that best matched their agreement level for each statement:

1 = Strongly disagree
2 = Somewhat disagree
3 = Neutral or no opinion
4 = Somewhat agree
5 = Strongly agree

These statements assess a student's general ability to communicate the world of contemporary research (S1–S2) and specific ability to read and communicate primary literature

Table 2. Perceived research communication skills and interests of students before and after taking Cell Biology at Kalamazoo College, as determined by a postcourse survey

Survey statements	Kalamazoo college		
	Mean perception[a]		Perception change (degree of significance)
	Precourse	Postcourse	
Communicating contemporary research			
S1. I can effectively communicate contemporary scientific research orally to my peers.	2.1	4.57	0.0001
S2. I can effectively communicate contemporary scientific research in writing to my peers.	2.3	4.48	0.0001
Primary literature comprehension and communication			
S3. I am knowledgeable about what a "primary research article" is and what its purpose is in the scientific world.	3.05	4.86	0.0001
S4. I can effectively read and comprehend a primary research article for myself.	1.82	4.41	0.0001
S5. I can effectively communicate findings of a primary research article to my science peers.	1.99	4.48	0.0001
S6. I can effectively communicate findings of a primary research article to my nonscience peers.	2.11	4.36	0.0001
S7. I can effectively integrate and synthesize information from several related primary research articles.	1.96	4.48	0.0001
S8. I am knowledgeable on how scientists communicate scientific information with each other and with the public.	3.02	4.68	0.0001
S9. I am knowledgeable on the state of current research in the field of cellular and molecular biology.	1.84	4.68	0.0001
S10. I have the skills to read primary research articles in scientific fields other than cell and molecular biology.	2.7	4.32	0.0001
Interest in scientific and health professions			
S11. I am interested in doing an undergraduate research internship and/or senior thesis in a scientific field.	4.46	4.76	0.05
S12. I am contemplating a future career that involves scientific research or health professions.	4.7	4.82	0.05
Relevance of primary literature to classroom learning			
S13. It is important that I am familiar with primary research and that I connect what I learn from understanding primary research to lecture and laboratory-based instruction.	4.29	4.87	0.05

[a]Scale: 1 = Strongly disagree; 2 = somewhat disagree; 3 = neutral or no opinion; 4 = somewhat agree; 5 = strongly agree.

(S3–S10), his on her interest in pursuing a scientific internship and a scientific career (S11–S12), and his or her need to be familiar with primary literature and to connect this familiarity to text and lab-based instruction (S13).

To complete the additional postcourse component, on the first day of class, students responded either "yes" or "no" to five statements marked A–E, which gauge prior student familiarity with the specific research skills that the five projects are designed to impart (Table 4). On the last day of class, students rated 12 statements marked A–L. Statements A–E assess whether students improved on five specific skills for which each project was designed (Table 5). Statements F–K assess whether students accomplished course goals (Table 6). Statement L determines whether projects strengthened laboratory and lecture-based learning (Table 6). For these 12 statements, in addition to being rated with the same Likert-type scale, students used a second scale (shown next) to determine which of the five projects was most relevant in supporting their overall rating for each statement. Students were allowed to rate more than one project with the same score.

1 = Detrimental
2 = Not relevant
3 = Somewhat relevant
4 = Relevant
5 = Most relevant

Participants

At Lake Forest College, all 22 students who took the course in spring 2002 participated. This survey was conducted on two occasions. The precourse part was initially conducted on the first day of class. Students also completed this part again on the last day of class (see SURVEY RESULTS for reasoning), when they completed the postcourse part. Kalamazoo students completed both the precourse part and the postcourse

Table 3. Lake Forest College precourse skills perception before and after taking Cell Biology

Statements common to precourse and postcourse survey	Lake Forest College: perception of precourse skills[a]		
	When asked after taking course	Increase or decrease in perception	Degree of significance
S1. I can effectively communicate contemporary scientific research orally to my peers.	2.68	↓	0.05
S2. I can effectively communicate contemporary scientific research in writing to my peers.	2.81	↓	0.01
S3. I am knowledgeable about what a "primary research article" is and what its purpose is in the scientific world.	3.38	↓	0.05
S4. I can effectively read and comprehend a primary research article for myself.	2.38	↓	0.001
S5. I can effectively communicate findings of a primary research article to my science peers.	2.28	↓	0.001
S6. I can effectively communicate findings of a primary research article to my nonscience peers.	2.29	↓	0.001
S7. I can effectively integrate and synthesize information from several related primary research articles.	2.19	↓	0.001
S8. I am knowledgeable on how scientists communicate scientific information with each other and with the public.	2.91	↑	ns
S9. I am knowledgeable on the state of current research in the field of cellular and molecular biology.	1.76	↓	0.01
S10. I have the skills to read primary research articles in scientific fields other than cell and molecular biology.	2.90	↓	0.05
S11. I am interested in doing an undergraduate research internship and/or senior thesis in a scientific field.	3.95	↓	ns
S12. I am contemplating a future career that involves scientific research or health professions.	4.53	↑	ns
S13. It is important that I am familiar with primary research and that I connect what I learn from understanding primary research to lecture and laboratory-based instruction.	4.29	↓	0.05

