Learning Gains in a Lecture-Based and a Web-Enhanced, Interactive Introductory Biology Course

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Abstract: The pedagogy used in our Introduction to Biology course (BIOL 1010) changed from a standard lecture-homework-exam format to an interactive one between 2003 and 2004. To measure conceptual learning gains in the traditional course in fall 2003 and in a section of the interactive course in fall 2004, we created concept inventories for each evolution and ecology. Both classes were taught by the same instructor who had taught BIOL 1010 since 1976. A significant increase in learning gain was observed with the interactive pedagogy in evolution (traditional, 0.10; interactive, 0.19; $p = 0.024$) and ecology (traditional, -0.05; interactive, 0.14; $p = 0.000009$). The interactive BIOL 1010 has now been taught three times by four senior faculty: 2 sections, fall 2004; 2 sections, spring 2005; and 3 sections, fall 2005. In these later sections (except 1 section fall 2004 indicated above) evolution and ecology learning gains were measured with two versions of a single concept inventory with fewer evolution and ecology questions than in original inventories. Learning gains in evolution and in ecology were also similar each semester for different instructors; however, in four instances, one instructor’s section had a considerably higher learning gain than the other section(s), indicating a possible instructor influence on learning gain. In addition to concept inventories, common multiple-choice exams were given to all sections in a semester with different exams being created for each semester. The average scores on exams each semester in different sections were almost identical, indicating that interactive materials and pedagogy, when presented by a seasoned instructor, facilitated similar learning as measured by a standard testing method. Taken together, the data on BIOL 1010 indicate that learning gains increase significantly when interactive pedagogies are employed. This result strengthens the case for augmenting or replacing instructor-centered teaching with interactive, student-centered pedagogy.

Introduction

Interactive exercises, where students learn through discovery by doing, have long been recognized as effective teaching activities (Atkin & Black 2003). Learning-by-doing was the foundational idea at the University of Edinburgh when teaching chemistry through experiments was first practiced in 1823 (Nye, 1993). Subsequently, this successful, hands-on pedagogy was adopted universally for teaching some aspects of chemistry, physics, and biology. Over the past several decades a growing number of practitioners in higher education have rediscovered that interactive, student-centered teaching enhance learning over that attained with traditional, lecture-based, instructor-centered pedagogies (Atkin & Black, 2003; Banet & Ayusso, 2003; Cummings, Max, Thornton, & Kuhl, 1999; Hake, 1998; Glinkowski, Hylan, & Lister, 1997; Handelsman, Ebert-May, Beichner, Bruns, Chang, DeHaan, Gentile, Lauffer, Stewart, Tilghman, & Wood, 2004; Knight & Wood, 2005; Mazur 1997; Udovic, Morris, Dickman, Postlethwait, & Wehterwax, 2002; Wirth & Perkins, 2005).

In the natural sciences, physics educators were among the first to effectively embrace interactive learning, including peer teaching, as supplements to traditional lecturing (Atkin & Black, 2003; Hake, 1998; Mazur, 1997; Thornton & Sokoloff, 1998). With the development of the Halloun-Hestenes Mechanics Diagnostic test (MD) (Halloun & Hestenes, 1985) and the Force Concept Inventory (FCI) (Hestenes, Wells, & Swackhammer, 1992), physics educators had a means to determine if their teaching innovations improved student understanding of Newtonian mechanics. Hake (1998) used data from MD and FCI in 14 traditional and 48 interactive-engagement physics courses to establish that learning gain doubled in those classes that employed an interactive-engagement pedagogy.

In the early 1990s, introductory physics at our university went from large lecture classes of several hundred students to classes with 40 to 60 students in which lectures, demonstrations, and laboratories were largely replaced by computer simulations and related hands-on exercises, a teaching method called the studio model. Cummings, Marx, Thronton, & Kuhl (1999) used FCI and the Force and Motion Conceptual Evaluation (FMCE) to establish that delivering traditional activities modified to fit the studio format did not improve conceptual learning. The inclusion, however, of Interactive Lecture Demonstrations (Skoloff & Thornton, 1997) and Cooperative Group Problem Solving (Heller, Keith, & Anderson, 1992) into studio classes doubled conceptual learning gains: measured by FCI, 0.18 (standard studio) to 0.35 (modified studio) (FCI); measured by FMCE, 0.21 versus 0.45 (FMCE).

Advances in computer-based, course-management systems have made it possible to extend learning-by-doing pedagogies beyond in-class into online, out-of-class sessions (Baxter, Lister, & Laplante, 2000; Ebert-May, Linton, Hodder, & Long, 2005; Lister, Siegmann, Byrnes, Cupples, & Laplante, 2000). For example, our studio ecology course employs computer-based, pre-class activities that prepare students for their interactive, in-class sessions. Students post answers online to a question or analyze data that relate to a video, simulation, or article they have engaged in preparation for their in-class sessions. When students come to class, they are prepared to discuss and expand on concepts at a depth not possible in the traditional lecture course (Lister, 2001).

Interactive, Student-Centered Pedagogies Introduced into Introductory Biology Course

In 2002 our Biology Department decided to restructure its one semester Introduction to Biology course (BIOL 1010) by building upon the model employed in our studio ecology course. In this process the content of BIOL 1010 was modified: development, behavior, and physiology were dropped and equal time was spent on just four areas—evolution, ecology, genetics, and molecular-cell biology. Employing WebCT as the course management tool, each session in the restructured BIOL 1010 is composed of pre-, in, and post-class activities that explore a major biological topic.

