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Article

Can an Inquiry Approach Improve College Student Learning in a Teaching Laboratory?

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We present an inquiry-based, hands-on laboratory exercise on enzyme activity for an introductory college biology course for science majors. We measure student performance on a series of objective and subjective questions before and after completion of this exercise; we also measure performance of a similar cohort of students before and after completion of an existing, standard, "direct" exercise over the same topics. Although student performance on these questions increased significantly after completion of the inquiry exercise, it did not increase after completion of the control, standard exercise. Pressure to "cover" many complex topics as preparation for high-stakes examinations such as the Medical College Admissions Test may account for persistence of highly efficient, yet dubiously effective "cookbook" laboratory exercises in many science classes.

INTRODUCTION

Educators generally endorse inquiry teaching methods yet do not agree that such methods are always superior, especially during early intellectual development (for recent views, see Bybee, 2006; Heppner *et al.*, 2006a,b, and references therein). At the college level, specifically at research universities where intellectual development of most students should be relatively high, reform of undergraduate science education from "direct" or "didactic" education and toward inquiry-based or "student centered" has been a "tough road" for various reasons (Brainard, 2007).

Few controlled studies report increase in college student performance on assessment instruments measuring understanding of content after inquiry-based instruction (for biology, see Cianciolo *et al.*, 2006; Lord and Orkwiszewski, 2006). We reformed a classic introductory biology, science majors, laboratory exercise to teach science to science college students more like the way science is done (Handelsman *et al.*, 2004). We designed assessment questions so colleagues and we could evaluate the effectiveness of an inquiry approach relative to existing, direct teaching methods of the same concepts in the local environment. We also responded to recent calls to integrate more mathematics learning into basic science education (National Research Council [NRC], 2003) and assessed this effort as well.

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MATERIALS AND METHODS

We chose to modify a traditional, expository, laboratory exercise demonstrating lysozyme activity on bacteria as monitored by students using a spectrophotometer. The existing format was direct, didactic, or "cookbook" (see Table 1, Standard format column for a list of some characteristics) and used in essentially identical format in other classes at our and our peer institutions. We designed a more open-ended, yet still guided, exercise that placed more observational/experimental decisions in the hands of teams of students. We assessed effectiveness of this exercise in improving the performance of students on a series of predetermined content and attitude questions. Results were compared with the performance of similar students on the same sets of questions before and after completing the existing, standard, enzyme laboratory protocol.

Our learning objectives for this exercise included emphasis on student inquiry (Lee, 2004), hands-on learning (Haury and Rillero, 1994) and an open, but guided, student exploration that permitted the instructor (or students on their own) to integrate mathematical modeling into their explorations. We also included training on basic laboratory topics such as significant digits, how to learn to use equipment, and what constitutes effective note taking; many of these latter topics were not included in the standard exercise we

Table 1. Distinguishing characteristics of the standard (see Anonymous, 2002, chapter 4) and inquiry (this study) enzyme laboratory protocols compared in this study

Characteristic	Standard format	Inquiry format
No. of terms defined explicitly	18	0
No. "terms . . . to learn the definition of" listed in "Objectives" section	11	0 (There is no "Objectives" section)
Source of enzyme	"Each group will be given . . . a tube containing the enzyme."	"Homogenize some (ca 2–4 g) of inner, peeled portion of a turnip in a blender with distilled water at high setting for <1 min."
No. predetermined reagent volumes specified for use by students	19	0
No. predetermined observation intervals	2: 1 min (Table 4.2 in lab manual); 5 min (Table 4.4)	Not specified; "This may take more than one trial."
No. blank, preprinted data tables/individual cells therein in manual	7/115 (excluding duplicates)	0/0
Spectrophotometer directions provided	Four steps starting with "1. Use the knob on the top of the spectrophotometer to set the wavelength."	"Refer to instruction on how a spectrophotometer works and how to use one (. . . pasted on it)."
No. of "hint(s)" or times students are told "correct" results to expect	3	0
No. of equations presented	3 (calculate a slope)	12 (for Michaelis–Menten derivations)
No. of specific steps for drawing graphs presented (e.g., "Use the entire piece of paper.")	11	0
"Just in time" explanation of pipettes (TD/TC); accuracy/precision, significant digits when needed?	No	Yes
No. of sections introduced as questions?	0	11
Discussion of history of enzymology (including technology and people)?	No	Yes
"Blank" lab report provided?	Yes	No
Linkage to past (including high school)/future coursework in topic area?	No/no	Yes/yes
Separate Instructor Guide?	No	Yes

targeted for reform. The protocol also emphasized cooperative learning.

