

# Genetics Education

## Innovations in Teaching and Learning Genetics

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### Introducing Student Inquiry in Large Introductory Genetics Classes

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#### ABSTRACT

An appreciation of genetic principles depends upon understanding the individual curiosity that sparked particular investigations, the creativity involved in imagining alternative outcomes and designing experiments to eliminate these outcomes, and the clarity of thought necessary to convince one's scientific peers of the validity of the conclusions. At large research universities, students usually begin their study of genetics in large lecture classes. It is widely assumed that the lecture format, coupled with the pressures to be certain that students become familiar with the principal conclusions of genetics investigations, constrains most if not all departures from the formats textbooks used to explain these conclusions. Here I present several examples of mechanisms to introduce meaningful student inquiry in an introductory genetics course and to evaluate student creative effort. Most of the examples involve altered student preparation prior to class and additional in-class activities, while a few depend upon a smaller recitation section, which accompanies the course from which the examples have been drawn. I conclude that large introductory classes are suitable venues to teach students how to identify scientific claims, determine the evidence that is essential to eliminate alternative conclusions, and convince their peers of the validity of their arguments.

**I**N most undergraduate biology curricula, students are introduced to genetics principles as a part of a "core" sequence of courses that are required of all majors. Given the current popularity of the major, these core subjects are usually taught in large lecture classes, sometimes with accompanying recitation sections. Students usually approach the subject with great excitement and fully appreciate that the increasing amount, accuracy, and availability of genetic information will have a measurable influence on their lives. Accompanying the current interest in the subject has been the widespread availability of new educational tools: CD-ROMs packaged with the textbooks, web-based resources, and easy access to computers and electronic communication. The challenge was to harness the benefits of large classes (their efficient use of instructor time, the presence of many different points of view, and the many opportunities for collaborative work) to teaching the essence of what is needed to

appreciate the field: the role of individual curiosity, the logic of experimental design, and the necessity to communicate effectively with one's peers.

While most textbooks include key experiments in genetics, most students find it difficult to make a meaningful distinction between a conclusion and the methods used to reach the conclusion. Instead, both represent material to be learned in preparation for a test. For students to appreciate the underlying logic, it appeared to be necessary for them to actually identify a claim, analyze the supporting evidence, and decide for themselves if the evidence justifies the conclusion or if the evidence is consistent with more than one possibility. Ideally, they should have the opportunity to describe their reasoning and receive feedback. The idea that students could learn a scientific subject in ways similar to those used by the scientists who made the discoveries is the basis of the inquiry-based learning approach (NATIONAL RESEARCH COUNCIL 2003). The importance of students having both an accurate knowledge base and a conceptual framework allowing them to extract meaning from information has also been emphasized (NATIONAL RESEARCH COUNCIL 2000). Others have pointed

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out that inquiry as practiced by scientists is not a simple linear process: even the questions and predictions are revised as a consequence of deeper reflection, conversations with others, and observation, and of course the data generated often stimulate new questions (KRAJCIK *et al.* 2000). One possible approach would have been to redesign the course completely and structure it around reading and analysis of the primary literature (EPSTEIN 1970). However, such an approach presented considerable pedagogical and logistical difficulties for an introductory genetics course taught in sections of 200 students. Instead, I looked for ways to make gradual and cumulative changes in the lecture course to provide meaningful opportunities for student inquiry within the constraints of a large class. The utility of incremental changes has been emphasized recently (WOOD 2003). Every opportunity would be sought, as B. Alberts has urged, to “allow students to conceptualize a problem that was solved by a scientific discovery, and then force them to wrestle with possible answers to the problem before they are told the answer” (ALBERTS 2000, p. 4). Where practical, I also created opportunities for the “answers” to develop from the class consensus, rather than from the instructor or the textbook. PALMER (1998) has suggested that we begin by asking, “How do we know what we know?” and then model our classrooms accordingly. He writes: “If we regard truth as something handed down from authorities on high, the classroom will look like a dictatorship. . . . If we regard truth as emerging from a complex process of mutual inquiry, the classroom will look like a resourceful and interdependent community” (PALMER 1998, p. 51).