One of us (Professor A) had taught BIOL 1010 for almost three decades employing the lecture-homework-exam format. This gave us the unique opportunity to measure the learning gains obtained in our traditional BIOL 1010 course in fall 2003 and to compare them to the learning gains obtained in the restructured BIOL 1010 in fall 2004, with both courses being taught by the same instructor. Since the new BIOL 1010 course would also be taught by other faculty, a comparison of learning among the sections could be used to indicate the relative importance of instructor, course structure, materials, and pedagogy in the observed learning.

Methods

Structure and Pedagogy of the traditional, lecture-based BIOL 1010 course

Students were given 3, 50 minute lectures each week that were well illustrated with 35 mm slides and sometimes a video. Attendance was not required, although course procedures encouraged attendance (for example, homework assignments were handed-out in class at the end of Friday’s class and homework papers had to be turned-in personally by each student in Monday’s class). Each lecture had a reading assignment from the text and, for a few lectures, a scientific article. Each week students were required for credit to submit answers to 9, short-answer, essay questions (3 questions per lecture). Two exams and a comprehensive final exam were given. Students also had a laboratory that was project-based and required, on average, about 5 hours per week. Table 1 summarizes this course and interactive BIOL 1010 taught by Professor A in fall 2004.

Table 1

Summary of the major characteristics of the traditional and interactive BIOL 1010 sections taught by Professor A in fall 2003 and fall 2004.

BIOL 1010	In-Class Structure	Out-of-Class Structure	Laboratory	In-Class Time on Evolution (minutes)	In-Class Time on Ecology (minutes)
Traditional	3, 50 min lectures per week; two exams and final	Weekly homework and text readings	About 5 hours per week	350	400
Interactive	2, 110 min periods of various activities per week; three exams and final	Pre- and post-class activities	About 5 hours per week in a separate 1 credit laboratory almost all students took in fall ‘04	605	495

Structure and Pedagogy of the interactive BIOL 1010 course

Students had two, 110 minute, in-class sessions per week. Every in-class session had on-line pre-class and post-class sessions that each required about 60 minutes to complete. Students were given three exams and a comprehensive final exam.

All pre-classes had a short essay question to be answered on-line, and all pre- and post-classes had 4, multiple-choice, review questions. The short essay and review questions were evaluated for credit. Students begin the pre-class activities with a brief video that makes topics like natural selection, species diversity, and gene expression come alive. The video is followed by a series of activities that include online experiments and simulations, web investigations, data analyses, short articles on classic and recent discoveries that relate to the topic at hand, and textbook readings. These activities are integrated with the video and prepare students for the up-coming, in-class period

In-class sessions involve active student participation and attendance is required. The in-class activities de-emphasize lecture per se. Students often work in small groups (2 to 5) answering questions, discovering concepts, and learning vocabulary by using it. For example, in an interactive learning activity (modeled after the Interactive Lecture Demonstration employed first in physics classes [Sokoloff & Thornton, 1997]) students are given an observation or a set of data and asked to answer a particular question(s). They work first individually and then as groups before reporting to the class. Concepts and topics are also explored in interactive discussions, mini tutorials, simulations, or Web-based research exercises. Learning is monitored and enhanced by concept queries. These are multiple choice questions that are first answered individually. If not answered correctly by every student, the concept query is posed a second time and answers solicited after being discussed in small groups to resolve misunderstandings. All of these peer-based discussions are facilitated by teaching assistants and the instructor. Following the in-class period students engage a set of post-class, online exercises similar to those in the pre-class, but with fewer activities, that iterate or expand upon concepts and information previously presented.

Concept Inventories

Many types of formative and summative learning assessments are available (for example, various types of questions—multiple choice, matching, fill-in-the-blank, true-false, and essay; one on one interviews; standardized concept inventories; knowledge surveys; and focus groups). The relative merits of each continues to be debated (Anderson, Fisher, & Norman, 2002; Brewer, 2004; Odon & Barrow, 1995; Roy, 2001, 2003; Thornton & Sokoloff, 1998; Udovic, Morris, Dickman, Postlethwait, & Wetherwax, 2002; Wirth & Perkins, 2005). We elected to assess learning gain with conceptual questions, following the model of FCI and FMCE (Cummings, Max, Thornton, & Kuhl, 1999; Hake, 1998; Mazur 1997; Thornton & Sokoloff, 1998). Although a number of biology educators have developed assessment tools for their courses, the biology community has not produced assessment tools like FCI and FMCE that we could employ to measure objectively learning gains (Anderson, Fisher & Norman, 2002; Banet & Ayusso, 2003; Brewer, 2004; Handelsman, Ebert-May, Beichner, Bruns, Chang, DeHaan, Gentile, Lauffer, Stewart, Tilghman, & Wood, 2004; Khodor, Halme, & Walker, 2004; Klymkowsky, Garvin-Doxas, & Zeilik, 2003; Odon & Barrow, 1995; Roy, 2001, 2003; Udovic, Morris, Dickman, Postlethwait, & Wetherwax, 2002). As a consequence, we developed evolution and ecology concept inventories to assess learning gains in BIOL 1010.

To develop the inventories, we independently compiled lists of evolution concepts. We then made a group list and reconciled it with what Professor A presented in his traditional BIOL 1010 course and what was covered in evolution chapters in several textbooks including *Biology: Life on Earth*, Audesirk, Audesirk, & Byers, sixth edition (the textbook used in our traditional BIOL 1010 course in 2003). We eventually identified 47 core evolution concepts.

Questions related to the identified evolution concepts were written and then vetted with half a dozen colleagues. In making these questions we reviewed and modified several questions from the Conceptual Inventory of Natural Selection (Anderson, Fisher, & Norman, 2002). We also drew upon the extensive literature on misconceptions in biology (D'Avanzo, 2003; Sinatra, Southerland, McConaughy, & Demastes, 2003). In this way, our 20-question evolution concept inventory was created. The questions covered most of the 47 concepts on our list but not all, because some of our concepts were mainly fact or vocabulary-based and others did not lend themselves to multiple choice questions. A 17-question ecology concept inventory, based on our list of 38 fundamental ecology concepts, was similarly created.