[a]Scale: 1 = Strongly disagree; 2 = somewhat disagree; 3 = neutral or no opinion; 4 = somewhat agree; 5 = strongly agree.

part as a single "after-the-course" survey in spring 2002, at least 1 yr after taking the course. Kalamazoo surveys were sent by mail to 101 students who had taken the course during three academic quarters (spring 2000, fall 2000, and spring 2001). Seventy-six Kalamazoo students (75%) returned completed surveys by mail, which I considered an extremely successful return rate because student participation was optional.

Data Analysis

Mean, standard deviation, and *t* tests were calculated by using Microsoft Excel. For each *t* test, the difference was considered not significant (ns) if the *T* value was not high enough to reject the null hypothesis $\alpha = 0.05$. In Tables 1 and 3, unpaired *t* tests for unequal variances were performed for comparing precourse–postcourse data because student anonymity was maintained during data collection. In Table 2, paired *t* tests were performed to compare precourse–postcourse Kalamazoo data. Lake Forest and Kalamazoo student data are shown separately in Tables 1–4, whereas pooled data are shown in postcourse assessments in Tables 5 and 6, because little to no difference was observed when the results calculated from individual college data sets (data not shown) were compared.

The complete survey form is available at the course web site listed in the Appendix.

SURVEY RESULTS

The results of the survey allowed me to draw five conclusions:

1. *Students improve several scientific process skills after taking the cell biology course*. Twenty-two Lake Forest College students perceived that they improved significantly in their general ability to communicate contemporary research and in their specific ability to communicate primary literature (Table 1). However, they did not perceive significant improvements in reading primary articles for themselves or in reading primary articles in fields other than cell and molecular biology. Students indicated a strong precourse interest, which persisted after course completion, in pursuing research internships and postgraduate careers in a scientific field. Students also maintained their strong precourse agreement that they should be familiar with primary research and that they should connect what they learn from understanding primary research to lecture and laboratory-based instruction.

2. *Comparisons between students of two colleges reveal both similarities and differences*. I surveyed Kalamazoo College students to determine whether their responses were consistent with the trend just described. Unlike the Lake Forest survey, in which the precourse data were gathered on the first day of class and the postcourse data on the last day, the

entire survey was done at Kalamazoo College at least 1 yr after course completion because I had designed it only after leaving that college. This "after-the-fact" survey, although imperfect, confirmed the Lake Forest trend but revealed a surprising difference. Like their Lake Forest counterparts, 76 Kalamazoo students thought that they had improved on several research skills, but these improved perceptions were consistently stronger and across the board for all 13 statements (Table 2). This difference occurred because Kalamazoo students perceived their precourse skills to be significantly lower than Lake Forest students did for most of these statements, whereas postcourse perception differences were mostly statistically indistinguishable (data not shown).

3. *Students altered their perceptions of precourse skill levels after taking the course*. Were Lake Forest students better prepared than the Kalamazoo students in the precourse skills? Or is this difference in precourse perception related to the timing of when students were surveyed? In some support of the first possibility, unlike Kalamazoo students, Lake Forest students do take an inquiry-based freshman seminar biology course that requires bibliographical, research and they are exposed to primary literature and inquiry-based labs in the field of ecology in another introductory biology course. To address the second possibility, I simply conducted a similar "after-the-fact" survey at Lake Forest College in which students reflected once again on their precourse skills, this time on the last day of class. Tellingly, Lake Forest students changed their ratings significantly for most statements (Table 3), lowering most to levels statistically indistinguishable from precourse perceptions reported by Kalamazoo students (Table 2). Contrary to what they believed before (Table 1) about whether they could comprehend primary articles for themselves and about reading non–cell biology primary articles, Lake Forest students now perceived significant improvement in these abilities (Table 3). Why did students lower their perception of precourse skills during the duration of a course? Although the answer may be more complicated, one possibility is that Lake Forest students did not realize how little they initially knew and gained better understanding of what these process-specific survey statements meant after taking the course and completing the rigorous projects. Possibly students were also less serious about the survey at the beginning of the course. In either case, they compensated for their earlier higher ratings without realizing it, because they were not shown the precourse skills ratings that they had posted at the beginning of the course. In fact, although after-the-course surveys may be considered flawed in some ways, they can reveal worthwhile insight into student perception.