We designed the new enzyme protocol as separate, independent components to accommodate variable instructor time to allocate to the exercise, equipment availability, and learning objectives. We assumed that our targeted students were familiar with, yet likely not facile with, appropriate background concepts from their K–12 science education as stated in national K–12 standards and the largely derived various state K–12 science standards. Nonetheless, our teaching protocol was not "confirmational," i.e., we intended it to *precede*, not follow, any "lecture" discussion of enzyme activity in the same or an aligned course.

The two treatments were both presented in the standard laboratory context of a large lecture course. Lab section size (24 students), physical layout, and context within the larger "lecture course" remained unchanged across the two treatments. No aspect of the course in which we assessed the two forms of "enzyme lab" was changed or required change between the two treatments other than the requirement that the lecture section instructor did not "cover" enzymes before the inquiry format ran in the lab sections associated with the lecture. Laboratory teaching associates were provided minimal orientation to the basic objectives of an inquiry approach in the single, standard, weekly planning "TA meeting" before offering that format of the exercise.

Before using the new protocol we developed a series of assessment questions based upon our learning objectives for the new exercise. Nineteen objective questions assessed increase in biological understanding after completing either the existing, standard exercise (control treatment taught in winter quarter 2004) or the new exercise ("inquiry," treatment taught in spring quarter 2004). We specifically designed questions to test student learning in basic enzyme biology and mathematical formulations of enzyme activity; fewer questions were also prepared to assess student learning gains in laboratory techniques and history of science as it pertains to the study of enzymes.

We developed 10 additional subjective questions asking students to assess their own understanding of aspects of enzyme biology. We asked all students assigned the "standard" or inquiry version of the enzyme laboratory to answer all questions before and after the exercise (2 wk apart). We asked students in both groups to answer a final set of 10 questions regarding the learning experience (e.g., the degree to which it engaged students) after completing either format of the protocol. Our research protocols were determined as exempt from human subjects requirements as determined by the U.S. Department of Education by The Ohio State University Institutional Review Board.

RESULTS

Students who completed the inquiry-based enzyme laboratory protocol showed significant improvement on our a priori objective and subjective assessment questions compared with students completing the existing, standard, laboratory protocol who showed no significant change in performance after completing their protocol (Table 2). After discovery of the initial overall trend in the complete data set, a posteriori testing of subsets of questions showed that students improved specifically in basic enzyme biology (Ta-

Table 2. Mean scores on objective assessment questions by students in a college introductory biology course for majors before and after completion of two alternative laboratory protocols teaching aspects of enzyme activity

Comparison	N	Before standard	SD	After standard	SD	Mean Δ[a]	Before inquiry	SD	After inquiry	SD	Mean Δ	$P <$
Overall	19	48.7	27.1	49.3	25.1	0.6	40.9	23.2	60.0	23.2	19.1	0.001
Basic enzymology	8	69.0	18.7	68.3	12.3	−0.7	53.5	18.8	69.9	18.3	16.4	0.05
Mathematics	5	30.6	19.6	30.0	20.3	−0.7	29.2	20.0	43.5	21.7	14.3	0.05
Techniques	3	46.0	33.9	53.0	30.8	7.0	43.0	33.8	77.3	23.2	34.3	ns
History	2	25.5	16.3	25.5	6.4	0.0	22.5	13.4	44.0	11.3	21.5	ns

ns, not significant.

[a] Mean change, Δ, is based on answers to N individual questions within each class and is compared across the two teaching protocols (paired *t* test, two-tailed).

ble 3) compared with students completing the standard protocol. We observed no difference in the "techniques" and "history" questions that included fewer questions. Improvement in mathematics assessment questions after the inquiry approach cannot be compared meaningfully with student performance following the standard approach that did not include mathematics in its objectives.

