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Article

Teaching the Process of Science: Faculty Perceptions and an Effective Methodology

David Coil,*†‡ Mary Pat Wenderoth,*† Matthew Cunningham,*§ and Clarissa Dirks*†¶

*Department of Biology, University of Washington, Seattle, WA 98195; and ¶Scientific Inquiry, The Evergreen State College, Olympia, WA, 98505

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Most scientific endeavors require science process skills such as data interpretation, problem solving, experimental design, scientific writing, oral communication, collaborative work, and critical analysis of primary literature. These are the fundamental skills upon which the conceptual framework of scientific expertise is built. Unfortunately, most college science departments lack a formalized curriculum for teaching undergraduates science process skills. However, evidence strongly suggests that explicitly teaching undergraduates skills early in their education may enhance their understanding of science content. Our research reveals that faculty overwhelming support teaching undergraduates science process skills but typically do not spend enough time teaching skills due to the perceived need to cover content. To encourage faculty to address this issue, we provide our pedagogical philosophies, methods, and materials for teaching science process skills to freshman pursuing life science majors. We build upon previous work, showing student learning gains in both reading primary literature and scientific writing, and share student perspectives about a course where teaching the process of science, not content, was the focus. We recommend a wider implementation of courses that teach undergraduates science process skills early in their studies with the goals of improving student success and retention in the sciences and enhancing general science literacy.

INTRODUCTION

Successful undergraduate programs in the life sciences are those programs that graduate students who are able to "think like a scientist" (Handelsman *et al.*, 2004; Handelsman *et al.*, 2007), that is, students who are able to solve problems in multiple contexts and effectively integrate information into meaningful scientific concepts. Scientists and science educators agree that a hallmark of a successful undergraduate science degree is the acquisition of skills such as data interpretation, problem solving, experimental design, scientific writing, oral communication, critical analysis of primary literature, collaborative work, and monitoring and regulating one's own learning process (Airey and Linder, 2009; Alberts, 2009a,b; Bao *et al.*, 2009; Brickman *et al.*, 2009; Carnegie Institute for Advanced Study Commission on Mathematics and Science Education, 2009). Although scientists use these skills daily, these skills are rarely taught to undergraduates in an explicit and scaffolded manner. Frequently, undergraduate life science programs primarily focus on the delivery of vast amounts of facts, and it is assumed that students will "magically" obtain science process skills somewhere during their four years of study. A more effective way to help students master science disciplines and better prepare them for careers in science would be through

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Address correspondence to: Clarissa Dirks (dirksc@evergreen.edu).
†These authors contributed equally to this work.
‡Current address: Department of Microbiology and Immunology, Rega Institute for Medical Research, Leuven, Belgium.
§Current address: Department of Medical Education and Biomedical Informatics, University of Washington, Seattle, WA 98195.

explicit instruction of science process skills, helping students acquire a repertoire of these skills early in the college curriculum and thereby augmenting their content acquisition and interdisciplinary ways of knowing. We propose that instructing freshman in the process of science may enable more students to excel in their disciplines, particularly biology, because of its ever accumulating and fragmented content.

Experts have a conceptual framework that allows them to recognize meaningful patterns of information, effectively organize content, flexibly retrieve pertinent knowledge with little effort, and assess their level of understanding of concepts. Novices lack this framework and the accompanying intellectual habits of mind (Bransford *et al*., 1999). In academia and science education, experts are the faculty, who possess both skills and content knowledge. Science process skills are the indispensable tools of scientists, helping them form their conceptual framework, thereby facilitating learning of new content associated with novel science problems (Wilensky and Reisman, 1998; Bransford *et al*., 1999; Hogan and Maglienti, 2001; National Research Council [NRC], 2005). Through explicit instruction and assessment of students' science process skills we can help students gain the same skills that faculty use every day and help them to approach science as scientists do. Indeed, these are the same skills strongly promoted by the American Association for the Advancement of Science (AAAS) for K–12 science education (AAAS 1993) and highlighted in reports that outline recommendations for collegiate science education (NRC, 2003; American Association of Medical Colleges and Howard Hughes Medical Institute, 2009; Labov *et al*., 2009).

Acquisition of science process skills can have a profound impact on student success in college science classes. In 2006, we reported evidence that freshmen who participated in a course in which they were explicitly taught science process skills outperformed students who did not participate in the program in subsequent introductory biology courses (Dirks and Cunningham, 2006). Similarly, students in a molecular biology course who practiced data analysis, diagrammatic visualization, and other analytical reasoning skills had improved test scores compared with those in a control course (Kitchen *et al*., 2003). Explicit instruction in generating and interpreting scientific graphs (Shah and Hoeffner, 2002) and experiential research projects that promoted science process skills also benefited students' learning and reinforcement of course content (Souchek and Meier, 1997; DebBurman, 2002; Wilke and Straits, 2005; Yeoman and Zamorski, 2008). The use of primary literature to improve critical thinking in undergraduates has also been well documented (Janick-Buckner, 1997; Fortner, 1999; Hermann, 1999; Henderson and Buising, 2000; Muench, 2000; Kozeracki *et al*., 2006; Hoskins *et al*., 2007; Gehring and Eastman, 2008). Lastly, faculty in other science, technology, engineering, and math (STEM) disciplines, such as chemistry (Bunce and Hutchinson, 1993; Veal *et al*., 2009), physical chemistry (Nicoll and Francisco, 2001), and geology (McConnell *et al*., 2003), have shown the connection between student acquisition of science process skills and academic success.

Here we present results from a survey indicating overwhelming support by faculty for teaching undergraduates science process skills, as well as the direct conflict they feel between spending time teaching content and process. We also provide an extensive description of the Biology Fellows Program (BFP) from our 2006 report, sharing our teaching philosophies, methods, and core course materials used to explicitly teach science process skills. By describing our pedagogical foundation and methods used in the BFP, we hope to help other faculty incorporate and formalize the teaching of science process skills as early as possible into undergraduate curricula.