4. *Students developed skills specific to each project and found all five projects relevant*. Most Lake Forest students were not previously familiar with the five projects developed in this course, except for Project 3 (Table 4). Kalamazoo students showed a lack of familiarity with these projects even more strongly. As expected at the sophomore level, students at both institutions had least experience with Project 5, which required writing an investigative laboratory report in the form of a primary article. Students then rated their abilities in five skill areas, for each of which I had developed one project (Table 5). The combined student response from both colleges was overwhelmingly positive for each of Statements A–E (Table 5). Remarkably, all 98 students gave the highest rating possible for Statement E, corresponding to Project 5, for which they had stated least prior experience (Table 4). Students consistently chose the same project that I had designed for developing a particular skill as the project that they too found most relevant for developing that skill (last column, Table 5). Not surprisingly, however, students found more than one project as relevant to communicating a primary article to science peers (Statement A) and to orally communicating synthesized information from several primary articles on a specific topic (Statement D). For example, for Statement A, students also rated the Disease Symposium Seminar and the Disease Review Article highly. Just like the Journal Club, these projects involved communicating information from primary articles to science peers, although their formats were different.

5. *Projects help accomplish course goals and strengthen content acquisition*. Both Kalamazoo and Lake Forest students strongly affirmed that projects helped achieve each content-specific and process-specific course goal (Statements F–K; Table 6). Not surprisingly, three projects or more were considered "relevant" (mean rating, 4.0 or more) for each course goal. The Journal Club, the Disease Symposium Seminar, and the Disease Review Article rated highest for all goals, which suggests that students enjoyed and gained the most from these three projects. Appropriately, all five projects were considered relevant in increasing written and oral communication skills (Statement J). Finally, students rated Statement L with a solid mandate demonstrating their belief that the projects strengthened cell biology learning and complemented traditional instruction (lecture and lab). Four of the five projects were found relevant to supporting this statement, and only the Medical News Journalism project fell short.

DISCUSSION

Success of Mock Experiential Research Projects

Three observations suggest that this course was successful in achieving its goals and that mock experiential research projects were important contributors to its success: 1) the consistent high quality of student performance on exams, in lab work, on papers, and during presentations associated with the projects; 2) the positive qualitative observations that students reported in course evaluations at both institutions; and 3) the positive comments that colleagues at both institutions shared on the level of preparation that students exhibit in their classroom after taking this course. Exams and project grading sheets that measure learning outcomes, as well as numerous examples of student work, are provided through the web sites listed in the Appendix.

The survey results quantitatively support the pedagogy's success by reporting consistently positive student attitudes toward their learning. Students perceived substantial improvements in several scientific process skills, and they found that projects helped strengthen cell biology learning and accomplishment of all course goals. Thus, the mock experiential research projects appear to provide strong scientific content while emphasizing process skill development, a valuable addition to introductory cell biology and other courses. I believe that lowering the barrier to understanding primary literature in particular allows students and instructors to approach even more sophisticated material in advanced courses. Mock experiential research projects will also better prepare science

Table 4. Prior student familiarity with projects specifically designed in this course

Precourse research project familiarity statements[a]	Response (%) Lake Forest	Response (%) Kalamazoo	Specific project designed
A. I have previously presented a primary article in the form of a scientific research journal club.	13.6	14.5	Journal Club
B. I have previously written a paper for a nonscientist audience that communicated scientific discoveries from a primary research article.	27.3	15.8	Medical News Journalism
C. I have previously reviewed a science topic by writing a research paper that required that I read and cite mostly primary research articles as my sources.	59.1	23.8	Disease Review Article
D. I have previously given a formal oral presentation of scientific research that involved reviewing a specific topic.	27.3	19.8	Disease Symposium Seminar
E. I have previously written on a scientific investigation in the format of a primary research article intended for a peer-reviewed research journal.	13.6	2.6	Lab Report Written as a Primary Article

[a]Students responded either "yes" or "no" to Statements A–E. Students responding "yes" are represented as the percentage of the total responses.