We pooled student responses to each assessment question from before and after completion of the standard and inquiry enzyme laboratory protocols. We calculated the mean change in response, Δ, after completion of the appropriate exercise and compared means for the standard and inquiry protocols with paired Student's *t* tests (two-tailed) on arcsine transformed percentage data. This pooling of individual student answers dramatically reduces sample size and degrees of freedom (because approximately 400 students answered each assessment question in both groups) yielding a very conservative test.

Six questions assessed student learning of the mathematical components included in the inquiry laboratory format but not the older, direct format. One question assessed a spreadsheet application in the inquiry format exercise; another assessed proper graphing of rate of substrate conversion with change in absorbance. The other questions assessed aspects of Michaelis-Menten derivations introduced in the inquiry exercise. Pooled percentage of students answering these questions correctly rose from 28.4 ± 19.8 (mean ± SD) to 43.0 ± 21.6 ($t = 2.43$, df = 5, $P < .05$).

Student subjective evaluations of their own understanding of various aspects of enzyme biology also increased significantly after completion of the inquiry laboratory format compared with the standard format for this exercise (Table 4).

Students who completed the inquiry version of the laboratory protocol generally scored lower on the assessment pretest than did their counterparts taking the same test before the standard format enzyme laboratory the previous quarter. This results in similar final scores in the subset of questions on basic enzyme biology along with significantly greater improvement in that category by students completing the inquiry version of the exercise (Table 2). This same trend also occurs in the student subjective evaluations of their own understanding of enzymes before performing their version of the laboratory exercise. This may reflect the greater percentage of freshman students (37% of 542 students) in the quarter when the inquiry format of the enzyme laboratory was introduced as opposed to the previous quarter (when 29% of 601 students were freshmen). Other external variables such as lecture and laboratory instructors also could not be controlled across the two academic quarters likely contributing to this unanticipated trend in the "before" assessments for the two protocols. Natural turnover of laboratory graduate teaching associates (~33%) and careful orientation of those instructors attempted to minimize any possible confounding effect of instructor attitude (a "Hawthorne effect").

Seventy-three percent of the 601 students enrolled in the BIO 113 course completed the before and after assessment questions, as did 91% of the 542 students enrolled in the subsequent quarter.