FACULTY VIEWS OF UNDERGRADUATES' ACQUISITION OF SCIENCE PROCESS SKILLS

Devoting more time to teaching the process of science may come at the expense of teaching content—is this tradeoff acceptable? To help answer this question, we created an online science process skills survey for faculty (Supplemental Material A, Faculty Survey). The survey was vetted by nine faculty from four institutions for question clarity and to validate the science process skills list we had generated. We sent the survey to approximately 450 life science faculty and postdoctoral fellows from a wide range of institutions of higher education using email lists from professional meetings, or by sending it to faculty and departmental chairs at specific institutions. To maximize the number of participants, our emails asked the recipients to forward the survey to other faculty within the life science departments at their institutions. We had 159 respondents, comprising 154 faculty and 5 postdoctoral fellows with teaching experience (all respondents will be referred to as faculty). On average, the respondents had been teaching for 14 years. Although half of respondents (51%) were from research 1 (R1) universities, others institutions were also represented: non-R1 (11%), liberal arts colleges (23%), and community colleges (14%). We asked faculty to identify how important it is, on a scale from 1 (unimportant) to 5 (very important), for undergraduates majoring in the life sciences to obtain 22 specific science process skills by the time they graduate with a 4-yr degree. On average, faculty signified that it was important for students to acquire all of the 22 skills listed in the survey, with all skills receiving a mean score of 3.5 or higher (Table 1). The list of 22 skills was clustered into 10 major categories based on similarity of skill, and faculty were asked to select the three *most* important skill categories. Faculty from all institution types indicated that problem solving/critical thinking, interpreting data, and communicating results: oral and written, were the most important (Figure 1). In contrast, when faculty were asked to select the three *least* important skill categories that students should acquire, we saw differences in faculty responses based on institution type. The least important skills for faculty from R1 universities, non-R1 universities, and liberal arts colleges related to metacognition and collaborative work (Figure 2A), whereas the least important skills selected by faculty at community colleges were those related to research (Figure 2B). However, regardless of the institution type, many respondents commented that it was "very difficult" to select the three least important skills students should acquire because *all* the listed skills were important. We received 14 comments from faculty indicating that the question was "impossible" to answer because it was "vital" or "critical" that students learn all the skills we provided on our list.

Table 1. Faculty ranking

Science process skills	Average score of importance[a]
Problem solving/critical thinking	4.9
Interpreting data: graphs and tables	4.9
Interpreting data: ability to construct an argument from data	4.8
Creating the appropriate graph from data	4.7
Communicating results: written	4.7
Ability to create a testable hypothesis	4.7
Ability to design an experiment: identifying and controlling variables	4.6
Ability to design an experiment: development of proper controls	4.6
Communicating results: oral	4.6
Knowing when to ask for guidance	4.6
Conducting an effective literature search	4.6
Reading and evaluating primary literature	4.5
Ability to design an experiment: proper alignment of experiment and hypothesis	4.5
Understanding basic statistics	4.5
Working independently when needed	4.5
Working collaboratively to accomplish a task	4.4
Being able to infer plausible reasons for failed experiments	4.4
Being able to effectively monitor their own learning progress	4.3
Creating a bibliography and proper citation of references	4.2
Interpreting data: gels, blots, microarrays, etc.	4
Being an effective peer mentor	3.6
Ability to use basic online bioinformatics tools (NCBI databases, BLAST, etc.)	3.5

[a] The average score of importance was determined by converting a descriptive Likert scale to a numerical scale (5 = Very Important, 4 = Important, 3 = Moderately Important, 2 = Of Little Importance, 1 = Unimportant), and taking the average.

In response to our open–ended question "What other skills do you think students should have by the time they graduate?," 69 faculty provided us with 74 suggestions. Of the 74 suggestions, six were restatements of skills provided in our survey, and the remaining 68 could be categorized under one of eight headings: to question or evaluate critically, to apply science to life, to do science—research and instrumentation, to teach or mentor, quantitative skills, to know what science is and is not, interdisciplinary ways of knowing, and time management or organization; the percent respondents for each category are shown in Figure 3.

While the respondents overwhelmingly agreed it is important that undergraduate life science majors acquire science process skills throughout their education, 67% felt that they did not spend a sufficient amount of time teaching these skills (Figure 4). Both the number of faculty who felt they did not spend enough time teaching science process skills and the percentage of time they reported teaching skills varied significantly depending on the institution type (Figure 5). Whereas 50% of faculty from liberal arts colleges feel they spend enough time teaching science process skills and devote, on average, 43% of their time to teaching the process of science, only 23% of the community college fac-

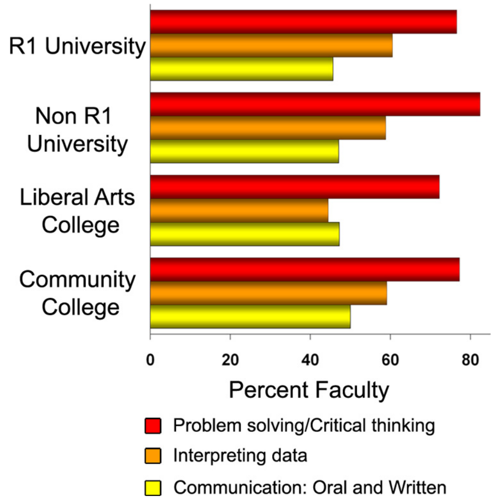

Figure 1. The three skills selected by faculty (N = 156) as the *most* important for students to acquire in an undergraduate education as determined by comparing all averages. The percent faculty at different institutions is reported for each skill.

