Attrition of undergraduates from Biology majors is a long-standing problem. Introductory courses that fail to engage students or spark their curiosity by emphasizing the open-ended and creative nature of biological investigation and discovery could contribute to student detachment from the field. Our hypothesis was that introductory biology books devote relatively few figures to illustration of the design and interpretation of experiments or field studies, thereby de-emphasizing the scientific process.

To investigate this possibility, we examined figures in six Introductory Biology textbooks published in 2008. On average, multistep scientific investigations were presented in fewer than 5% of the hundreds of figures in each book. Devoting such a small percentage of figures to the processes by which discoveries are made discourages an emphasis on scientific thinking. We suggest that by increasing significantly the illustration of scientific investigations, textbooks could support undergraduates' early interest in biology, stimulate the development of design and analytical skills, and inspire some students to participate in investigations of their own.

INTRODUCTION

Many academically prepared students who initially have a high interest in the sciences switch to non-STEM (science, technology, engineering, and math) majors after taking an introductory course. Commonly cited reasons include: feeling overwhelmed by information, thinking that the field is not as interesting as it initially appeared, and being stressed by the intense competition with classmates for grades (52, 53, 14). Students in such courses do not appear to be experiencing science teaching as recommended in numerous reports from blue-ribbon education panels (20, 33-35). The National Science Education Standards (NSES) Guiding Principles for Teaching of Science states that “education should reflect the way science is done,” and the NSES Science Teaching Guiding Principle 2 asserts: “students learn best by active participation in the learning process” (54). Science educators have noted that college students learn optimally when they “construct meanings rather than just receiving them” (15). The recent Vision and Change document suggests that “the scientific process should be introduced to [college] students early in their studies” (4, p. 5) and integrated throughout an undergraduate Biology program. Decades of reports written by science education reformers urge increased emphasis on scientific thinking and the processes by which scientific understanding is constructed (3, 33-37).

Many reforms have centered on changes in classroom practice because, while research science methods have changed dramatically in the last three decades, science teaching methods have not kept pace (3, 5, 38, 20, 34, 17, 43). A common theme emerging from these analyses is that students taught science in traditional ways neither achieve deep understanding of content (11), nor develop an overall sense of “how science works” (8, 50). In traditional Biology classrooms, undergraduates rarely participate in cognitive activities typical of working scientists, such as debating ideas, models or interpretations (11, 40). Few students taught in traditional ways develop a robust understanding of the nature of science (41, 32). It is likely that introductory courses that are taught without engaging students in creative thinking contribute to their disengagement from biology. Because many instructors of such courses rely heavily on the organization and content of their textbooks, textbooks likely also play a role.

Improvement of the textbooks used in biology courses has been on the agenda of science reformers for decades. In the 1990 National Research Council publication “Fulfilling the Promise: Biology Education in the Nation’s Schools”, one of seven “key needs” for textbook revision was: “Representation of biology as an experimental subject. Textbooks should explicitly convey to students that the information presented is the result of experimentation and that understanding is constantly being refined and is subject to change as new experiments are conducted. Textbooks should also describe the nature of experimentation” (33, p. 29). Two decades later, the Vision and Change document, based on input from over 500 biologists and science education specialists dedicated to “transforming” college science...
education, warned that textbooks can in fact be detrimental to the educational experience, stating that “Faculty need to look beyond existing textbooks for course resources since strict adherence to texts can impede reform ...” (4). Because text illustrations can have significant effects on learning (26, 30, 29, 13), one way biology textbooks could help students construct understanding of the nature and practices of science is by illustrating numerous research studies — bona fide multistep scientific investigations — rather than focusing primarily on results of such investigations. If textbooks emphasized the varied routes by which scientific discoveries are made instead of mainly reporting the outcomes of studies, they might better support undergraduates’ interest in biology. We hypothesized that introductory textbooks under-represent the processes of scientific investigation and discovery.