In the concept inventories given in fall 2003, some of the questions had more than one correct answer. In order to facilitate machine grading of the concept inventories given in fall 2004, we modified the format of the questions with more than one answer so that each multiple choice answer had a place for an answer on the answer form. This change makes the 2003 and 2004 inventories slightly different in format, but the influence this may have had on the results is likely to be minor. Of more importance is the time students spent on evolution and ecology. Interactive BIOL 1010 had more in-class-time for evolution and ecology than did the traditional course (Table 1). In addition, required attendance and credit for some pre- and post-activities in the interactive BIOL 1010 also increased student time on task. These time differences and other course differences described above likely influenced learning gains.

Administering two concept inventories required 4, 50-minute class periods. We decided that too much time was taken from instruction, and we created a single concept inventory for other BIOL 1010 sections. In 2004 fall and 2005 spring we used a 31-question concept inventory, and in 2005 fall we used a 40-question concept inventory. In the 31-question inventory, there were 8 evolution, 8 genetics, 8 molecular-cell, and 7 ecology questions. The 40-

question concept inventory had 10 questions in each area. From these two inventories we present learning-gain data only for the evolution and ecology questions for two reasons. First, almost all of the evolution and ecology questions were validated and modified and had been tested in the traditional BIOL 1010 and in the pilot of the interactive BIOL 1010. Second, the results for evolution and ecology were sufficient to establish that students with different instructors during a given semester had similar learning gains, although a possible instructor influence was also observed in a few instances.

The questions in all of our concept inventories were sufficiently difficult that no student achieved 100% on either a pre-instruction or a post-instruction administration of an inventory. Thus, we did not have a ceiling effect where students maxed-out the learning gain that the inventory could measure.

We also used the common course exams given to all sections in a particular semester to compare learning between sections of interactive BIOL 1010 taught by different instructors.

Instructors and Course sections

The traditional and interactive sections taught by Professor A in fall 2003 and 2004 are summarized in Table 1. In traditional BIOL 1010 fall 2003, seven lectures were exclusively focused on evolution (in-class time, 350 minutes) and were given at the beginning of course. In addition to evolution homework questions, students had an hour exam on evolution during the semester. The 20-question evolution concept inventory was given in the first class of the semester and in the next-to-last class. Eight lectures exclusively focused on ecology (in-class time, 400 minutes) and were given at the end of the course. Students had ecology homework questions but did not have an exam on ecology during the semester. The 17-question ecology concept inventory was given near the end of the course in the class just before the first ecology lecture and in the last class of the semester.

In interactive BIOL 1010 fall 2004 (Professor A), 5.5 sessions focused exclusively on evolution (in-class time, 605 minutes) and were given at the beginning of the course. Students had an hour exam on evolution during the semester. The 20-question evolution concept inventory was given in the first class of the semester and in the next-to-last class. Students had 4.5 sessions that exclusively focused on ecology (in-class time, 495 minutes). They did not have an exam on the ecology materials during the semester. The 17-question ecology concept inventory was given in the second class of the semester and during the last class of the semester. The 37 questions of the combined evolution and ecology concept inventories were also included as part of the comprehensive final exam.

Instructors and information on all interactive sections are summarized in Table 2.

Table 2

Summary of instructors and interactive BIOL 1010 sections

Instructor, Semester	Instructor Experience Teaching BIOL 1010	Instructor Involvement in Developing Interactive Course	Concept Inventory (# Questions)	In-Class Time on Subject Area (minutes)	# Students, Biology Majors
A fall 2004	29 times	13 sessions	Evolution (20) Ecology (17)	Evol: 605 Ecol: 495	56 ~95%
B fall 2004	None but 26 times teaching Introduction to Cell & Molecular Biology	8 sessions	Evolution (8) Ecology (7)	Evol: 660 Ecol: 660	58 ~95%
C spring 2005	None in past 20 years	None	Evolution (8) Ecology (7)	Evol: 660 Ecol: 660	55 ~5%
D spring 2005	None in past 20 years	4 sessions	Evolution (8) Ecology (7)	Evol: 660 Ecol: 660	43 ~5%
A fall 2005	30 times	13 sessions	Evolution (10) Ecology (10)	Evol: 660 Ecol: 660	57 ~35%
B fall 2005	1 time and 26 times teaching Introduction to Cell & Molecular Biology	8 sessions	Evolution (10) Ecology (10)	Evol: 660 Ecol: 660	62 ~35%
D fall 2005	1 time	4 sessions	Evolution (10) Ecology (10)	Evol: 660 Ecol: 660	63 ~35%

All interactive BIOL 1010 sections, except Professor A's fall 2004 section, had the same time (660 minutes) devoted to each of the four units and used the same sets of activities. In fall 2004 (Professor B's section), the 31-question concept inventory containing evolution and ecology questions was given in the first class, the last class, and as part of the final exam. The evolution and ecology materials were essentially the same in Professor A and B's fall 2004 sections; however, because of giving two separate inventories and the cancellation of classes on one day, Professor A had less in-class time than Professor B (evolution, 605 minutes versus 660 minutes; ecology, 495 minutes versus 660 minutes). BIOL 1010 sections in spring and fall 2005 had the concept inventory given in the first and last classes.