Table 5. Project relevance to acquiring specific skills for which projects were designed

Postcourse research skills statements[a]	Mean[b]	Which project was most relevant?[c,d]
A. I increased my ability to understand and communicate a primary research article to my science peers.	4.85	**Journal Club (4.67)** Disease Symposium Seminar (4.54) Disease Review Article (4.22) Lab Report Written as a Primary Article (3.4) Medical News Journalism (2.8)
B. I increased my ability to understand and communicate a primary research article to my non-science peers.	4.64	**Medical News Journalism (4.56)** Disease Symposium Seminar (3.91) Journal Club (3.61) Disease Review Article (3.24) Lab Report Written as a Primary Article (2.89)
C. I increased my ability to scientifically communicate in writing, information that I integrated and synthesized from primary research articles on a specific topic.	4.75	**Disease Review Article (4.67)** Medical News Journalism (3.65) Lab Report Written as a Primary Article (3.46) Disease Symposium Seminar (3.21) Journal Club (3.17)
D. I increased my ability to scientifically communicate orally, information that I integrated and synthesized from primary research articles on a specific topic.	4.8	**Disease Symposium Seminar (4.93)** Journal Club (4.54) Disease Review Article (2.8) Medical News Journalism (2.72) Lab Report Written as a Primary Article (2.48)
E. I increased my ability to understand and present experimental data that I generated in laboratory investigations in a professional scientific format.	5.0	**Lab Report Written as a Primary Article (4.59)** Disease Review Article (3.4) Journal Club (2.92) Medical News Journalism (2.89) Disease Symposium Seminar (2.55)

[a]Students rated the postcourse statements according to the statement scale. The project rating scale was used to indicate which of the five experiential projects were relevant to each statement rating, as shown in the last column.
[b]Statement scale: 1 = Strongly disagree; 2 = somewhat disagree; 3 = neutral/no opinion; 4 = somewhat agree; 5 = strongly agree.
[c]Listed on order of relevance, with most relevant listed first and in boldface.
[d]Project rating scale: 1 = Detrimental; 2 = not relevant; 3 = somewhat relevant; 4 = relevant; 5 = most relevant.

Table 6. Project relevance to course goal accomplishment and overall pedagogy

Postcourse survey statements[a]	Mean[b]	Which projects were relevant[c,d]?
Content-specific course goals		
F. These projects increased my ability to understand why and how cells are the units of life and why I should care about cells.	4.48	**Disease Symposium Seminar (4.41)** **Disease Review Article (4.30)** **Journal Club (4.26)** Medical News Journalism (3.97) Lab Report Written as a Primary Article (3.86)
G. These projects increased my ability to appreciate that cells hold the key to both human health and human disease.	4.83	**Disease Symposium Seminar (4.82)** **Disease Review Article (4.68)** **Journal Club (4.43)** **Medical News Journalism (4.03)** Lab Report Written as a Primary Article (3.74)
Process-specific course goals		
H. These projects increased my engagement in the world of contemporary biology research.	4.63	**Disease Symposium Seminar (4.7)** **Disease Review Article (4.68)** **Journal Club (4.55)** Lab Report Written as a Primary Article (3.98) Medical News Journalism (3.89)
I. These projects increased my understanding of the scientific discovery process and how to think scientifically.	4.58	**Journal Club (4.53)** **Disease Symposium Seminar (4.44)** **Disease Review Article (4.41)** **Lab Report Written as a Primary Article (4.06)** Medical News Journalism (3.84)
J. These projects increased my ability to communicate science effectively both orally and in writing.	4.86	**Disease Symposium Seminar (4.89)** **Journal Club (4.83)** **Disease Review Article (4.8)** **Medical News Journalism (4.36)** **Lab Report Written as a Primary Article (4.14)**
K. These projects increased my ability to collaborate with my peers and integrate our individual talents.	4.68	**Disease Symposium Seminar (4.81)** **Journal Club (4.69)** **Disease Review Article (4.63)** Lab Report Written as a Primary Article (3.91) Medical News Journalism (2.83)
Supporting tripartite pedagogy		
L. Experiential projects complemented and strengthened cell biology concepts I learned from lecture and laboratory-based instruction.	4.54	**Journal Club (4.53)** **Disease Symposium Seminar (4.44)** **Disease Review Article (4.41)** **Lab Report Written as a Primary Article (4.06)** Medical News Journalism (3.74)

[a]Students rated the postcourse statements according to the statement scale. The project rating scale was used to indicate which of the five experiential projects were relevant to each statement rating, as shown in the last column.
[b]Statement scale: 1 = Strongly disagree; 2 = somewhat disagree; 3 = neutral/no opinion; 4 = somewhat agree; 5 = strongly agree.
[c]Listed in order of relevance. Relevant projects (4.0 or more) are boldface.
[d]Project rating scale: 1 = Detrimental; 2 = not relevant; 3 = somewhat relevant; 4 = relevant; 5 = most relevant.

students for postgraduate careers and in general make them academically stronger liberal arts graduates with a greater appreciation of scientific research and the contributions of scientists.