## RESULTS

**Course background information:** At the University of North Carolina at Chapel Hill, Biology 50 (Molecular Biology and Genetics) is a sophomore-level course and is the first course in the core sequence for biology majors. It is taught in sections of 200 students with accompanying recitation sections (25 students) led by graduate teaching assistants (TAs). Student backgrounds can range from those who took advanced placement biology in high school several years prior and have taken no college level biology classes (these students placed out of the one-semester Introduction to Biology course) to senior biochemistry majors who often defer this required course until after they have substantial scientific sophistication. It is usually team taught, so that students spend the first half of the semester studying genetics and the second half of the semester studying molecular biology with a different faculty member. In some semesters, both instructors incorporated inquiry-based methods into the course, but the following discussion will focus only on modifications made to the genetics portion, since different molecular biology instructors were involved during the time under consideration (1996–

2002). Three different textbooks were used, and each proved adequate to provide the essential factual basis for the course. The courses each met for 150 min/week (either 50 min on Monday/Wednesday/Friday or 75 min on Tuesday/Thursday) plus a 50-min recitation each week for a total of 8 weeks. Topics discussed included DNA structure and replication, Mendelian genetics, complementation, epistasis, pedigrees, and meiotic and mitotic chromosome behavior, including recombination, mapping, and chromosome aberrations.

**Student preparation prior to class:** As more inquiry was introduced into the course, the advance preparation of the students became increasingly important. The students needed to have identified the principal facts and conclusions prior to class if we were to use class time to explore the validity of the claims. While there are a variety of ways to encourage advance preparation, such as reading guides, assignments to turn in prior to class, or quizzes, these proved to be difficult to implement effectively, given the heterogeneous backgrounds of the students in the course. What proved to be far more effective for this diverse student body was to focus students on their preparation. Prior to each class, one figure from the reading was assigned, together with a few associated questions requiring the students to assimilate the information in the diagram and to demonstrate that they understood one or more implications of the information (see Figure 1, sections 1–3). Less-experienced students could target their advance reading to answer the specific questions and defer their detailed study of the chapter until after the class period had indicated the major points of emphasis. More sophisticated students could read more broadly if they wished. The assignments were made using a restricted website (Blackboard), so that the instructor could post a copy of the figure and the students could print it out and bring it to class, together with their answers.

**Collaborative exploration in class:** One clear advantage of a large class is that multiple points of view are natural and can be both informative and exciting if channeled into a collaborative exploration. This approach depends upon each student accepting the responsibilities to prepare in advance as described above and also to be willing to contribute in class. It is important for students to experience the benefits of offering their own perspectives early in the course. Accordingly, early on the first day of class, I ask the students to take out a sheet of paper and diagram their concept of a gene and also to provide a brief written response to a particular question, such as “A deeper understanding of genetics and molecular biology is important to me because. . . .” I then ask them to exchange papers with each other and compare their neighbor’s diagram with their own. This stimulates a spirited discussion among them. It becomes clear to them (and to me) after a show of hands that their concepts of a gene differ wildly and that it is hard to understand what their neighbor

### 1. For Meiosis:

Students print out the text figure illustrating MITOSIS in a diploid cell. They are asked to consider if the organism illustrated could, in fact, have been haploid, and either redraw the metaphase nucleus with appropriate locus designations to illustrate haploid mitosis, or explain why the organism could not be haploid.

*Comment: This advance preparation helps students understand the criteria for deciding if chromosomes are homologous, for distinguishing sister chromatids and homologous chromatids, and for designating alleles and loci correctly.*

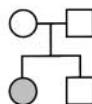
### 2. For Mendelian Genetics:

Students print out the text figure illustrating independent assortment in a dihybrid cross. They are asked to circle each homozygous individual in the F2 generation.