Learning gain

Learning gain is defined as:

$$\text{learning gain} = \frac{\text{post-instruction score - pre-instruction score}}{\text{total points - pre-instruction score}}$$

Learning gain was calculated for each student in Professor A's 2003 and 2004 classes who had taken the pre-instruction and post-instruction evolution and ecology inventories. These individual learning gains were averaged to give the section learning gain. The same procedure was employed to calculate learning gains in other sections based on the evolution and ecology questions in the 31-question or 40-question concept inventories.

Results

In traditional BIOL 1010 (Professor A, fall 2003), the end-of-the-semester conceptual learning gains were: evolution 0.10±0.20 sd ($n = 63$), ecology -0.05±0.25 sd ($n = 83$) (Figure 1). In the interactive BIOL 1010 section taught by Professor A (fall 2004), the end-of-the-semester gains were: evolution 0.19±0.24 sd ($n = 49$), ecology 0.14±0.21 sd ($n = 54$). A two-tailed, two-sample, equal variance *t*-test indicated that evolution and ecology learning gains in the traditional and interactive BIOL 1010 were significantly different (evolution, $p = 0.024$; ecology, $p = 0.000009$).

Plots of pre-instruction scores vs learning gains for traditional BIOL 1010 and interactive BIOL 1010 do not show a strong correlation for either evolution or ecology inventories (Figures 2, 3, 4, 5). All 4 linear regressions have negative slopes, indicating that students who knew less at the beginning learned more than those who knew more. This pattern was observed in both traditional and interactive BIOL 1010 and was most pronounced in ecology.

When learning gains were measured from concept inventories imbedded in the interactive BIOL 1010 final exam, learning gains increased 95% in evolution and 143% in ecology when compared to learning gains measured with the concept inventories given in the last week of classes: evolution 0.37±0.19 sd (n = 49), ecology 0.34±0.21 sd (n = 54) (Figure 1). A *t*-test indicated that these learning gains in both evolution and ecology were significantly different from those measured in the last week of classes (evolution, p = 0.0001; ecology, p = 0.000003).

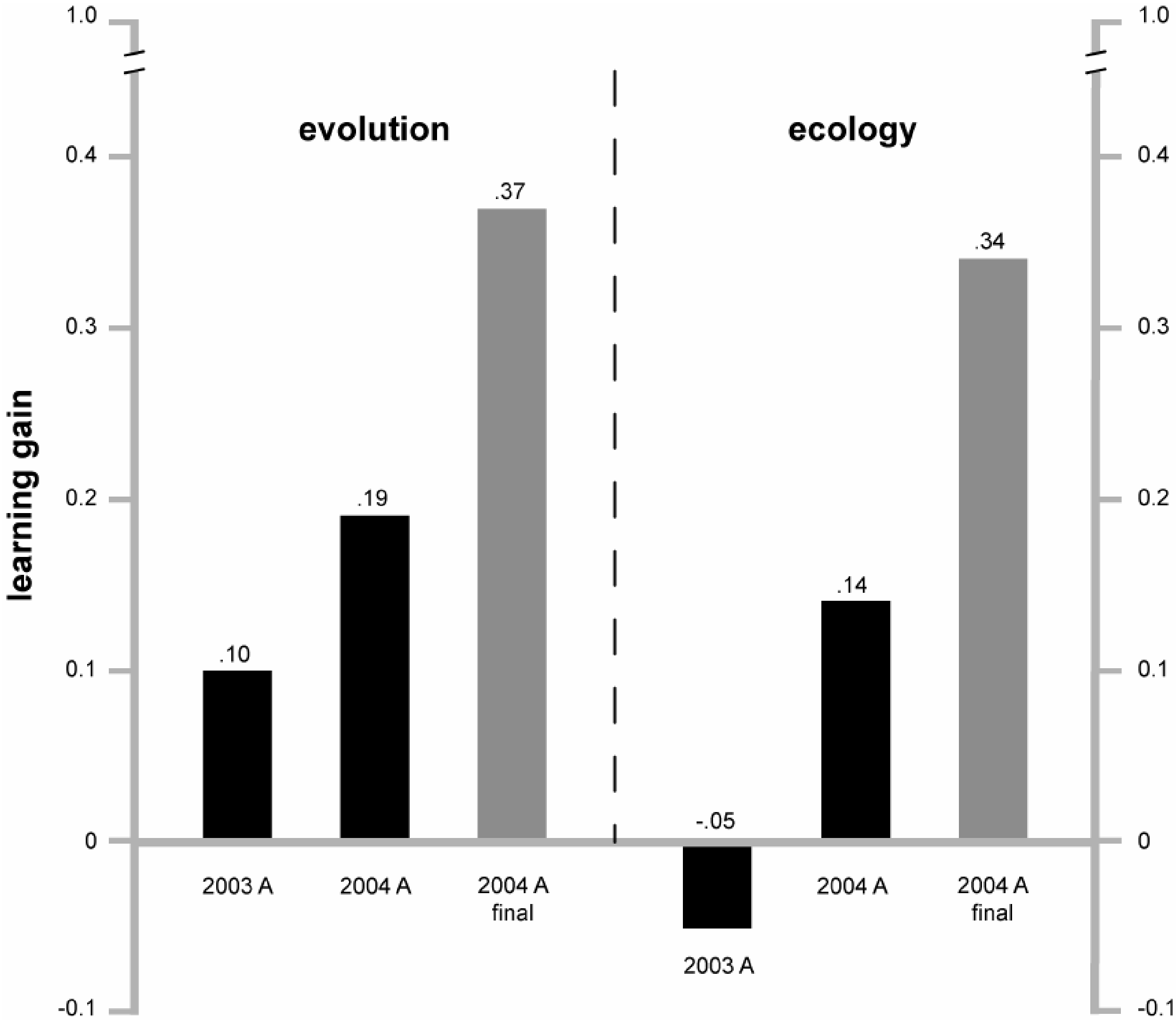

Figure 1. Average learning gains in evolution and ecology in traditional and interactive BIOL 1010 courses. Traditional BIOL 1010 (2003 A) and interactive BIOL 1010 (2004 A) were taught by Professor A. Learning gains were calculated from concept inventories given in the last week of classes (2003 A, 2004 A) and from concept inventories embedded in the final exam (2004 A, final). Learning gains are the average of each student's learning gain.