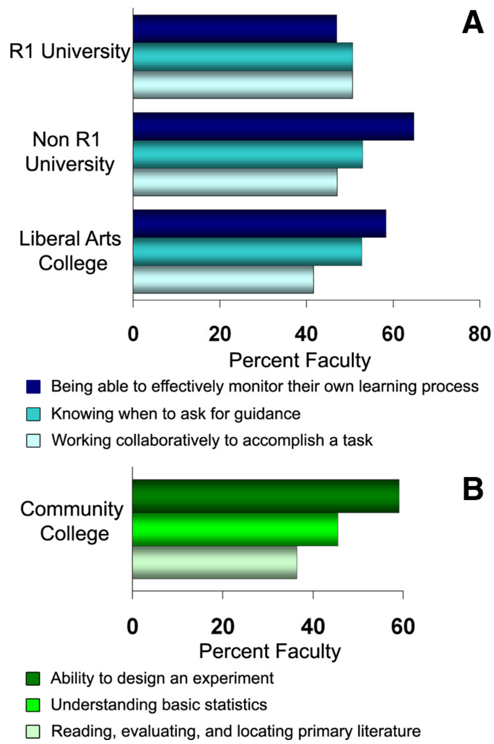

Figure 2. The three skills selected by faculty (N = 156) as the *least* important for students to acquire in an undergraduate education as determined by comparing all averages. Percent faculty at (A) R-1, non-R1, and liberal arts institutions and (B) community college is reported for each skill.

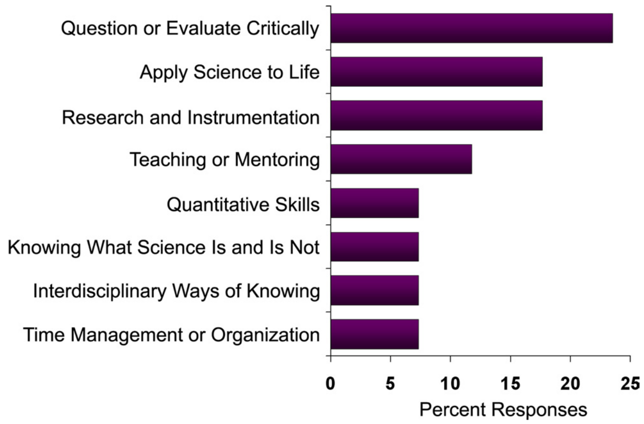

Figure 3. Faculty offered other skills (N = 74) that students should have by the time they graduate. These skills generally fell into one of eight categories and are reported as percent of the total.

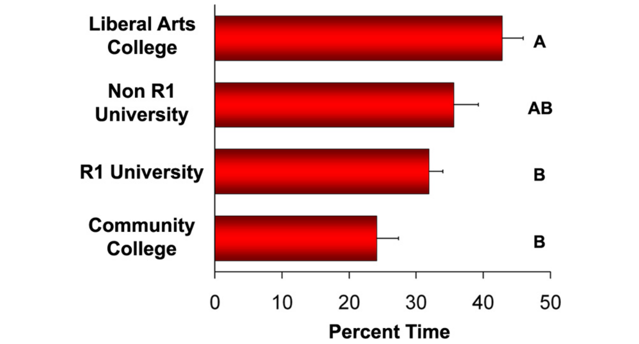

Figure 5. Percent time (mean ± SEM) faculty (N = 156) at different institutions reported teaching skills as opposed to content. Values not sharing the same letter are significantly different from each other as determined by a one-way ANOVA and post hoc Tukey test.

ulty feel they spend enough time teaching skills and devote on average only 24% of their class time to development of science skills. As the average class size at liberal arts and community colleges are comparable, class size is not likely to account for the difference in time that faculty spend teaching science process skills. It is interesting that the perceived time spent teaching skills at R1 universities was not significantly different from that reported by community colleges. This is surprising as one might imagine that faculty who are actively engaged in research would devote more class time to teaching the skills inherent to their own work.

The dissonance between faculty views about the importance of undergraduates acquiring science process skills and the amount of time they actually spend teaching these skills was addressed by asking faculty to select any or all reasons (from a list of five reasons, as well as an option to suggest their own reason; see question #7 in Supplemental Material A, Faculty Survey) for why they spend so little time teaching skills. The most common reason selected by faculty was "teaching skills is too time-consuming" followed by "I think students need to have adequate content before they can learn science process skills" (Figure 6). However, 37% of responders cited one or more other reasons; these open-ended responses generally fell into five main categories: time constraints due to need to cover content (65%), large class size or lack of student preparation (12%), students will learn skills elsewhere (10%), lack of support (not enough teaching assistants or assessment tools; 10%), and professional obligations such as tenure (5%). In the open-ended responses, as in the "check all that apply" responses, covering content was one of the main reasons faculty offered as to why they could not devote more class time to teaching the process of science.

Collectively it appears that the need to cover content outweighs faculty's desire to teach the process of science even when faculty feel it is critically important that students learn these skills. This is especially alarming because the faculty we surveyed also reported that in a 4-yr period they teach, on average, twice as many freshman and sophomore courses as they do junior- and senior-level courses. This indicates that beginning college students who take science courses are much more likely to learn content rather than science process skills. Many students who take introductory science courses do not go on to earn science degrees (Seymour and Hewitt, 1997). For most of these students this course is probably their only formal science class, and they leave college without having the skills to critique scientific reports in the news media or make informed decisions concerning science public policy and the environment. For students who do go on in science, the introductory course has

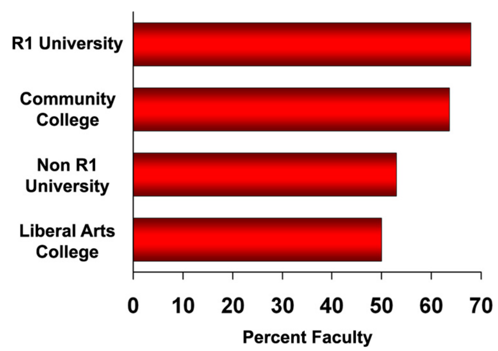

Figure 4. Percent faculty (N = 156) at different institutions who felt that the amount of time they spent teaching science process skills was NOT sufficient.