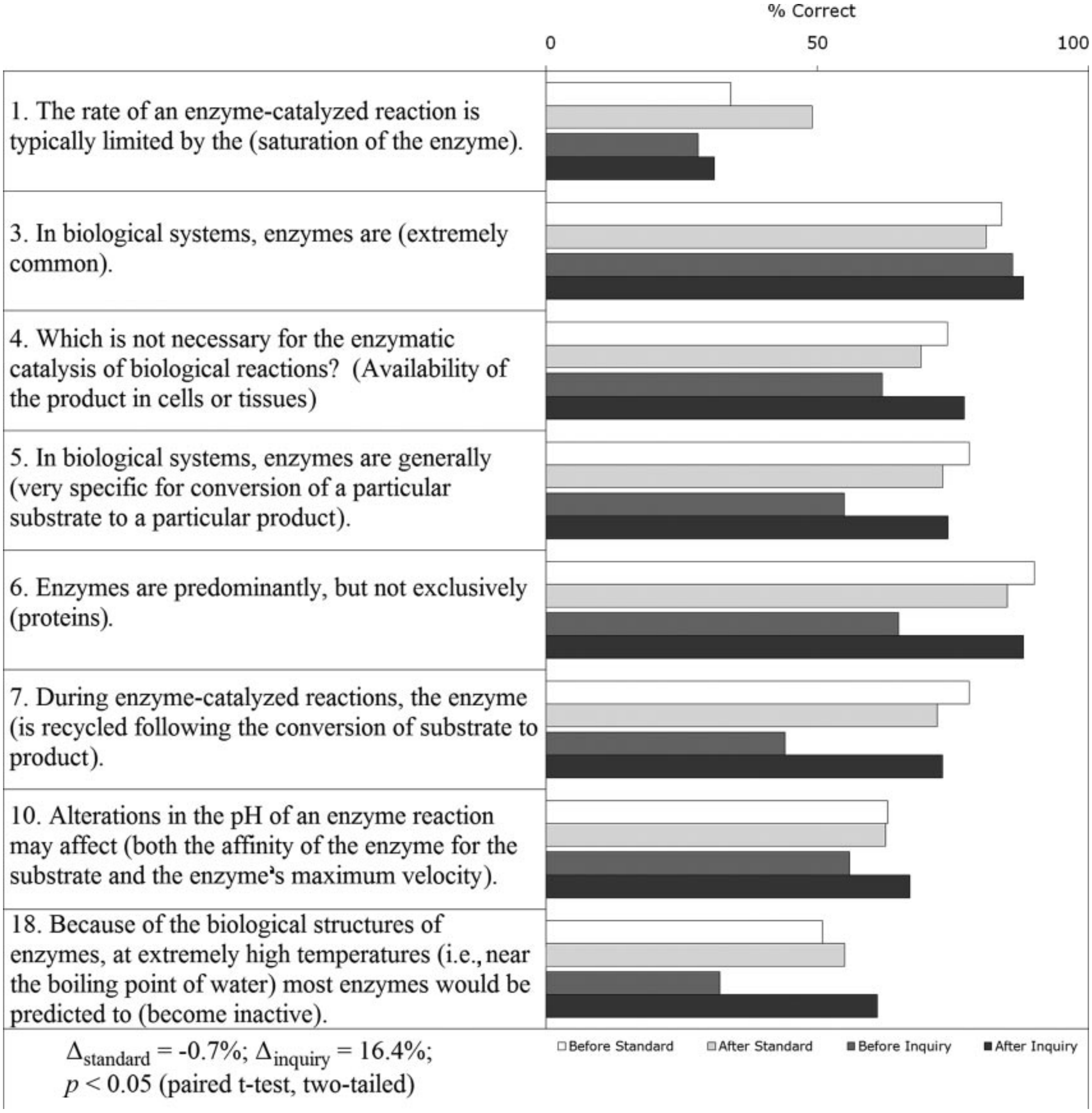
DISCUSSION

Our results support the hypothesis that inquiry-based, hands-on learning approaches to teaching complex biological concepts such as enzyme activity can increase student performance on assessment tests compared with standard or cookbook formats. Furthermore, student self-evaluation of their understanding of and confidence with the information and techniques presented in an enzyme laboratory exercise increased after participation in an inquiry-based enzyme activity compared with a standard version enzyme exercise. Indeed, completion of the standard enzyme laboratory exercise (in use in similar form in many university teaching laboratories) had no discernible effect on student performance on most of our objective and subjective questions. It is not clear that students gained anything from completion of the standard enzyme laboratory protocol.

We were not surprised that student performance on the mathematical assessment questions did not improve after completion of the standard enzyme exercise because that exercise did not include mathematical modeling of enzyme activity. But student performance on assessment questions of other aspects of enzyme activity that *were* presented in the standard exercise such as basic enzyme biology did not improve after completion of the standard exercise either even though that was the apparent, sole, learning objective of that format.

The current version of inquiry-based enzyme exercise for introductory, majors, college biology students that forms the

Table 3. Mean responses to assessment questions regarding basic aspects of enzyme activity before and after respondents completed a standard or inquiry-based laboratory exercise on the topic