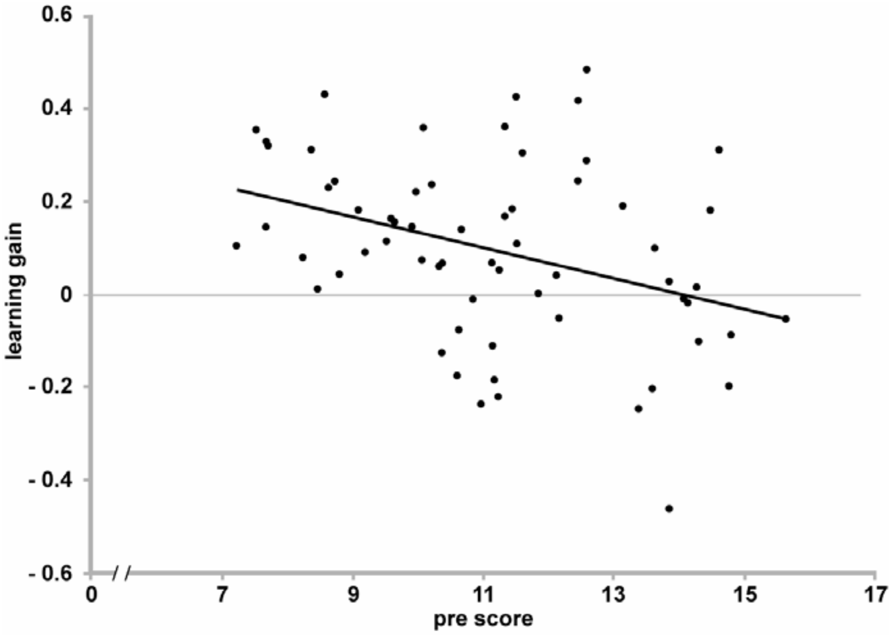

Figure 2. Evolution learning gain versus pre-instruction score for students in traditional BIOL 1010 course taught in fall 2003 by Professor A. Regression line: Y = -0.03X + 0.46 (R^2 = 0.13). The regression of learning gain on pre score was significant (p = 0.004).

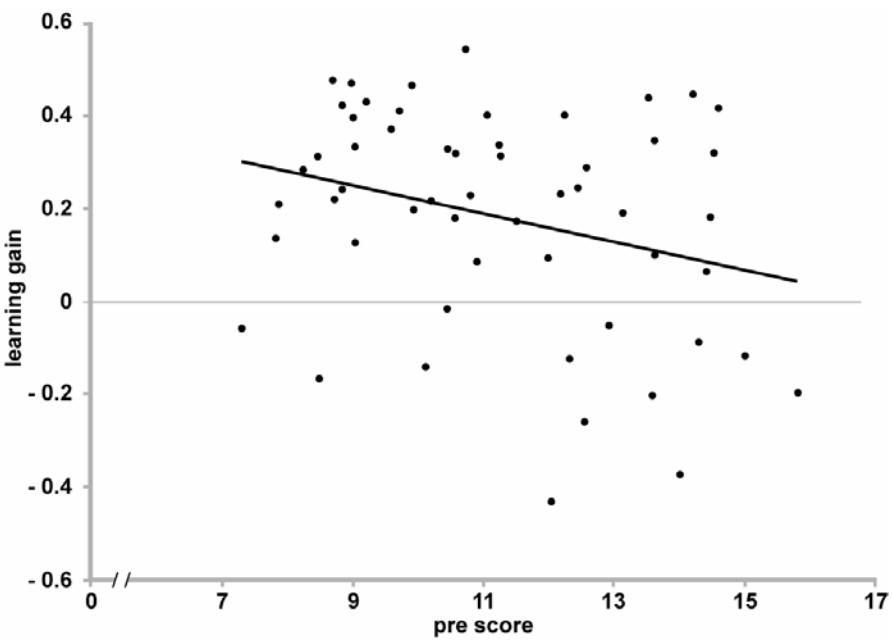

Figure 3. Evolution learning gain versus pre-instruction score for students in interactive BIOL 1010 course taught in fall 2004 by Professor A. Regression line: Y = -0.03X + 0.53 (R^2 = 0.08). The regression of learning gain on pre score was significant (p = 0.049).