*Comment: Many students circle only the homozygous recessive individual, some students circle both the individual that is homozygous for both dominant loci and the individual that is homozygous for both recessive loci. Usually enough students have circled the 4 homozygous individuals to enable them to convince their neighbors that 1/4 of the F2 will be homozygous and true-breeding at the two loci. The discussions help students to abandon erroneous assumptions.*

### 3. For Pedigrees

Students label the individuals in pedigrees such as the following. They then state a mode of inheritance that is EXCLUDED by the pedigree, and identify 1 individual whose phenotype is inconsistent with the excluded mode.



*Comment: Students examine many alternative interpretations of the pedigree and realize that drawing conclusions from pedigrees can be more complicated than they assumed.*

### 4. For Experimental Design

Curt Stern designed an experiment to demonstrate that mitotic recombination can occur by starting with *Drosophila melanogaster* heterozygous for two morphological traits (such as singed bristles and yellow body) and observing twin spots of mutant tissue following irradiation and subsequent growth and development. Imagine that he had used flies that were heterozygous ONLY at the yellow locus. List all the ways that a yellow spot could arise IN ADDITION to mitotic recombination. How many of these alternatives were excluded by the inclusion of the singed locus?

*Comment: During the class discussion, students suggest mutation, suppression, deletion, non-disjunction, chromosome loss, and gene silencing. After discussing the expected frequency and consequences of these events, students can more readily appreciate that the twin spots must have arisen from mitotic recombination.*

has diagrammed without additional explanation. In addition to alerting them to the existence of many points of view, the experience also helps them to appreciate the uses of both diagrams and written explanations and the need to agree on rather narrow definitions of key terms to facilitate discussion. The TAs collect the papers so that they can be used as the basis for a discussion near the end of the course (see below), which helps the students to appreciate how much they have learned in a relatively short period of time. The entire segment occupies <10 min of the first class, but never fails to transform a group of 200 silent, somewhat apprehensive students into an animated, curious, and attentive class.

Most of the students' in-class contributions occur through structured conversations with their neighbor, modeled after the approach pioneered by E. Mazur in his introductory physics course (TOBIAS 1992; TRAVIS 1994; MAZUR 1997). Mazur structures his course around periodic concept tests in which students first record both their answers and their confidence in their answers and then discuss their answers with their neighbors to try to reach an agreement. The instructor then takes a straw poll and either discusses the topic further or moves

FIGURE 1.—Assigned figures and associated questions. Question 4 was not assigned in advance.

on to another point or topic. As Mazur and others have reported, both the students and the instructor benefit from the peer instruction because the students often have excellent ways to explain ideas to each other, and the instructor has the thrill of listening to 100 animated conversations about course issues (TOBIAS 1992). Initially, Mazur's approach was followed closely, with students asked to respond to "what if . . ." questions that they had not seen previously, make predictions, record their answers and confidence levels on machine-readable sheets, and then discuss their answers with a neighbor. Subsequently, it proved more effective to assign most of the questions prior to class (see Figure 1, sections 1–3), ask students to exchange papers, discuss their answers, and then contribute to the class consensus. This approach encourages students to prepare for class and allows for shorter and more substantive discussions. Typically, students are allowed 2–5 min to compare their answers, and the length of the subsequent class discussion can range from 2–10 min, depending on the complexity of the topic. Some of the assignments ask students to improve upon a textbook diagram that is incomplete or misleading. They are also able to com-

pare their points of view, which were a product of their out-of-class reading, assimilation, and reflection, with their peers. The questions that result from these discussions are very valuable indicators of what material students understand and what aspects of the book or the class discussion are still insufficient for them to understand the material. The machine-readable sheets did not really provide additional useful information, and since they took considerable time to collect and process, they were abandoned. For some of the questions, the students are asked to revise their answers if necessary and turn in the work to be evaluated by a TA. This encourages reflection upon the class discussion and increases overall accuracy.