Challenges for introductory biology courses

Half of the undergraduates in the United States are enrolled at large state universities (51) where faculty are challenged to deliver Introductory Biology lectures to hundreds of students en masse. Many students who switch out of Biology majors report experiences in such courses that contrast sharply with recommendations of science education reformers (33-35, 39, 53, 55). The importance of improving undergraduates’ first biology course to support their declared interest in the field has driven development of specialized innovative approaches. These approaches are aimed at infusing active learning, working in small groups, and the use of inquiry methods into large lectures. This includes transforming the courses’ associated labs from cookbook-style to ‘hands-on, brains-on’ — or inquiry — activities that stimulate student engagement (57, 2, 45, 6). Biology majors have also been encouraged to engage in undergraduate research experiences as early as possible (5, 34, 32). Ideally, such interventions bring the excitement of scientific thinking and research discovery into the science classroom. Still, students with initial high interest in the field continue to exit the Biology major (14), voicing complaints similar to those documented years ago (52, 53).

Issues of breadth and depth

Textbooks have been criticized for a “mile-wide, inch-deep” approach that emphasizes facts and fails to guide students to an integrated understanding of science concepts (47). For high school students, approximately 75% of class time and 90% of homework time is textbook-based (9, 28). In 1990, the NRC noted that “There is clearly a tension between the demands for textbook comprehensiveness and the limitations of [high school] textbook size. The usual casualty is the presentation of biology as an experimental science” (33, p.30). Project 2061’s more recent extensive review of high school textbooks stated: “the textbooks rarely provide opportunities for students to draw connections between ideas — a significant cognitive step toward forming the kind of coherent understanding of a concept that characterizes expertise” (25). In a report critical of the “encyclopedic” approach to content coverage in K-12 science, textbooks were characterized as having established “de facto national standards” for students in middle and high schools, despite their deficiencies (47). College biology textbooks similarly do a great deal to shape college biology courses. Instructors’ editions of such books include a large assortment of accessory “course development” materials such as lab manuals, test banks, pre-printed lecture outlines, and PowerPoint slides. These encourage Biology faculty to deliver a textbook-based course largely prepared in advance by others, and shaped by the order and organization of chapters in a particular textbook. First-year undergraduates accustomed to studying from high school textbooks may approach college texts in a parallel way, mainly using memorization as an approach to learning (44).

Introductory Biology faculty may decide against including activities such as considering the thought process by which an original question was developed into a particular research plan, discussing the steps of a research study illustrated in a figure, examining the data generated, and drawing independent conclusions because such activities take class time which could otherwise be devoted to coverage of additional content. However, a primary focus on content breadth and coverage may not be beneficial (23, 24). Students from countries whose standardized curricula include significantly fewer topics substantially outperform American high school students on standardized math and science tests (47). At the college level, in a recent survey of over 8000 college freshmen at 55 institutions, Schwartz and colleagues (51) found that students earning the best grades in college science were those whose high school experience had included a single topic studied in depth for four or more weeks. Taking time for discussion and reflection when studying in depth may promote the development of metacognitive strategies that can both deepen understanding and be applied in subsequent science courses (21, 51).

Textbooks, figures, and scientific process

To examine the extent to which representations of processes of scientific investigation appear in textbooks used in Introductory Biology courses, we examined figures in the 2008 edition of six such books. We tracked the number of figures presenting descriptive information (e.g., illustration of ribosomal subunits in prokaryotes and eukaryotes) and the number that outlined a study by illustrating a multistep process (Table 1). We did not attempt to analyze every book used in such classes, but instead chose a sample that included textbooks that have been in use for decades (e.g., Starr and Taggart 11th edition (56); Campbell 8th edition (12)) and others written more recently (e.g., Freeman, 3rd edition (18); Brooker et al. 1st edition (10)). We did not survey supplementary materials (websites, CD-ROMs and the like), instead focusing exclusively on figures and tables in
the chapter pages. Because the cost of textbooks is so high, many faculty are reluctant to shift book requirements every time a new edition becomes available; it is thus likely that these editions will be used by large numbers of students, including high school students in AP biology classes (16).