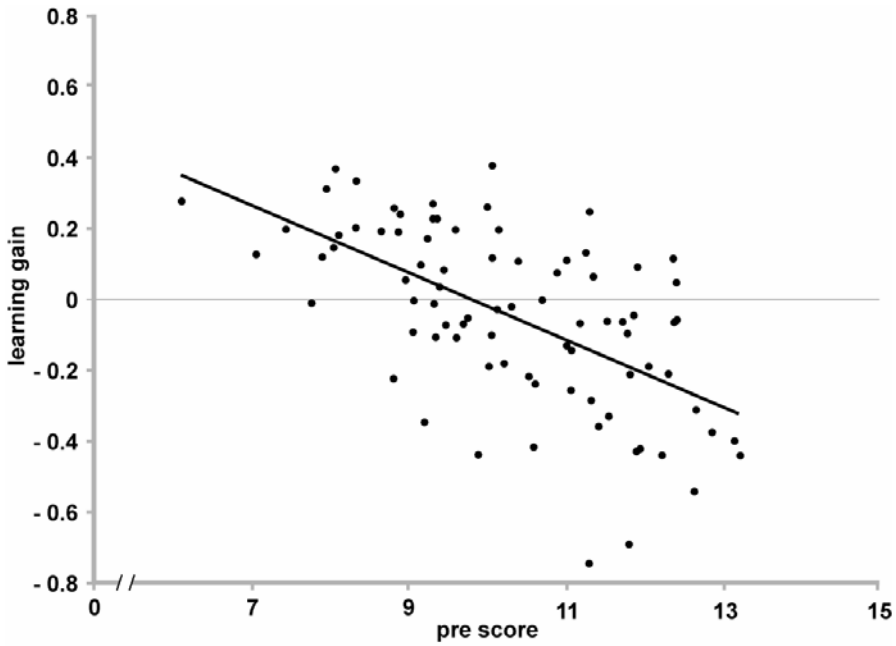

Figure 4. Ecology learning gain versus pre-instruction score for students in traditional BIOL 1010 course taught in fall 2003 by Professor A. Regression line: Y = -0.10X + 0.93 ($R^2 = 0.36$). The regression of learning gain on pre score was significant ($p < 0.0001$).

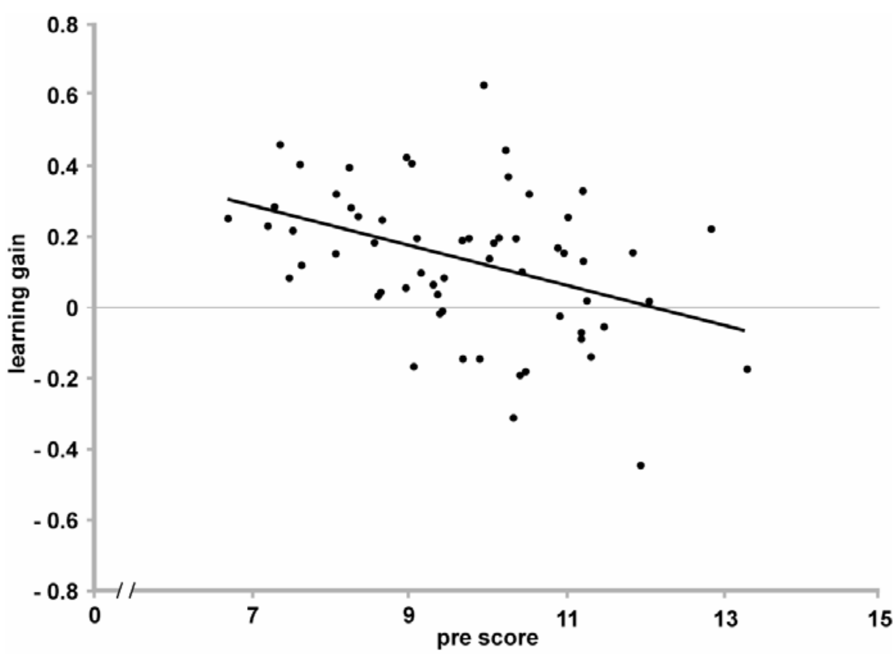

Figure 5. Ecology learning gain versus pre-instruction score for students in interactive BIOL 1010 course taught in fall 2004 by Professor A. Regression line: Y = -0.06X + 0.68 ($R^2 = 0.17$). The regression of learning gain on pre score was significant ($p = 0.002$).