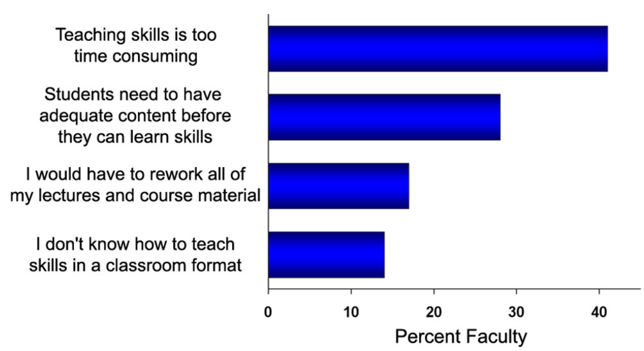

Figure 6. Percent faculty (N = 100) selecting reasons that prevent them from spending more time teaching science skills. Numbers sum to greater than 100% due to respondents choosing more than one response.

failed to provide them with the conceptual framework needed for them to succeed in subsequent science courses.

TEACHING THE PROCESS OF SCIENCE

There are only a few documented programs that formally aim to place a greater emphasis on teaching the process of science as opposed to just delivering content for life science majors. A project at Brigham Young University (BYU) refocused undergraduate biology teaching efforts toward training students to interpret data and think analytically (Kitchen *et al*., 2003). BYU students who were taught these skills achieved higher exam and diagnostic test scores than students in a course where the focus was solely on information transfer. Student response to the course design was generally positive, and some students indicated that they wished they had learned these skills earlier in their education (Kitchen *et al*., 2003). Similarly, faculty at Lake Forest College (LFC) successfully integrated the teaching of science process skills with content in a sophomore-level introductory biology class (DebBurman, 2002). LFC students who were taught science process skills in this relatively explicit manner reported that this helped them more readily acquire content in other classes and made them realize that they needed to improve their proficiencies in these areas. In 2006, we reported that incoming freshmen who participated in a unique premajors program (BFP) that explicitly taught science process skills had significantly greater success in subsequent introductory biology courses compared with students who did not participate in the program (Dirks and Cunningham, 2006). In that report we showed 1) the demographic make-up of the BFP, 2) a comparison of non-BFP and BFP students' grades in the introductory biology series, and 3) BFP students' learning gains on pre- and posttests in graphing and experimental design. In response to many requests by faculty, here we provide a detailed description of our pedagogical philosophies, methodologies, and materials for teaching the course, as well as additional assessment results of student learning gains in scientific communication and survey information about BFP participants' views of the program.

Pedagogical Foundations of the BFP: Helping Students Learn How to Learn

The BFP at the University of Washington was founded to increase student success and retention in the biological sciences, particularly students from underrepresented groups. The three main programmatic goals were to 1) teach freshmen science process skills, 2) help them to develop more robust study techniques and metacognition, and 3) introduce them to the culture of science. This premajor program was offered for two credits during winter and spring quarters, meeting once a week for 1.5 h; thus it was a relatively small time commitment for students who had other academic requirements to fulfill. The BFP class size ranged from 50 to 60 students each quarter.

While the BFP had several components, we believe the success of the program was primarily due to a combination of pedagogical methods. We designed the BFP to be a "low-stakes" learning environment where students would be held accountable for their own education without incurring large penalties for their failures. Thus the grading emphasis was on students' in-class participation and improvements on their assignments over time, rather than the quality of their initial work. Students also frequently worked in groups of three to four, modeling the collaborative aspects of science. This low-stakes, noncompetitive approach allowed students to take more risks when completing assignments and generated a more productive learning environment for a cohort who would subsequently be taking biology together in a much larger (400+ students) class. This approach to learning was perceived as less stressful and threatening by the BFP students based on student comments as well as the fact that from 2003 to 2006 (the time frame in which we evaluated the program) we observed a very high retention rate with 98% of the 196 BFP students successfully completing both quarters of the BFP.

Other teaching strategies focused on helping students develop better study and metacognitive skills. We began the program by discussing our learning objectives and the role of metacognition in learning (Bransford *et al*., 1999; Table 2). After a brief introduction, students had small group discussions about what they hoped to accomplish in the program and in their first year as a college student, how they learn best, and how they know when they really know something. As an assignment we gave students time management sheets, asking them to indicate their hour-by-hour activities for the week and identify the blocks of time that they thought were "quality" study hours—those hours when they were fully awake and not distracted. We also instructed students to work toward being an active learner (i.e., taking notes while reading their textbook, drawing models of concepts, and creating questions). A critical aspect of our approach was to keep our pedagogy transparent throughout the course, taking time each class period to reflect on the purpose of an activity or assignment, as well as keeping a positive learning environment—one that was predominantly student-centered, collaborative, and active.

To further develop students' metacognition we would address their tendencies to overestimate their proficiency at science process skills. We found that many students had been exposed to some skills, such as reading graphs or designing experiments, but were not proficient at these tasks, even if they thought they were. Therefore, before extensive instruction in any given skill area, students were challenged with a moderately difficult assignment for which they received detailed feedback without penalty. These assignments also served as our diagnostic pretests for determining student learning gains throughout the program (Supplemental Material B; SM1). From our experience, we found that students were more receptive to instruction after trying these assignments on their own. This "try and fail" approach to learning has been demonstrated to be successful in other contexts, especially mathematics, where students are asked to attempt difficult problems on the board on a regular basis (Mahavier, 1997).