For the analysis, two or in some cases three readers examined each page of each book, noting the number of chapters, number of pages per chapter, and the number and types of figures and tables. We counted “chapter pages” as “pages a student would read as part of the chapter narrative” and did not include post-chapter questions and activities pages. We tracked whether figures presented photographs, drawings or a combination of both, and whether tables summarized verbal information, words with illustrations, or numerical entries. We then rescanned all figures to find any that outlined multiple aspects of the process of carrying out a study, collecting data, and interpreting it; that is, illustrations presenting a series of steps paralleling those delineated in introductory sections of each book devoted to “The Scientific Process,” “How Science Is Done,” or equivalent. These included: generating a question; forming a hypothesis, considering alternative hypotheses; making predictions or designing models based on the hypotheses; carrying out an experiment or study; collecting data; interpreting results; drawing a conclusion; and/or formulating the next step(s). Different books delineated different aspects of the scientific process in their illustrations (Table 2). We counted figures as “depicting the research process” if they addressed a focused research question in an illustration that included a series (three or more) of such steps. For example, the Brooker et al. text used “Feature investigation” boxes for discussion of experiments. Featured studies typically were presented with “Hypothesis,” “Starting materials,” an illustration of the experiment, and “The Data” noted individually in the illustration (Table 2). In the Freeman text, illustrations of studies began with a “Question” followed by “Hypothesis,” “Null (sometimes Alternative) Hypothesis,” “Experimental Setup,” “Prediction of Hypothesis,” “Prediction of Null Hypothesis,” “Results,” and “Conclusion.” Because we were interested in illustrations of the process of scientific investigation, a figure showing a single graph of data from an experiment did not meet our criterion for “showing scientific process” as outlined in Methods.

The vast majority of tables contained additional details of chapter content. Many were composed entirely of words (e.g., “Summary definitions for microevolutionary events,” Table 18.1, Starr and Taggart, p. 298; “Some drugs derived from land plants,” Table 30.1, Freeman, p. 630), or a combination of words and illustrations (e.g., “Major orders of birds,” Table 35.4, Raven et al., p. 701 (27); “Categories of proteins found in the proteome,” Table 21.3, Brooker et al., p. 447). Stand-alone tables rarely included data from experiments, and only a tiny minority of tables contained numerical data (e.g., “Life Table of the 1978 Cohort of the Cactus Finch (Geospiza scandens) on Isla Daphne,” Table 54.1, Sadava et al., p. 1170 (46)). The paucity of tables containing data from illustrated research studies led us to narrow our focus to the figures.

The books surveyed averaged 56 chapters (range 49–60); 1112 pages (range 865–1203); 1180 figures (range 933–1286), and 66 tables (range 29–113; Table 1). Figures...
were often multipart, including drawings, photographs, or a combination of the two, with drawings predominating (data not shown). As a consequence, 1180 figures, the average number per book, represents well over two thousand individual panels. Students reading any of the books would thus encounter a substantial amount of information in the form of illustrations in every chapter.

While the books were similar in overall structure and scope, their approaches to presenting scientific studies differed (Table 2). Four (Brooker et al. 2008; Campbell et al. 2008; Freeman, 2008, Sadava et al. 2008) used a standard approach, while one (Raven et al. 2008) changed format in different chapters and for different experiments. One textbook (Starr & Taggart, 2008) lacked any illustrations that met our criteria for scientific process. A number of classic molecular genetics experiments (e.g., work of Griffith, Hershey/Chase, Avery/McLeod/McCarty, and Meselson/Stahl) appeared in every book, but were not always presented in a “scientific process” format. Other studies (e.g., Spemann/Mangold on embryonic induction) were included in many but not all the books, and a few studies appeared in a single textbook (data not shown). Most of the textbooks covered the period from Mendel’s work to the “present” (ca. 2007), with a few including earlier work of Louis Pasteur.

On average, 4.5% of figures were devoted to representations of multistep scientific process (Table 1). No book represented scientific process in more than 9% of figures. This finding led us to revisit each textbook’s introductory chapter, where aspects of “how scientists learn about the world” are discussed. Table 3 compares for each book the scientific process as introduced in Chapter 1 with the renderings of process in subsequent chapters. A single book (Freeman) carried the same themes set up in the first chapter into all illustrations of scientific process presented in subsequent chapters, and was the only book that routinely included “alternate hypotheses” in representations of scientific process. For most of the textbooks, representations of scientific research studies in later chapters included fewer steps, or different steps than had been set out in Chapter 1.

The different textbooks varied in presentation of many of the same experiments. We highlight in Table 4 the way in which one canonical study, the Miller-Urey origin-of-life experiment, is presented in each volume. Every book shows essentially the same drawing of the experimental apparatus. Two texts (Campbell et al., Freeman) title the illustration with a question to be addressed by the study, one (Sadava et al.) states a hypothesis, and one (Brooker et al.) makes reference to a hypothesis discussed in the narrative text. Three of the six textbooks illustrate multistep processes of scientific investigation: hypothesis/methods/results/conclusion (Sadava et al.); question/experiment/results/conclusion (Campbell et al.); and question/hypothesis/null hypothesis/experimental setup/prediction/prediction of null hypothesis/results/conclusion (Freeman). The other texts simply include descriptive labels on the apparatus pictured.