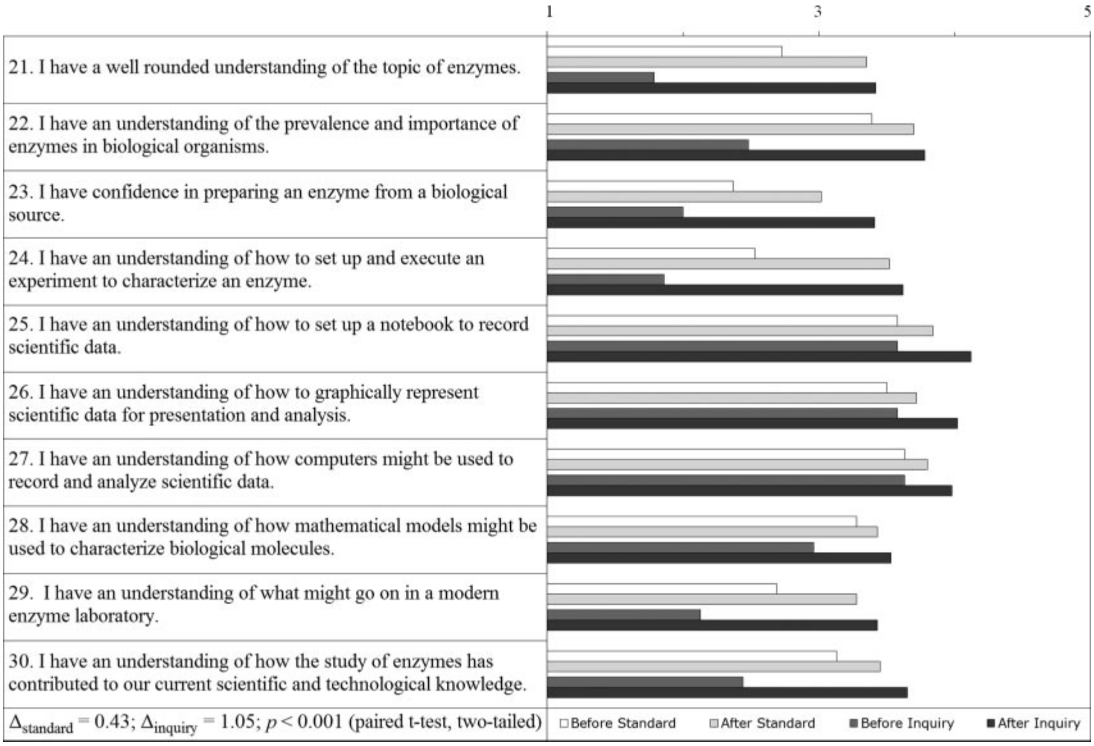


basis for the comparison between alternative laboratory teaching methods discussed here along with an instructor's version of the exercise is available from the first author. The inquiry format of the exercise uses a learning cycle initial exploration of guided questions regarding enzyme activity, followed by hypothesis building and testing, term introduction, and application (Lawson, 1995). The optional application phases of the exercise permit testing of subsequent hypotheses regarding changes in initial experimental conditions (e.g., enzyme/substrate concentrations, pH, temperature).

We develop student understanding and modeling of mathematical aspects of enzyme activity as described initially by Michaelis and Menten (1913) in the inquiry-based laboratory format through guided discovery and cooperative learning; calculus is not required. Optional (for the instructor and/or student) portions of the exercise discuss the interaction of science and technology in the history of understanding enzyme activity; for example, spectrophotometers were patented 22 years *after* Michaelis and Menten's pioneering models of enzyme activity. Another optional portion presents the biography of Dr. Maude Menten who was born in Canada but "had to leave Canada to pursue a career as a research scientist because in those days women were not allowed to do research in Canadian universities" (Enersen, 2007).

We chose the topic of enzyme activity for this effort to demonstrate the flexibility of inquiry-based approaches in biology teaching laboratories no matter the specific topic. We also wanted to evaluate the effectiveness of such ap-

Table 4. Changes in indicated subjective questions by students in an introductory biology course for majors before and after completing a standard or inquiry-based laboratory exercise on enzyme activity



For answers, 1 is strongly disagree, 3 is undecided, and 5 is strongly agree. Sample sizes for each question in each laboratory type ~400.

proaches relative to standard cookbook teaching formats that, according to our results, are often of little if any value in meeting course learning objectives.

We designed our inquiry-based exercise for use in other courses as well. For example, our inclusion of history, technology and diversity considerations as they apply to studies of enzymes aligns the exercise with the learning objectives of the general education curriculum requirement for natural science courses at most colleges and universities. Although the exercise assumes students have met the learning goals of our (and most) state's K–12 science content standards, the exercise could also be used in advanced high school biology courses.

The two laboratory formats compared here address different learning objectives. The standard format states explicitly its aim as follows: "1. To study the properties of (enzymes) . . . including the effects of enzyme concentration and temperature" (Anonymous, 2002, chapter 4, p. 4). Additional objectives include the following: "2. To study the role of controls . . ., 3. To study protein denaturation, 4. To learn to write a formal report, 5. To learn the definition of the following (11) terms . . ." (Anonymous, 2002, chapter 4, p. 4). The inquiry format has no explicit objective section and poses, instead, a general opening question ("How can we characterize the relative activity rates of enzymes?") followed by a series of 10 nested, increasingly specific questions (e.g., "How can the reaction rate of enzymes be compared?").