Many studies clearly show that surveys are useful assessment tools for teaching innovations, whether they assess laboratory-based or non-laboratory-based research projects (Houde, 2000; Guziewicz *et al.*, 2002; Odom and Grossel, 2002, White *et al.*, 2002). Despite their usefulness, an important limitation is that such surveys gauge student attitudes and perceptions without objectively measuring content proficiency or process development (Sundberg, 2002). Another concern is the seriousness with which students complete such surveys (Sundberg, 2002), but given that 76 of 101 Kalamazoo students returned an optional survey by mail, lack of seriousness is likely less of an issue in this case. Also, small colleges represent small sample sizes; however, with future precourse–postcourse surveys such as the Lake Forest survey, I will be able to increase the sample size. Finally, Likert-type scale questionnaires may bias responses depending on the wording of questions. Posing statements contrary in tone to that of the statements I made in this survey or statements not relevant to the teaching innovations tested would have been useful discriminators.

Ideally, instructors interested in assessment should support opinion-based surveys with qualitative assessment approaches such as concept maps (Mintzes *et al.*, 1999) and interviews (Wright *et al.*, 1998), but they should realize that such approaches, too, have limitations (for further discussion, see Sundberg, 2002). In the future, I will be able to track changes in the numbers of students majoring in biology, but because I teach this course to all biology majors once a year, I cannot determine its impact on enrollment in direct comparison with that of a cell biology course taught in a more traditional way. I will also be able to track student enrollment in advanced cell and molecular biology courses, student participation in undergraduate research, and students seeking postgraduate education, although changes in these measures cannot be directly attributable to pedagogy in the introductory cell biology course.

Students acquire several skills not assessed by the survey. Computer literacy improves because they work with PowerPoint, Excel, computer graphics programs, and scanning software. Moreover, at Kalamazoo College, I gave bonus credit to students if they submitted a web-based portfolio of their projects and connected project relevance to their overall liberal arts education. I gave guidelines for portfolio design, but I left ample room for individual creativity. Astonishingly, between 1999 and 2001, more than 95% of the students submitted such online portfolios, learning either Dreamweaver or Netscape Composer. Many students thus engaged in reflective experiential learning, in addition to analytical and synthetic critical thinking (in all projects), quantitative skills (in laboratory work), and peer assessment (in Project 4). They also acquired skills in time management, group management, multitasking, and peer teaching.

Pedagogical Transferability

These projects can be successfully adapted in other courses and other institutions. I have taught this course multiple times and at two similar undergraduate institutions operating under different academic calendars. Despite the repeated successes at quarter-based Kalamazoo, implementing these projects favors semesters because the extra weeks allow better-spaced deadlines that aid the completion of multiple challenging projects (Figure 2). The projects were equally successful in classes varying in size from 9 to 48, which suggests adaptability for enrollments of 50 or fewer. For larger courses, or quarter-based calendars, I suggest reducing the number of projects by one or more, so that instructors are not overburdened with an increased number of groups and increased grading. As a guide to reducing the number of projects, I suggest keeping one of following cores: Projects 1, 3, and 5; or Projects 3, 4, and 5; Projects 1, 4, and 5.

Although these projects were successful in a cell biology course, in principle such projects can be applied to any science or nonscience discipline. Primary literature also likely serves as a comprehension barrier for beginning students in nonscience disciplines. Recently, other variations in role-playing activities in the undergraduate classroom have been recognized as effective pedagogical tools both in nonscience courses (Fogg, 2001) and in science courses (Aubusson *et al*. 1997; Burton 1997; Harwood *et al*., 2002). Symposium-like settings have previously been used to introduce science students to primary literature comprehension (Houde, 2000). I have implemented more advanced mock experiential research projects in a neurobiology course, in which students role-play renowned neuroscientists attending an all-day neurobiology conference and present seminars alongside real-life neuroscientists who also present seminars (DebBurman, 2002; manuscript in preparation).