Early in the program we introduced students to Bloom's taxonomy of cognitive domains (Bloom *et al*., 1956), explaining the different levels at which they would be challenged in the BFP and their future science courses. To emphasize the value of Bloom's taxonomy, we gave students practice at

Table 2. Syllabus for the two-quarter (20 wk) BFP

	Faculty instruction and student activities per 1.5-hour sessions	
	Faculty	Student
Session 1	Introductions Finding a research experience - I • Science interests discussion How people learn • Study skills I – Bloom's taxonomy, learning styles, and metacognition • Identifying your learning styles • Creating time-management tables	Scientific literature pretest Primary literature • Overview of scientific literature papers • Finding journal articles Writing assignment 1 (pretest) • Outline • Experimental design
Session 2	Writing assignment 1 (pretest) collected Scientific writing • Structuring your writing - outlines • Grading rubrics	Study skills II • Diagramming questions • Answering short essay questions • Collaborative learning
Session 3	Experimental design • Basic experimental design – controls, variables, hypotheses, predictions, and sample size	Oral reports group A • Primary literature papers • Science communication
Session 4	Graphing in the computer laboratory • Graphs I – types of graphs, reading graphs, graphs to text • Data display and analysis • Graphing in Excel	Computer laboratory exercise Writing assignment 2 • Outline • Experimental design
Session 5	Writing assignment 2 collected Finding a research experience - II • Research opportunities • Drafting a letter to potential mentors	Oral reports group B • Primary literature papers • Science communication
Session 6	Basic Statistics • Graphs II – practice exercises, error bars, and data presentation • Statistics – p values, variance, and the effect of sample size	Oral reports group C • Primary literature papers • Science communication
Session 7	Data Analysis • Working with and graphing data sets • Interpreting results – supporting or refuting your hypothesis Oral Reports Group D • Primary literature papers • Science communication	Writing assignment 3 • Outline • Experimental design • Graphing • Basic statistics • Data analysis • Structure of a scientific paper
Session 8	Writing assignment 3 collected Practice activities • Experimental design • Data analysis	Oral Reports Group E • Primary literature papers • Science communication
Session 9	Basic bioinformatics • National Center for Biotechnology Information databases and tools • Protein structures and Cn3D software	Computer laboratory exercises • Data analysis • Science tools and communication
Session 10	Guest panel • Physicians, scientists, dentists, nurses, graduate students	Question and answer session • Careers in science and medicine
Session 11	Science posters • Schematics in biology • Components of scientific posters	Computer laboratory exercise • Drawing in PowerPoint • Data analysis
Session 12	Study skills III • Concept mapping	Oral presentations group 1 • Primary literature papers • Science communication
Session 13	Practice activities • Experimental design • Data analysis Oral presentations group 2 • Science communication • Primary literature papers	Writing assignment 4 • Scientific writing • Experimental design • Graphing • Data analysis
Session 14	Undergraduate research symposium • Career booths • Graduate school programs • Biology Fellows program • Undergraduate research opportunities	Undergraduate scientific poster sessions (Biology Fellows required to attend) Closing celebration

Continued

Table 2. *Continued*

	Faculty instruction and student activities per 1.5-hour sessions	
	Faculty	Student
Session 15	Writing Assignment 4 collected Practice activities • Experimental design • Data analysis	Oral presentations group 3 • Primary literature papers • Science communication
Session 16	Study skills IV • Collaborative learning - peer teaching Oral presentations group 4 • Primary literature papers • Science communication	Writing assignment 5 (posttest) • Scientific writing • Experimental design
Session 17	Writing assignment 5 collected Study skills V • Collaborative learning, group problem solving	Oral presentations group 6 • Primary literature papers • Science communication
Session 18	Careers in science • Graduate and medical school topics • Alternative science careers	Student career interests • Casting ahead • Five and ten year plans Scientific literature posttest
Session 19	Pathway planning • Identifying components necessary for meeting career goals	Academic and professional roadmaps • Mapping out a plan to meet a professional goal
Session 20	Deconstructing the BFP • Review of BFP learning objectives and program activities • Planning ahead – supplemental instruction for introductory biology and BFP as a scholarly network	Student planning and social time • Students share their academic schedules • Students form future study groups for subsequent science courses

identifying the cognitive levels at which they were working by deconstructing activities from both the perspective of the educator and student. This pedagogical transparency helped students to invest more in their work and better assess their own learning.

We also dedicated several class periods to helping students practice different learning strategies and providing them with tools for effective studying. Students were taught how to diagram questions by circling key terms and underlining parts that they had been specifically asked to address. We gave instruction and practice for concept mapping (Novak, 1990) and for creating diagrams or drawings as representational models; we frequently required students to use these tools during mini-lectures to organize their interpretation of biological content. Many of these activities were followed by an evaluation session in which students would use their diagrams to teach their peers content while the instructor assessed their materials. By requiring students to practice a repertoire of study skills during each class period, we reinforced new approaches to studying and learning.

Teaching Science Process Skills

We used a constructivist approach to teaching (Dewey, 1933; Duckworth *et al.*, 1990; Brooks and Brooks, 1999; Leonard, 2000; Fink, 2003; Shepard, 2005), whereby we successively introduced increasingly complex activities that required students to practice and integrate many different skills and allowed them to sequentially build, test, and refine their conceptual understanding. We also put skills in context—giving students just enough content to allow them to practice skills. Class instruction about a particular skill always preceded graded assignments that required students to practice that skill. After an initial exercise that required the student to use a skill (i.e., reading primary literature, scientific writing, etc.), students were provided with a grading rubric (Supplemental Material B, SM2), given detailed instruction on the science process skill that was part of the initial exercise, and then introduced to new science content. The same skill was then incorporated into subsequent assignments, allowing students to practice skills in the context of different content (Figure 7). For example, in class we would introduce basic statistics