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**Table 2: Standard style used throughout each textbook for presentation of research studies.**

<table>
<thead>
<tr>
<th>Textbook</th>
<th>Title of figure representing steps of a study</th>
<th>Statement of question</th>
<th>Statement of hypothesis</th>
<th>Statement of null or alternative hypothesis</th>
<th>Illustration of methods or experimental setup</th>
<th>Statement of predictions of hypothesis and of null or alternative hypothesis</th>
<th>Illustration of results or data</th>
<th>Statement of conclusion‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brooker et al.</td>
<td>Feature investigation</td>
<td>X</td>
<td>X</td>
<td>X†</td>
<td>X§</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Campbell et al.</td>
<td>Inquiry</td>
<td>X</td>
<td>X</td>
<td>X‡</td>
<td>X§</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Freeman</td>
<td>Experiment</td>
<td>X</td>
<td>X</td>
<td>X‡</td>
<td>X§</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Raven et al.</td>
<td>John Doe’s Experiment</td>
<td>X</td>
<td>X</td>
<td>X‡</td>
<td>X§</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sadava et al.</td>
<td>Experiment</td>
<td>X</td>
<td>X</td>
<td>X‡</td>
<td>X§</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Starr &amp; Taggart</td>
<td>No such figures</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Figure usually shows either the experimental setup or the results.
‡ Several authors note that not every study leads to a conclusion.
Table 3.
Scientific process as presented in the books’ introductions or in illustrated studies of individual chapters.
All books discuss approaches to scientific investigation within their first 20 pages; however the alignment between components of scientific investigation as presented in chapter 1 and as presented in the subsequent chapters of the books is variable among the different texts.

<table>
<thead>
<tr>
<th>Textbook</th>
<th>Book chapter</th>
<th>Steps of Scientific Process as Presented in Chapter 1 or Illustrated in Subsequent Chapters</th>
<th>Subsections of Figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brooker et al.</td>
<td>Chapter 1.2: “Biology as a scientific discipline”</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td></td>
<td></td>
<td>observations lead to hypothesis</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Subsequent chapters</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Campbell et al.</td>
<td>Concept 1.3: “Scientists use two main forms of inquiry in their study of nature”*</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Subsequent chapters</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Freeman</td>
<td>Chapter 1.4: “Doing Biology”</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Subsequent chapters</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Raven et al.</td>
<td>Chapter 1.2: “The nature of science”</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Subsequent chapters</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Sadava et al.</td>
<td>Chapter 1.3: “How do biologists investigate life?” Observations, then question</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Subsequent chapters</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Starr &amp; Taggart</td>
<td>Section 1.5: “The Nature of Biological Inquiry” No such figures</td>
<td>√</td>
<td>√</td>
</tr>
</tbody>
</table>
CONCLUSION

Students’ ability to learn is influenced by their epistemological beliefs, and STEM course faculty have recently been encouraged to engage in “teaching epistemology explicitly and coherently” (37, p. 24). College freshmen tend to hold naïve epistemological beliefs; for example, that knowledge is certain, scientific ability innate and fixed, and science not a creative endeavor (22, 42, 48, 49). Such views can interfere with learning by influencing students’ approaches to studying (44), as well as their ability to develop deeper understanding of the nature of science through inquiry experiences (32). Naive beliefs are not easily changed unless students experience cognitive challenges in the form of “epistemic load” (8), and textbook illustrations that do not invite engagement and analysis may not provide the cognitive challenges that could support epistemological maturation.