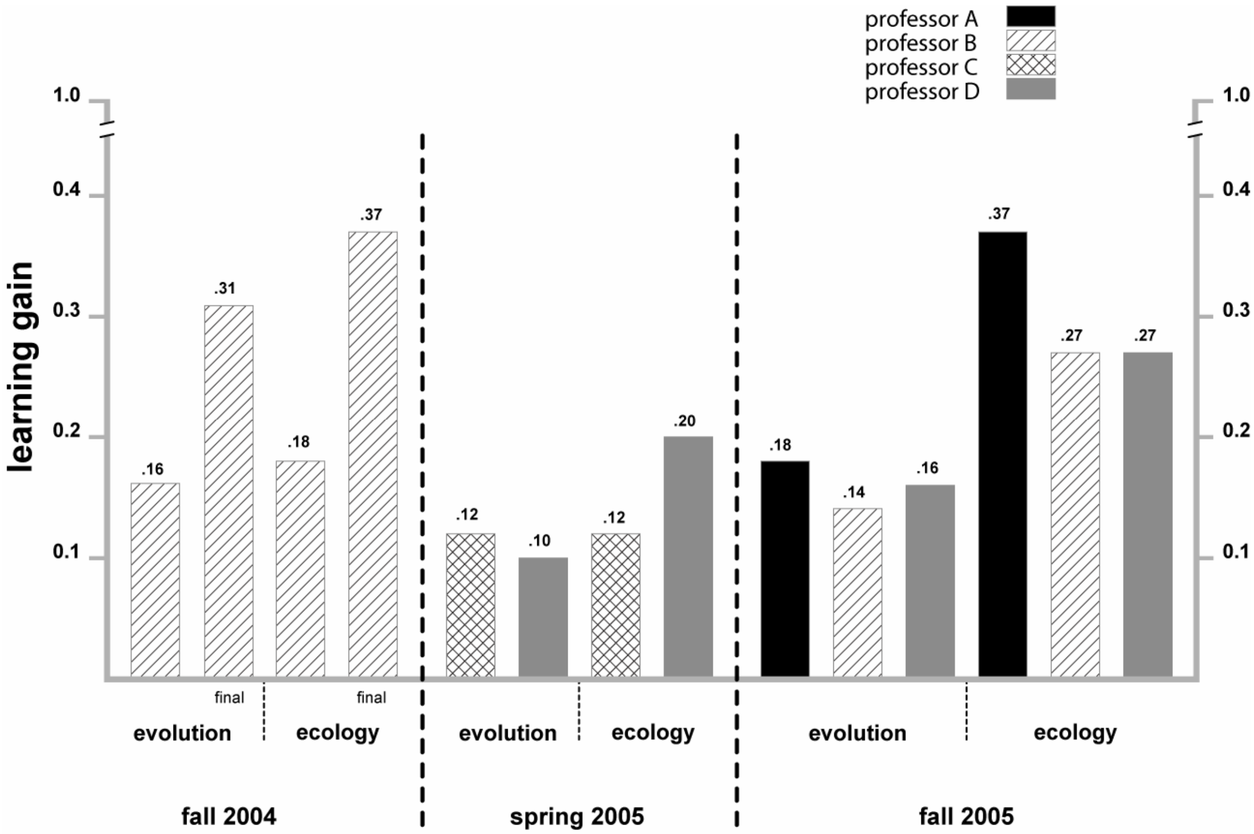

Figure 6. Average learning gains in evolution and ecology in BIOL 1010 sections taught by Professor B in 2004 fall and by other instructors in 2005 spring and fall. In fall 2004, spring 2005, and fall 2005 learning gains were calculated from concept inventories given in the last class of the semester. In fall 2004 learning gains were also calculated from concept inventory questions embedded in the final exam (“final” under bar). Learning gains are the average of each student’s learning gain.

In Professor B’s section (fall 2004), learning gains were measured using the 8 evolution and 7 ecology questions included in the 31-question concept inventory. Learning gains were 0.16±0.35 sd (53) (evolution) and 0.18±0.75 sd (53) (ecology) (Figure 6). Learning gains measured from concept inventories imbedded in the final exam increased 94% in evolution and 111% in ecology when compared to learning gains measured with concept inventories given in the last week of classes: evolution 0.0.31±0.31 sd (n = 53), ecology 0.37±0.48 sd (n = 53) (Figure 6). A *t*-test indicated that the learning gains in evolution were significantly different (p = 0.03) and in ecology the learning gains were not significantly different (primarily because the standard deviations were large) (p = 0.13).

In Professors C and D’s sections (spring 2005), learning gains were again measured using the 8 evolution and 7 ecology questions from the 31-question concept inventory. Learning gains for Professor C were 0.12±0.27 sd (n=55) (evolution) and 0.12±0.37 sd (n=55) (ecology) (Figure 6). Learning gains for Professor D were 0.10±0.36 sd (n=42) (evolution) and 0.20±0.41 sd (n=42) (ecology). Ecology learning gains in Professor C and D’s sections were not significantly different (*t*-test, p = 0.36).

In Professors A, B, and D’s sections (fall 2005), learning gains were measured using the 10 evolution and 10 ecology questions from the 40-question concept inventory. Learning gains for Professor A’s section were 0.18±0.48 sd (n=52) (evolution) and 0.37±0.35 sd (n=52) (ecology) (Figure 6). Learning gains for Professor B’s section were 0.14±0.38 sd (n=55) (evolution) and 0.27±0.27 sd (n=55) (ecology). Learning gains for Professor D’s section were 0.16±0.47 sd (n=46) (evolution) and 0.27±0.24 sd (n=46) (ecology). Evolution learning gains in Professor A and B’s sections were not significantly different (*t* test, p = 0.58). Ecology learning gains in Professor A and B’s sections appeared to be different; a *t*-est indicated they were not quite significant (p = 0.09). Ecology learning gains in Professor A and D’s sections appeared to be different; *t*-test indicated they were also were not quite significantly (p = 0.10).

In the interactive BIOL 1010 course, 3 hour exams and a comprehensive final, composed of multiple-choice questions, were given. The exams given during a given semester were identical, but different exams were used each semester. In a given semester the average exam scores for the two and three sections were very similar (Table 3). Since the average scores on the pre-instruction, 31-question concept inventory for the two sections in 2005 spring were similar (Table 3), as they were on the 40-question concept inventory for the three sections in 2005 fall (Table 3), the students in the sections in each of these semesters began BIOL 1010 with equivalent levels of biological knowledge.

Table 3.

Average exam and pre-instruction concept inventory scores in BIOL 1010 in fall 2004, spring and fall 2005. Hour exams had 25 possible points (25 questions) and the values given are the average number of questions answered correctly. The finals in fall 2004 and spring 2005 had 75 questions and in fall 2005 had 35 questions, and the values given are the average number of questions answered correctly. The same exams were used by professors A and B (2004 fall), by professors C and D (2005 spring), and by professors A, B, and C (2005 fall). The same 31-question concept inventory was used by Professor B (2004 fall), C (2005 spring), and D (2005 spring). The same 40-question concept inventory was used by Professor A, B, and D (2005 fall). Concept inventory score is the average pre-instruction score. In fall 2004 Professor A used different concept inventories than subsequent sections as described in text.

Topic	A 2004 fall	B 2004 fall	C 2005 spring	D 2005 spring	A 2005 fall	B 2005 fall	D 2005 fall
Evolution	18.2	19.2	17.9	16.7	18.9	18.7	19.2
Genetics	16.2	16.3	16.4	15.1	19.4	19.3	18.9
Molecular	17.2	16.6	18.5	17.1	19.0	18.2	18.9
Final	53.2	51.9	50.3	47.2	25.6	22.9	22.6
Concept Inventory	-----	13.9	11.7	11.6	19.8	18.9	19.6

Discussion

When our biology department decided to radically change the pedagogy employed in BIOL 1010, a considerable body of research indicated that the student-centered, interactive activities we proposed to develop would improve learning. The question remained, would learning really be enhanced in our particular case? In the absence of established biology concept inventories, we created sets of evolution and ecology concept questions to measure learning gains objectively. Clearly the concept inventories we employed are a work in progress, but they have yielded useful information.