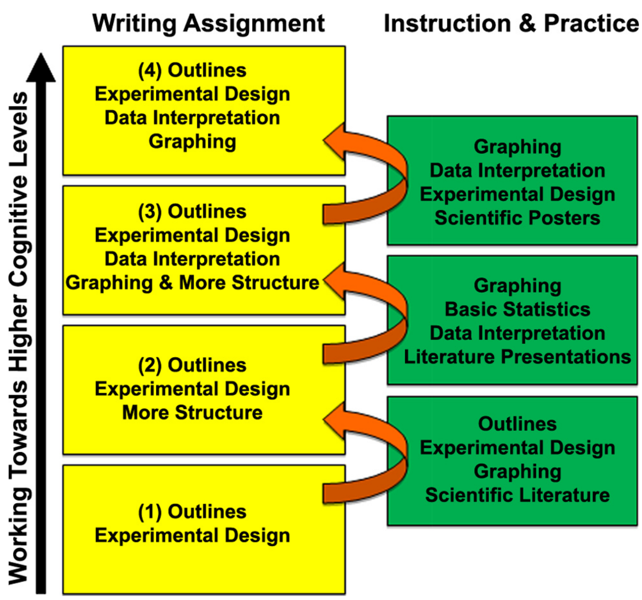

Figure 7. A schematic representing the kinds and timing of class instruction and practice between assignments.

and appropriate ways to display data graphically, followed by an assignment that required them to properly use these skills to make inferences and pose future experiments. Iterative practice and frequent assessment of students' skills helped to reinforce the key learning objectives of the course, while the presentation of new content helped foster their interest in science. As a result of these scaffolded activities, students showed significant gains in their abilities to generate graphs, interpret data, design experiments (Dirks and Cunningham, 2006), write in a scientific manner, and understand the purpose and structure of scientific literature (data presented below).

The ability to write well is crucial for success in both undergraduate classes and any science-related career. Undergraduate research advisors (and results from our survey) cite scientific writing as a skill all students should master (Kardash, 2000). To help students learn how scientists communicate in written form, we gave them a few primary research and review articles very early in the course and taught them the structure of scientific literature. The papers, which contained a variety of content, were selected because they required a minimal understanding of complex techniques. In small groups and then as a class, students compared the overall structure of the different articles and discussed the kinds of information presented in the sections of each paper. We also instructed students on how to search life science databases (e.g., PubMed) and assigned small groups to present to the class a portion of a scientific paper they had found. Although students sometimes had difficulty interpreting the entire paper they selected, they described the parts they did understand and identified areas with which they struggled. Because they worked in small groups to present their paper, the activities gave students practice at working with scientific literature and communicating science orally without being solely responsible for the success or failure of their work. We created a Scientific Literature Test (SLT; Supplemental Material B, SM3) to assess students' understanding of the organization and components of a primary literature paper. After students took the SLT in the first quarter of the program, it was vetted by having a class discussion about their interpretation of the questions and their responses; the test was modified and implemented in subsequent years. Pre- and posttests were administered at the beginning and end of the program, respectively, and scoring was completed by the same grader. BFP students' scores on the SLT increased, on average, from 32% to 86% on the pre- and posttest, respectively ($p < 0.001$ by paired T-test; Figure 8).

We used multiple writing assignments as a vehicle to enhance students' mastery of a range of science process skills, particularly scientific writing (Supplemental Material B, SM1). Each writing assignment increased in difficulty as it called for students to integrate several science process skills and required them to work at progressively higher cognitive levels (see Figure 7). For example, in assessing whether students could create an effective outline for a paper, students were given an abstract from a relatively easy-to-interpret primary literature paper and asked to produce an outline for the paper. This exercise was followed by an assignment that required students to read a scenario, pose a hypothesis, design an experiment, and create an outline for a paper they would write. By the third assignment, students were given a scenario and raw data for which they had to graph, analyze, and write about in the format of a primary literature paper (Supplemental Material B, SM1, writing assignment 3). We also required students to sequentially add more structure to their writing, culminating in the goal of writing a short scientific manuscript. Each writing assignment was evaluated using a Scientific Writing Rubric (SWR; Supplemental Matrial B, SM2) that assessed six functional categories: following instructions, outlining, writing structure, writing mechanics, experimental design, and graphing. Each category of the SWR was scored on a scale of 0–3, yielding a maximum score of 18. Throughout the program three faculty used and iteratively improved the SWR. A single rater then used the finalized SWR to analyze identical pre- and postwriting assignments administered during the first and penultimate sessions of the program. We found that students had made significant improvement in their scientific writing skills, with average scores increasing from 62% to 83% between pre- and posttests, respectively ($p < 0.001$ by paired T-test; Figure 8). Importantly, students showed significant gains in all six categories designated on the grading SWR. Thus our students learned many of the science process skills that form the foundation for most scientific endeavors by receiving explicit instruction for, and iteratively practicing, the skills of a scientist.

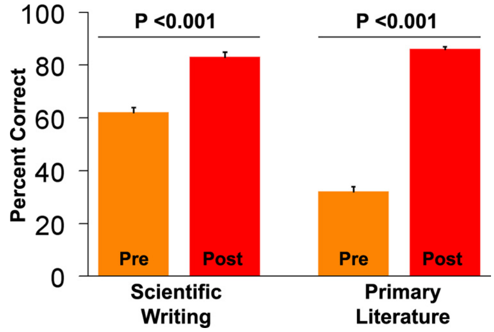

Figure 8. Percent of total points (mean ± SEM) received during either a pretest or a posttest on scientific writing (graded with the SWR; N = 44) or SLT (N = 42) for 2006 BFP students. Statistically significant differences by paired *t*-test are indicated in the figure.

Incorporating the Culture of Science into the BFP

Students in the BFP came to college with an interest in the life sciences, so we provided them with opportunities to build a professional network of science colleagues, inclusive of faculty. We instructed students in the process of finding an undergraduate research opportunity or a volunteer experience in a medical profession or related field. We also held a panel session in which physicians, scientists, and other life science professionals answered students' questions about their careers. Lastly, we required all BFP students to participate in an annual symposium where they attended an undergraduate research poster session and visited booths to get information about graduate and professional schools, undergraduate organizations in the life sciences, and other opportunities that might help them achieve their career goals. These experiences were extremely valuable to BFP students as indicated by their remarks in closing surveys; students indicated that they felt connected to the life science community on campus and could more clearly see a pathway for their future careers. One indicator that suggests BFP participants maintained a connection to science is that approximately 60% of BFP students were engaged in undergraduate research by their sophomore year.