Complementary Role of Projects in Strengthening Scientific Process and Content

This course provides one model of incorporating realistic scientific projects into a traditionally content-rich course. Despite the strong focus on using research projects to build process skills, students consistently acknowledge the projects' impact on strengthening cell biology content. This deep engagement with primary literature helps make the lecture-based content come alive and raises curiosity for science. Just as important, the lecture based content allows students to develop the sophisticated language and the confidence consistently seen in their presentations and papers. Incorporating these projects without concurrently building content may lower the quality of the work and make the academic experience less rewarding for both student and instructor. Notably, sophomores, rather than juniors or seniors, conduct these sophisticated projects. Despite their sophomore status, most of the students have met my expectations, many achieving work more typical of juniors and seniors. As a result, the expectations themselves have risen with time.

Three Caveats

One caveat is that most students consistently find the workload time consuming and sometimes stressful, despite their giving high ratings for the course and the instructor in course evaluations. Following are examples of the overwhelmingly positive responses and declarations of increased self-confidence and perseverance from most students in a recent class of 48, when they were commenting on the "course's value to their academic and personal growth":

> "I have grown immensely through this course. I have gained so many skills that I know I will keep with me always. This course has excited me more about the exciting world of biology and has shown me that I am able to meet a challenge and do well at meeting it."
>
> "I now feel as if I am part of the scientific community and can talk with others seriously about scientific topics because I can understand them."
>
> "This is by far the most rewarding and interesting course I have taken. It opened a whole new perspective on biology."
>
> "I have always had problems with public speaking. After our first presentation I know that the fear has almost dissipated completely. The best part of this course was the group projects. It exposed me to the real world of science, something I had never had before. This is the kind of stuff many of us will be doing in the future and this has been a wonderful introduction."
>
> "This course has great value to my academic growth and personal growth because it is the foundation of knowledge that I will need to pursue a career in the medical field."
>
> "I will always remember this class as the first that really pushed me. . . . I have reached new limits, extended new boundaries."
>
> "I think this course will be very valuable to me. The information we learned in class will be important to me as a biologist and the skills I learned from the projects will also be very important in my career as a scientist."
>
> "This was the best/hardest/most rewarding course I've ever taken and it helped me think/change/grow and believe in myself and in my abilities."

> "Class was challenging yet rewarding. It was hard but in hindsight I had fun and even learned some cool things along the way."
>
> "This has been the single most valuable course in my life. I have never learned so much about the field of biology and about myself as I have learned in this class."

The rest of the class believed that the course held strong value but held varying opinions on the time-consuming workload (all comments with negative content are shown next):

> "While it was a struggle all the way through, this class really taught me quite a bit about myself."
>
> "I have been looking forward to this class all year long. And it was harder, more trying, and more stressful. It was one of the best classes I had."
>
> "I could write an essay here but this course taught me to manage my life, time wise and stress wise. It gave me a challenge that I've never had before and showed me what I can do if I put my mind into it."
>
> "It was a valuable part of my college experience even though my social life was non-existent."
>
> "I have learned a ton, but you can do the same with less workload. . . . Academically, I grew, but personally, I did not benefit."
>
> "As many people will say this course is extremely difficult, but absolutely essential for academic growth. For all the upper-level science courses ahead, knowledge gained in this class will be built on. I learned so much more than just about cells."
>
> "Value-wise, this is probably my most valuable course. It pushed me and forced me to work for the first time, and as much as I whined during it, it feels good now. There is no doubt in my mind that I am a stronger student for it."
>
> "I have to admit that the things I did learn from this class will have more use and value in my life than just a lecture and lab-based class would, even learning about myself and how much stress I can or cannot take."

To address the student workload, I initially removed several less pertinent aspects from the lecture, laboratory, and projects, on the basis of student feedback and personal insight, and I have since been satisfied with the balance struck between workload and positive outcome. So, now I simply motivate students to increase self-expectations by making course goals, project explanations, and grading expectations very explicit. I also encourage students to think "outside the box" and to not feel constrained by my strict grading parameters; this flexibility has led to frequent demonstrations of superior creativity in student work. Adding teaching supports such as peer teachers, writing consultants, a syllabus workshop, skills workshops, and the course research guide have boosted assignment quality and alleviated the instructor's load. Furthermore, I provide built-in flexibility on project deadlines and respond to midterm feedback with syllabus adjustments, which helps students feel part ownership of their learning and thus improves their motivation to perform.

Second caveat is that this pedagogy requires considerable instructor time the first year of implementation because of his or her investment in the initial project design and assessment, after which the workload significantly decreases. Because beginning students need more guidance than advanced students do, office hours will often be well spent in engaged guiding. I now take routine advantage of the projects by having students explore topics that interest me professionally, with the result that I read recently published primary papers for which I have not been able to make time. Thus, my investment in student learning becomes an investment in my own continued scientific learning.