We designed the inquiry format as an "integrated instructional unit" (sensu NRC, 2006) in a larger effort for students to gain experience "doing science" (as in "teach science the way you do science"; Handelsman *et al.*, 2004). Decisions regarding timing of observations, recording and presenting data, and experimental conditions, including dependent and independent variables, all become part of the students' learning experience/decisions and not external and assigned to preprinted, blank data tables provided for students. In the inquiry format, students make decisions when something seems to "not work."

Both formats inform students of the rubrics used to determine their grade. The standard format includes a "formal report" for which individual students "will be graded on all sections of the report but Sections 4 (*Results and Data Analysis*) and 5 (*Discussion and Conclusions*) will be weighted most heavily." A weekly quiz "will be divided between material from the previous experiment and the experiment (for) that day." The inquiry protocol includes 30 equal-valued questions answered by the collaborative groups established in each laboratory section. There are no weekly memory/recall quizzes.

In a recent review, Heppner *et al*. (2006a) note that only "A few articles provided quantitative evidence generally in favor of inquiry" (p. 390), but this criticism cuts both ways and applies equally well to direct teaching methods. Some college instructors insist that the final course grade provides a meaningful assessment of learning gains yet grades hardly constitute a before-after assessment of knowledge gains and would fail as a meaningful experiment of possible treatment (i.e., course components such as individual laboratory exercises assessed here) in any research area from which those instructors hail. When put to such a test, our standard, existing protocol seemed minimally effective at best even in meeting its relatively narrow objectives. Conversely, completion of the inquiry protocol correlated with improved performance on content and attitude questions.

Why have inquiry protocols for laboratory and other course components not become more common in undergraduate science courses, especially at research universities? Although several factors likely contribute to this situation (Brainard, 2007), one factor obvious from our trials is the additional time required for students to complete, much less benefit from, the inquiry format.

Acknowledging the trade-off between quantity and quality of topics considered is hardly new in education, and completion of all components of our inquiry protocol requires more time than traditionally budgeted for the "enzyme lab," usually one weekly laboratory meeting in a majors introductory sequence or similar course. To some extent, some of the time necessary for deeper consideration and reflection of topics comes from not repeating instruction that students have had or should have had. Some elementary aspects of science understanding such as experimental controls, discussed in the existing, standard protocol is not addressed as extensively in the newer, inquiry format because all of our students have completed at least one year of high school biology (often more) and passed our state's high-stakes graduation examination before college matriculation. Of course, this is not always the case, but explicit recognition of both of these components of the academic training of students, something often not reasonable when our enzyme and many similar direct protocols were written, increases student motivation and responsibility for their own learning—consistent with the objectives of the inquiry format assessed here.

Emphasis on efficient "coverage" of many topics at the expense of the quality of that coverage is exacerbated by the nearly universal discounting of the contribution of "lab hours" relative to "lecture hours" (usually by as much as 66%) in allocating course credit and the subsequent diminution of the impact and importance of laboratory contribution to overall course grade. This practice seems almost anachronistic given recent calls for more active, hands-on, real research experience for today's science students, majors (NRC, 2003) and nonmajors (Howard Hughes Medical Institute, 1996; National Science Foundation, 1996).

This emphasis on topic coverage, often at the expense of deeper understanding of fewer topics, represents the higher education equivalent of the "mile wide and inch deep" characterization of many K–12 mathematics and science curricula (Gonzales *et al*., 2000). Topic coverage in college science classes also seems driven by internal and external pressures on students, transferred frequently and often vociferously, to instructors to perform well on graduate and professional school qualifying examinations, especially the Medical College Admissions examination. This emphasis "constrains course offerings and content at most institutions (of higher education)" (NRC 2003, p. 5). An informal survey of students enrolled in our first quarter, majors, introductory sequence course (where we conducted out enzyme protocol comparisons) suggests only ~25% of our students are considering applying to medical colleges at that time. An unknown number of other students in these same courses are or will consider K–12 science education careers. Some of the prevalence and persistence of didactic teaching strategies in K–12 science education classrooms may come inadvertently from the preservice academic experiences of K–12 science teachers and this emphasis on topic quantity at the expense of quality to meet the perceived professional needs of a small, but vocal, number of college science students in courses taken by both groups as college students.

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