Supplemental Instruction after the BFP

Supplemental instruction (SI) has been shown to be a very effective method to help students learn the content of large lecture courses (Preszler, 2006). Therefore, as BFP students moved through their science courses in smaller cohorts, we provided each with SI sessions while enrolled in the rigorous introductory biology series. Many of our BFP students were designated as underrepresented minorities (URMs) or those identified for the Educational Opportunity Program (EOP; first generation and economically disadvantaged college students). Unfortunately, URMs and EOPs have traditionally performed poorly in introductory biology courses compared with their majority counterparts; almost half of URMs and EOP students do not continue in science after these courses (Dirks and Cunningham, 2006). SI sessions were designed to build on the foundational skills that BFP students practiced during their time in the program; key parts of these sessions included collaborative learning in small groups, peer instruction, diagramming and ranking old exam questions according to Bloom's taxonomy, and completing practice activities about a topic (e.g., natural selection, Mendelian genetics) concurrently taught in their biology course. To help BFP students develop the ability to identify their level of preparation for an exam, students' took isomorphic quizzes (based on Bloom's levels) before and after practice activities. The tests were not graded, nor were students given the answers until after the session. Four times throughout the session students took a survey in which they were asked to rate their current understanding of the topic on a scale from 1 to 5, with "don't understand at all" being a 1 and "understand very well" a 5 (Table 3). Results from this survey allowed us and the student to track their metacognition. Survey data across multiple deliveries of SI were averaged to create a composite score for each student (N = 39) at each of the four time points during their instruction. Student self-rating of their understanding of the covered material changed significantly over the course of the SI sessions (Repeated measures ANOVA; $p < 0.001$; Figure 9), leading us to perform post hoc pairwise comparisons between time points by paired *t*-test. Understanding scores averaged 2.6 ± 0.1 (SEM) for students before answering the pretest questions. This score showed a statistically significant drop after students took the pretest, to an average score of 2.2 ± 0.1 ($p < 0.001$ versus before pretest). After completing the practice activities, students' mean understanding score increased to 3.6 ± 0.1 ($p < 0.001$ versus after pretest). After the posttest, students' rating of their understanding showed a small, but statistically significant drop to 3.4 ± 0.1 ($p < 0.03$ versus before posttest). Thus, on average, students felt significantly more confident about their understanding of the content before they were challenged with the pretest than after it, and their confidence significantly increased and remained high after approximately an hour of practice and thinking about content. Although we do not have direct evidence linking a student's understanding score to their exam scores in biology, we believe these structured activities may help to enhance students' ability to monitor their true level of preparation going into an exam by providing them with practice at recognizing what they don't know before any assessment. Because almost all of the BFP students participated in the SI sessions, we cannot assess the impact that the SI may have had on the success of the Biology Fellows in the introductory biology series. However, the SI sessions were an essential component of the program because they provided BFP students with practice at some of the many skills we taught: good study skills, reflection about learning, and effective group work.

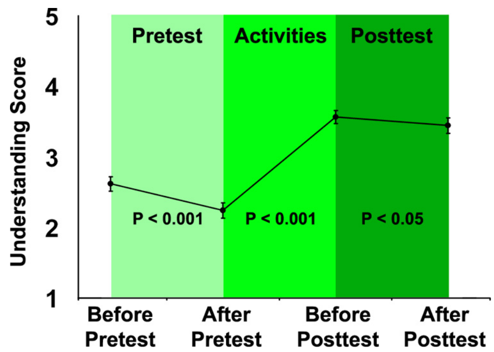

Figure 9. Students' understanding scores (mean ± SEM) for each of the topics (7–8 per module) were averaged to give the student one understanding score at each of the four time points for that module. Individual students completed between one and four modules. If students completed more than one module, their understanding scores were averaged across modules. Thus, each student (N = 39) received a composite score at each time point. Statistically significant differences by paired *t*-test are indicated in the figure.

Student Perceptions about the Program

Overall, students were very satisfied with their experience in the BFP. The overwhelming majority (94%) perceived that they learned skills that will help them succeed in subsequent science classes (N = 104). Even more telling is the fact that 98% of BFP students would recommend this program to

Table 3. Flowchart of BFP activities during supplemental instruction sessions

Survey	Pretest	Survey	Practice activities	Survey	Posttest	Survey
2 min	30 min 10 short answer questions at 6 levels of Blooms	2 min	50 min Content problems from multiple sources	2 min	30 min 10 short answer questions at 6 levels of Blooms	2 min

Table 4. Sample student quotes

Q: What do you consider to be the most positive aspects of the program?

I definitely appreciate that we were introduced to research papers. Although it was difficult I gained a lot for having to not only read the papers but also having to present them.

We got the opportunity to read primary research papers, which is great practice for the future. We are learning how to write scientifically at an early point in our education that is going to benefit me so much. Thanks!

I like how I started knowing very little and the instructors built from there. Instead of researching on my own the turtle experiment or any of the others, I was supposed to try and figure it out on my own. I did learn a lot that way and I also surprised myself that I actually could take what information they gave me and turn it into a report.

Q: What aspects of this program, if any, contributed most to your learning?

Learning the basis of experimental design and constructing papers based on questions presented.

Learning how to effectively design experiments was quite useful, and it was something I hadn't really been taught very much of before.

Writing papers was really helpful because it taught me how to write as a scientist instead of just a literary writer, and the comments that I received on the papers were really helpful.

I also liked getting insights on areas I should be focusing in on to prepare myself for the future. I didn't realize that I needed to improve my statistics, or my fluency in excel. And I most certainly did not know how to write an experimental design before I took this course.