The third and final caveat is to reiterate that incorporating such projects into a laboratory-based introductory course will likely come at the expense of either doing fewer labs and/or spending less time on lecture and discussion. My choice has been to maintain the time spent on lecture and discussion because of the importance of content mastery and to offer fewer but still rigorous and substantial labs. Although, it was not my goal, the replacement of projects for labs did reduce the overall course budget.

CONCLUSION

The goal of developing a transferable pedagogy that imparts strong scientific subject matter and develops sophisticated scientific and intellectual skills in an introductory-level science curriculum has been achieved. Grasping primary literature by means of the five mock experiential research projects presented here is an effective way to accomplish both these goals and to connect students to contemporary research and the fast-paced world of biomedical discovery. Course surveys provide useful quantitative assessment tools for measuring specific learning outcomes, but they should be supplemented by other forms of qualitative and objective assessment.

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REFERENCES

Alberts, B., Bray, D., Johnson, A., Lewis, J., Raff, M., Roberts, K., and Walter, P. (1998). Essential Cell Biology: An Introduction to the Molecular Biology of the Cell, New York: Garland.

Aubusson, P., Fogwill, S., Perkovic, L., and Barr, R. (1997). What happens when students do simulation role-play in science?. Res. Sci. Educ. *4*, 565–579.

Brody, C. M. (1995). Collaborative or cooperative learning? Complementary practices for instructional reform. J. Staff Prog. Org. Dev. *12*, 133–143.

Bruffee, K.A. (1993). Collaborative Learning: Higher Education, Interdependence, and the Authority of Knowledge, Baltimore: Johns Hopkins University Press.

Burton, L.D. (1997). Hitting the Issues Head On: Using Role Play in Science Education. (ERIC Document Reproduction Service No. 411162).

Cantor, J.A. (1995). Experiential Learning in Higher Education: Linking Classroom and Community (ASHE-ERIC Higher Education Report No. 7), Washington, DC: George Washington University, Graduate School of Education and Human Development.

Chaplin, S.B., Manske, J.M., and Cruise, J.L. (1997). Introducing freshman to investigative research—a course for biology majors. J. Coll. Sci. Teach. *27(5)*, 347–351.

DebBurman, S.K. (2002). Mock Experiential Research Projects Requiring Primary Article Comprehension Promote Student Learning in an Undergraduate Neurobiology Course (Program No. 22.2; 2002 Abstract Viewer/Itinerary Planner), Washington, DC: Society for Neuroscience, Online.

Fogg, P. (2001, November 16). A history professor engages students by giving them a role in the action. Chronicle Higher Educ. *48(12)*, A12–A13.

Fortner, R.W. (1999). Using cooperative learning to introduce undergraduates to professional literature. J. Coll. Sci. Teach. *281*, 261–265.

Glasson, G.E., and McKenzie, W.L. (1998). Investigative learning in undergraduate freshmen biology laboratories. J. Coll. Sci. Teach. *28*, 189–193.

Gotz, J., Chen, C., Van Dorpe, J., and Nitsch, R.M. (2001). Formation of neurofibrillary tangles in P301L tau transgenic mice induced by Aβ42 fibrils. Science *293*, 1491–1495.

Grant, B.W., and Vatnick, I. (1998). A multi-week inquiry for an undergraduate introductory laboratory. J. Coll. Sci. Teach. *28*, 109–112.

Guziewicz, M., Vitullo, T., Simmons, B., and Kohn, R.E. (2002). Analyzing defects in the *Caenorhabditis elegans* nervous system using organismal and cell biological approaches. Cell Biol. Educ. *1*, 18–25.

Harwood, W.S., Mackinster, J.G., Cruz, L., and Gabel, D. (2002). Acting out science. J. Coll. Sci. Teach. *31*, 442–47.

Henderson, L., and Buising, C. (2000). A peer-reviewed research assignment for large classes. J. Coll. Sci. Teach. *30*, 109–114.

Henderson, L., and Buising, C. (2001). A research-based molecular biology laboratory: turning novice researchers into practicing scientists. J. Coll. Sci. Teach. *30*, 317–322.

Hermann, C. (1999). Reading the literature in the jargon-intensive field of molecular genetics. J. Coll. Sci. Teach. *28*, 252–253.

Houde, A.E. (2000). Student symposia on primary research articles: a window into the world of scientific research. J. Coll. Sci. Teach. *30*, 184–187.

Janick-Buckner, D. (1997). Getting undergraduates to really read and discuss primary literature. J. Coll. Sci. Teach. *27*, 29–32.