Learning gain for the evolution component of our traditional biology course was 0.10. A significantly higher gain (0.19, $p = 0.024$) was obtained in the interactive BIOL 1010 taught by the same instructor. The interactive pedagogy we employed is likely responsible for much of the increased learning in evolution.

This conclusion is strengthened by the differences observed in ecology learning gains. In the traditional course, students did not have an exam on ecology during the semester but did have lectures and homework on ecology. When they took the post-instruction ecology concept inventory, they exhibited no learning gain (-0.05). This result is consistent with the contention that people learn and retain little after only hearing a lecture. In contrast, students in the interactive BIOL 1010 course, who also had not taken an exam on ecology, had a significantly higher learning gain (0.14, $p = 0.000009$).

These substantial increases in learning gain are consistent with results from other studies indicating that interactive courses are considerably more effective than lecture-based courses. Above we considered the evidence from physics education (Cummings Max, Thornton, & Kuhl, 1999; Hake, 1998; Mazur, 1997; Thornton & Sokoloff, 1998). In a developmental biology course, Knight & Wood (2005) obtained significantly higher learning gains with student participation and cooperative problem solving than in a course with the same syllabus taught in a lecture-based format. Knowledge surveys (a comprehensive set of questions that students do not answer but indicate their perceived ability to answer) provided similar results (Wirth & Perkins, 2005; Wirth, personal communication). Wirth and Perkins established that knowledge surveys accurately measure what students know and used them in several geology courses to demonstrate that in courses employing problem-based and collaborative-learning, students learned substantially more than students in traditional, lecture-based courses.

In addition to interactive pedagogy, however, other factors are likely to have contributed to the increased learning gain we observed in interactive BIOL 1010. In the lecture-based course students did homework questions and reading assignments out of class but had little guidance or accountability. In contrast, each interactive BIOL 1010 class had a pre- and post-class session with assignments that focused on specific concepts. Students were also accountable for answering a question with a short essay in the pre-class and for doing a set of 4 multiple-choice review questions in pre- and post-classes that required a student to engage with the pre- or post-class activities. These directed pre- and post-class activities, and the increased time in-class of about 70% in evolution and 25% in ecology (see Table 1), mean that the average student spent more time on evolution and ecology in the interactive course than in the lecture-based course. This time-on-task difference was also enhanced because attendance was required in the interactive class (3 absences permitted but few students missed more than 1 class in fall 2004) while attendance was not required for the lecture-based class (attendance varied from about 60 to 95% in fall 2003 based upon random head counts and the number of homework papers turned in).

Professor A's students were given no credit for the concept inventories but rather were verbally encouraged to do their best "because the inventories were important." In addition, students were not told in advance that an inventory would be given. It was therefore expected that when the concept inventories were part of the final exam, learning gains would be substantially higher; in fact, they doubled (evolution: 0.19 to 0.37; ecology: 0.14 to 0.34). Three factors contributed to this result: students had prepared for the final exam, were more motivated because the score was part of their grade, and were seeing the questions for a third time.

Learning gains measured with fewer questions in Professor B's section (fall 2004) were 0.16 in evolution and 0.18 in ecology versus 0.19 and 0.14 for Professor A's section (2004 fall). The similar results indicated that a substantial part of the gains was a result of course structure, materials, and pedagogy. Professor B's section also showed a study-credit effect; learning gains measured from the concept inventories imbedded in the final exam were double those measured in the last week of classes (evolution: 0.16 to 0.31; ecology 0.18 to 0.37). Overall the average learning gain measured at the time of the final exam for Professor A and B's sections was 111% greater than that measured in the last week of classes.

The almost identical scores on exams for the two sections in fall 2004, and again for the two sections in spring 2005 and three sections in fall 2005, indicated the effectiveness of the materials with minimal instructor influence when the instructor is experienced and committed to teaching. Relevant to this assertion is the fact that Professor C—unlike Professors A, B, and D—had no hand in development of course activities and was reluctant to teach the course. Professor C had not taught in BIOL 1010 for 2 decades and first examined the new materials at the beginning of spring semester in January 2005. Yet, Professor C section's overall exam grades were only 7% lower than those of Professor D's section. In fall 2004 the overall exam grades were separated by less than 1% and in fall 2005 the greatest separation was 5%. Although multiple-choice exam questions indicated minimal instructor effect, concept inventories showed a possible instructor influence on learning gain. In two instances, one instructor had a substantially greater learning gain than another instructor that approached significance ($p = 0.09$ and 0.10).

The traditional instructor-centered, lecture-based pedagogy employed in BIOL 1010 (Professor A, fall 2003) yielded small learning gains. The implementation in BIOL 1010 of student-centered, interactive pedagogy that employed computer-based technologies was effective in increasing learning gains significantly in both evolution and ecology. These materials and pedagogy also led to similar levels of learning when employed by teachers with different backgrounds and degrees of experience in teaching introductory biology. Our results strengthen the case for augmenting or replacing instructor-centered teaching with interactive, student-centered pedagogy, and they are consistent with a large body of literature on the effectiveness of active student participation for enhancing learning (Atkin & Black 2003; Banet & Ayusso 2003; Cummings, Max, Thornton, & Kuhl, 1999; Hake, 1998; Handelsman 2003; Knight & Wood, 2005; Mazur 1997; NRC, 1997; Udovic, Morris, Dickman, Postlethwait, & Wetherwax, 2002; Wirth and Perkins, 2005).

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