Q: Would you recommend this program to other incoming freshmen interested in science? Why or why not?

Yes. it teaches you a lot of useful scientific skills, such as, designing experiments, writing papers, etc . . .

Definitely, this class has greatly improved my writing skills, which I am tremendously grateful for.

Yes. It gives good, early exposure to primary literature, to practical concepts in science, and to the many opportunities available to students which might otherwise go unnoticed.

Yes, it gives you skills on how to do well in science classes and these skills can even be used in other classes.

Yes; Biology Fellows is a very rewarding program that challenges your ability to implement certain skills that are not necessarily stressed in the typical classroom setting.

other incoming freshmen (N = 98). A selection of BFP student responses about their experiences while in the program is found in Table 4.

DISCUSSION

Science process skills form the core of scientific endeavors, so we wished to gain a better perspective on faculty views about teaching these skills to their students. Our survey of numerous faculty and postdocs from a variety of institutions indicated that they highly value undergraduates' acquisition of science process skills yet most did not spend enough time teaching skills because they used class time to cover course content. What is at the root of this contradiction? According to the responses in our survey and reports from others (Allen and Tanner, 2007; Sirum *et al.*, 2009), the expectation that faculty will cover a certain amount of content in introductory life science courses is systemic and communal. It seems to be a collegial obligation to provide students with a certain amount of content knowledge before they enter more advanced courses. Many faculty commented that students often learn skills "somewhere else"—a research experience, laboratory sessions, upper-division classes—other than in an introductory course. Thus it is assumed that students will somehow acquire these skills in their education, which tends to focus more on content than skills.

Although content is clearly important, science process skills provide the tools and ways of thinking that enable students to build the robust conceptual frameworks needed to gain expertise in the life sciences. Scientists use these process skills to approach inquiry in a particular way, leading to a scientifically valid method for obtaining results from which they base new investigations. It is interesting that faculty who teach introductory courses find themselves in this conflicted position—teaching undergraduates content without the skills needed to help them master that content. It is with the best of intentions that faculty provide introductory life science students with a foundation of content knowledge so that they may be better prepared to pursue science with passion, yet this pedagogical philosophy also fails many of the same students they are trying to educate. Introductory science students are often inundated with content—the syllabus that must be covered—at the expense of developing a conceptual framework in which to work with new content. For many students this teaching approach is uninspiring and causes them to leave science (Seymour, 1995; Seymour and Hewitt, 1997), but for those students who stay, it may delay their development into scientists. After a year of introductory science courses, many would agree that most students are still scientifically illiterate (Wright and Klymkowsky, 2005), incapable of applying the scientific method, critically reading news articles, or finding and evaluating pertinent information in their field of study.

We have described a program explicitly designed to teach incoming freshmen science process skills and effective learning techniques, and showed learning gains and perspectives of students who completed the program. To foster undergraduates' intellectual development for using science process skills in subsequent science courses, we contextualized instruction by using scientific content to help emphasize the teaching of skills. Throughout the program, BFP students practiced scientific writing, reading primary literature papers, experimental design, graphing, data interpretation, basic statistics in biology, collaborative work, oral communication, effective studying, and metacognition. Although we do not know which components of the BFP helped students the most, on average, students exited the program very pleased with their experience, showed learning gains in several skill areas, and were highly successful in the Introductory Biology series at the University of Washington (Dirks and Cunningham, 2006). Given that many undergraduates leave science early, especially underrepresented minorities who are often less prepared for the rigorous nature of collegiate science courses (Cota-Robles and Gordan, 1999; Gandara and Maxwell-Jolly, 1999), we believe it is imperative that students receive this type of instruction early in their education. When students begin to master science process skills, it helps them develop a conceptual framework in which to assimilate new science content and allows them to approach their learning as a scientist.

The general format of the BFP is flexible enough to accommodate content from a wide variety of disciplines and can be implemented in many different settings. The explicit instruction, transparent pedagogy, scaffolding approach, and iterative practice of science process skills can be applied at several academic levels, helping students to achieve mastery of these skills earlier in their education. Many aspects of this program could be adopted in high school science courses, giving students a head start before transitioning to college (Wood, 2009). At the university level, instruction of this nature could be used either as a requirement for science premajors or integrated as part of an introductory science course. We recommend the latter approach be taken because learning skills in the context of course content is likely to be a much richer experience for students (Wilensky and Reisman, 1998; Airey and Linder, 2009), particularly if this integration occurs in all their courses. A wider implementation of programs similar to the BFP could help convey the process of science to incoming freshmen and increase student success and retention, particularly for those students less prepared for college. Armed with the skills of scientists, students are more likely to successfully complete their undergraduate science degrees and be better prepared to pursue graduate study or other rewarding science careers. For students who do not go on in science, learning science process skills will help increase their science literacy.

What do we really want our students to learn in an undergraduate science curriculum, and when do we want them to learn it? When faculty are asked this question their responses vary, but with few exceptions they state they want students to have the skills for interpreting data, critically reading and evaluating different types of literature, problem solving, communicating to others, making connections, and applying scientific content to life. Science faculty take pleasure in doing science because we explore phenomena that interest us, ask questions, pose hypotheses, design experiments to test our hypotheses, and write about our findings for a broader audience. If we redesigned our introductory courses to be more similar to what we like about science, then perhaps our students would far exceed our expectations for investigating the world in a passionate and meaningful way. Students who major in life sciences, and even those who don't go on in science, would possess an ability to use science process skills in a scientifically literate manner. Students taking more advanced science courses would be able to approach our subdisciplines with enthusiasm for learning new content because they would have a skill set for higher cognitive work. However, all of this would have to come at the expense of teaching introductory students the long list of content that makes up the syllabus; syllabi would have to be restructured to include learning goals and objectives that are skill based. We argue that teaching introductory students less content to teach the process of science is both imperative and long overdue.

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