Recent work on characteristics of students choosing PhD vs MD careers post-college indicates that the two groups are intriguingly dissimilar. Out of 200 different issues surveyed, the top predictors for research careers were “curiosity to discover the unknown” and “enjoyment of problem solving” (31). Such themes are inherent to discussions of processes of scientific investigation. As the first college biology class for majors, the Introductory Biology course and textbook provide an opportunity to stimulate curiosity by highlighting and illustrating surprising data, dead ends, rejected hypotheses, unexpected insights, serendipitous discoveries, and collaborative synergies among researchers, in addition to findings generated through the traditionally emphasized and fairly linear Scientific Method. Interestingly, science educators have cautioned that if a focus on scientific process does not realistically convey scientific investigation, instead presenting science as a linear path toward “truth” with no uncertainties or errors, there is a risk of mythologizing the participants, presenting students a distorted view of science, and ultimately doing more harm than good (1, 7, 19). By underemphasizing the research side of science and

<table>
<thead>
<tr>
<th>Textbook</th>
<th>Title of figure</th>
<th>Figure illustrates</th>
<th>Figure illustrates multistep process of science</th>
<th>Additional question in figure or appended to caption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brooker et al.</td>
<td>“Testing the reducing atmosphere hypothesis for the origin of life—the Miller Urey experiment”</td>
<td>the apparatus</td>
<td>---</td>
<td>“Biological Inquiry: With regard to the origin of life, why are biologists interested in the abiotic synthesis of organic molecules?”</td>
</tr>
<tr>
<td>Campbell et al.</td>
<td>“Can organic molecules form under conditions believed to simulate those on the early Earth?”</td>
<td>the apparatus</td>
<td>√</td>
<td>“What If” question: If Miller had increased the concentration of NH₃ in his experiment, how might the relative amounts of the products HCN and CH₂O have differed?</td>
</tr>
<tr>
<td>Freeman</td>
<td>“Can simple molecules and kinetic energy lead to chemical evolution?”</td>
<td>the apparatus</td>
<td>√</td>
<td>“Exercise: Label the parts of the apparatus that mimic the ocean, the atmosphere, and the lightning”</td>
</tr>
<tr>
<td>Raven et al.</td>
<td>“The Miller Urey experiment”</td>
<td>the apparatus</td>
<td>---</td>
<td>none</td>
</tr>
<tr>
<td>Sadava et al.</td>
<td>“Organic chemical compounds can be generated under conditions similar to those that existed on primitive Earth”</td>
<td>the apparatus</td>
<td>√</td>
<td>“Further research: If O₂ were present in the ‘atmosphere’ in this experiment, what results would you predict?”</td>
</tr>
<tr>
<td>Starr &amp; Taggart</td>
<td>No individual title*</td>
<td>first two panels are renderings of the primitive Earth, the apparatus is shown in the third panel</td>
<td>---</td>
<td>none</td>
</tr>
</tbody>
</table>

* In caption: “Sketch of the apparatus Stanley Miller used to test whether small organic compounds could form spontaneously in such a harsh environment.”
including research process in only a small fraction of figures, textbooks present biology as “mainly known,” reinforce students’ naive epistemologies, and fail to build students’ understanding of the nature of science (50).

Most college faculty who teach introductory biology cover subfields (e.g., bioinformatics), describe processes (e.g., microRNA mechanisms), and introduce groups of organisms (e.g., newly-discovered invertebrates of the deep ocean floor) that were not included in their own undergraduate introductory biology course. There is every reason to believe that today’s college students will similarly study and potentially teach a 21st century biology significantly broader than that covered in their college years. Thus, it is essential that students develop transferable learning skills that facilitate integration of new material with existing understanding (11, 21, 23, 24). To support this process, textbook authors might better serve students by focusing more on how the information in their chapters was discovered, rather than devoting most illustrations to describing biology by representing what is known. Examining the design of scientific studies gives students the opportunity to connect scientific ideas, consider alternatives, critically analyze interpretations, and examine the sometimes nonlinear pathways to scientific discovery. Learning that science is not as cut-and-dried as textbooks imply but, instead, a creative process open to a diverse variety of inquisitive individuals, could make biology research careers more appealing, particularly for students who enter college with misconceptions about the nature of research careers.

As the cornerstone of many Introductory Biology courses, textbooks could in principle be an important influence on undergraduates’ understanding of the processes of science. Regarding such books, Bio 2010 cites a “need for works that sculpt science in ways that inform, enlighten and empower the next generation of researchers” (34, p. 66). We suggest that a lack of emphasis on processes of scientific investigation in the figures that appear in introductory college textbooks is an impediment to students’ understanding of science. A shift in the balance of illustrations toward scientific thinking as reflected in the design and interpretation of models, experiments and field studies, and inclusion of more findings based on the unexpected twists and turns that underlie much scientific discovery, could help undergraduates gain deeper understanding of the nature of science. It will also strengthen the critical, analytical, and interpretive skills that will serve them in good stead in their growth as scientists.

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