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 overwhelmingly 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...
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 Buisng, 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.
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 these 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 faculty agreed.

Table 1. Faculty ranking

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

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.

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.
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
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 (DeB Burman, 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 predominately 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

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

*Continued*
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 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

### Table 2. Continued

<table>
<thead>
<tr>
<th>Faculty instruction and student activities per 1.5-hour sessions</th>
<th>Faculty</th>
<th>Student</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Session 15</strong> Writing Assignment 4 collected</td>
<td></td>
<td>Oral presentations group 3</td>
</tr>
<tr>
<td><strong>Session 16</strong> Study skills IV</td>
<td></td>
<td>Writing assignment 5 (posttest)</td>
</tr>
<tr>
<td><strong>Session 17</strong> Writing assignment 5 collected</td>
<td></td>
<td>Oral presentations group 6</td>
</tr>
<tr>
<td><strong>Session 18</strong> Careers in science</td>
<td></td>
<td>Student career interests</td>
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<tr>
<td><strong>Session 19</strong> Pathway planning</td>
<td></td>
<td>Academic and professional roadmaps</td>
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<tr>
<td><strong>Session 20</strong> Deconstructing the BFP</td>
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<td>Student planning and social time</td>
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</tbody>
</table>

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 Material 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.

**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.

**Table 3.** Flowchart of BFP activities during supplemental instruction sessions

<table>
<thead>
<tr>
<th>Survey</th>
<th>Pretest</th>
<th>Survey</th>
<th>Practice activities</th>
<th>Survey</th>
<th>Posttest</th>
<th>Survey</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 min</td>
<td>30 min</td>
<td>2 min</td>
<td>50 min</td>
<td>2 min</td>
<td>30 min</td>
<td>2 min</td>
</tr>
<tr>
<td>10 short</td>
<td>at 6 levels of Blooms</td>
<td>Content problems from multiple sources</td>
<td>10 short answer questions at 6 levels of Blooms</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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![Figure 9](http://www.lifescied.org/)

Software: 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.

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**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 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 from 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 must 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 stu-
dent 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 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 intro-
ductive 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, lead-
ing 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 intro-
ductive 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 con-
tent—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 learn-
ing techniques, and showed learning gains and perspectives
of students who completed the program. To foster under-
graduates’ intellectual development for using science pro-
cess 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 pa-
ers, experimental design, graphing, data interpretation, ba-
sic statistics in biology, collaborative work, oral communi-
cation, effective studying, and metacognition. Although we
do not know which components of the BFP helped students
the most, on average, students exited the program rather
pleased with their experience, showed learning gains in
several skill areas, and were highly successful in the Intro-
ductive Biology series at the University of Washington
(Dirkx and Cunningham, 2006). Given that many under-
graduates leave science early, especially underrepresented
minorities who are often less prepared for the rigorous
nature of collegiate science courses (Cota-Robles and Gor-
dan, 1999; Gandara and Maxwell-Jolly, 1999), we believe it is
impertative 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 ac-
commodate courses 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 who major in life sciences, and even those who do not go on in science, learning science.

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