Ledbetter, M.S., and Lippert, M.J. (2002). Glucose transport in cultured animal cells: an exercise for the undergraduate cell biology laboratory. Cell Biol. Educ. *1*, 76–86.

Leonard, W.H. (2000). How do college students best learn science? J. Coll. Sci. Teach. *29*, 385–388.

Lord, T.R. (2001). 101 reasons for using cooperative learning in biology teaching. Am. Bio. Teacher *63*, 30–38.

Mazur, E. (1997). Peer Instruction: A User's Manual, Englewood Cliffs, NJ: Prentice Hall.

McNeal, A.P., and D'Avanzo, C. (1997). Student-Active Science: Models of Innovation in College Science Teaching, Orlando, FL: Saunders.

Millis, B.J., and Cottell, P.G., Jr. (1997). Cooperative Learning for Higher Education Faculty, Westwood, CT: Greenwood. (American Council on Education Oryx Press Series on Higher Education).

Mintzes, J.L., Wandersee, J.H., and Novak, J.D. (1999). Assessing Science Understanding: A Human Constructivist View, New York: Academic Press.

Muench, S.B. (2000). Choosing primary literature in biology to achieve specific educational goals. J. Coll. Sci. Teach. *29*, 255–260.

National Research Council. (1997). Science Teaching Reconsidered, Washington, DC: National Academy Press.

National Science Foundation. (NSF). (1996). Shaping the Future: New Expectations for Undergraduate Education in Science, Mathematics, Engineering, and Technology, Arlington, VA: NSF.

Novak, J.D., and Gowin, D.B. (1984). Learning How to Learn, Cambridge, UK: Cambridge University Press.

Odom, D.P., and Grossel, M.J. (2002). Using the two-hybrid screen in the classroom laboratory. Cell Biol. Educ. *1*, 43–62.

Piper, A. (1998). Light on a dark lady. Trends Biochem. Sci. *23*, 151–154.

Rothman, F., and Narum, J. (1999). Then, Now and in the Next Decade: A Commentary on Strengthening Undergraduate Science, Mathematics, Engineering and Technology Education, Washington, DC: Project Kaleidoscope.

Silberman, M. (1996). Active Learning: 101 Strategies to Teach Any Subject, Boston: Allyn & Bacon.

Stukus, P., and Lennox, J.E. (1995). Use of investigative semester-length laboratory project in an introductory microbiology course. J. Coll. Sci. Teach. *25*, 135–139.

Sundberg, M.D. (2002). Assessing student learning. Cell Biol. Educ. *1*, 11–15.

Sundberg, M.D., and Moncada, G.J. (1994). Creating effective investigative laboratories for undergraduates. BioScience *44*, 698–704.

Wade, N. (1998). The Science Times Book of the Brain, New York: Lyons Press.

Watson, J.D. (1998). The Double Helix: A Personal Account of the Discovery of the Structure of DNA, New York: Scribner's.

Watson, J.D., and Crick, F.H.C. (1953a). Genetic implications of the structure of deoxyribonucleic acid. Nature *171*, 964–967.

Watson, J.D., and Crick, F.H.C. (1953b). Molecular structure of nucleic acids. Nature *171*, 737–738.

White, B., Kim, S., Sherman, K., and Weber, N. (2002). Evaluation of molecular visualization software for teaching protein structure: differing outcomes from lecture and lab. Biochem. Educ. *30*, 130–136.

Wright, J.C., Millar, S.B., Kosciuk, S.A., Penberthy, D.L., William, P.H., and Wampold, B.E. (1998). A novel strategy for assessing the effects of curriculum reform on student competence. J. Chem. Educ. *75*, 986–992.

Zoller, U. (2000). Teaching tomorrow's college science courses—are we getting it right?. J. Coll. Sci. Teach. *29*, 409–414.

Appendix

These two web sites provide supplementary materials to support the pedagogy discussed in this article:

1. *Teacher Resources*: http://www.lfc.edu/~debburman/cbesupplement.html
   This site specifically provides examples of student work for the mock experiential research projects from the past 4 yr. It also contains grading sheets used to evaluate these projects and sample quizzes and exams (all available either as downloadable pdf documents or viewable PowerPoint presentations).
2. *Spring Semester 2001–2002 Course Web Site*: http://www.lfc.edu/~debburman/BIO221S02/outerframe.html.
   This comprehensive site provides downloadable forms of the syllabus, lecture and project schedules, and the course survey used in this study. Additional examples of student work, the bibliographical research guide, and information on other aspects of pedagogical support as used in the spring semester 2001–2002 are also provided.