Two other types of in-class contributions involving prior student preparation are useful in certain circumstances. Students have been assigned to work collaboratively to write out their approaches to answering old exam questions. They describe both their reasoning and the difficulties they encountered. The clearest example for each question is then briefly discussed in class and posted for the class to review. The students benefit from analyzing what made the questions difficult, and the approach does not require extensive class time to implement. More recently, old exam questions have been posted on the web, and students have used the discussion forum feature to compare approaches. The instructor reads the forum and intervenes only to prevent the propagation of serious misunderstandings. In a second approach, students are invited to submit questions about course concepts that arise during their advance preparation for class or during class discussions. If the topic is complex (DNA replication or recombination, for example), they are encouraged to include diagrams illustrating how they think the processes occur. In a subsequent class, the questions and diagrams are enlarged and displayed on an overhead projector, and the instructor guides a class discussion of the evidence known by the students that can eliminate the erroneous views. Usually the instructor poses the questions, asks the students to discuss possible answers among themselves, and then helps the class to reach a consensus. Near the end of the course, a few of the gene diagrams drawn by the students on the first day of class are displayed and the features that make some diagrams more accurate and more compelling than others are discussed.

Some issues, particularly those involving experimental design, are introduced in class. For example, instead of simply describing how an experiment was performed, the instructor asks students to predict the consequences of a slightly altered experiment (see Figure 1, section 4). In this situation a large class is particularly advantageous because of the increased probability of novel and interesting answers. Such a list of possible explanations then serves as the starting point for an examination of the

features of the experiments that were actually performed that allowed the alternatives to be eliminated.

Currently, the course is designed to include at least one and usually two structured conversations per class period. In addition, students are repeatedly invited to ask questions following instructor explanations or demonstrations. It is interesting to note that these questions span the range from students who are anticipating the direction of the discussion or wish to explore a particular aspect in more depth to students who have an erroneous underlying assumption. On occasion, the student questions are appropriate for a spontaneous structured discussion, so students are invited to consider the opinion just expressed by their classmate before the instructor helps the class to reach a consensus.

Hearing the voices of 200 students debating course-related issues is powerful and energizing. It also revealed problems with pronunciation and correct use of scientific terminology, especially when individual students contribute to the subsequent class discussion to build a consensus. A useful way to begin to correct these problems is to invite the entire class to pronounce scientific terms together (*e.g.*, *Neurospora crassa*, locus, loci) and insist that they use the terminology correctly when contributing to the discussions.

**Collaborative exploration in the recitation section:** The class has an associated recitation section in which the students meet weekly in groups of 25 with a graduate TA. Performance in recitation contributes 15% of the final grade. Students receive points for attendance, for turning in assignments on time (if the assignments contain errors they do not receive full credit unless they turn in corrected versions), and for the collaborative projects. The sessions are structured around student discussion of recitation assignments in small groups and student presentation of their reasoning to the entire recitation section. These methods are designed to help students think effectively and learn to use genetic terminology accurately in conversation. For many TAs more accustomed to “going over” what has happened in class or explaining correct answers to assignments, this represents a serious shift of responsibilities. It takes some preparation to watch inexperienced undergraduates explain the logic that their groups used to the others in the recitation section and to intervene at the appropriate moments to ensure that the conclusions most likely to be remembered by the class are reasonable. The most effective TA preparation has been essentially to ask the TAs to assume the role of the students while the instructor assumes the role of the TA. Accordingly, the instructor meets with the TAs in advance, helps them compare their independent approaches to the questions (which often differ wildly), and asks them to explain their logic (sometimes erroneous), so that they learn to correct each other. Thus the compilation of “correct” approaches emerges in the way that we hope it will emerge for the students: a discussion of possible approaches and

Many textbooks explain crossing over by supposing that sister chromatids separate from each other and "swap" positions to pair with the homologous chromatid, and then they break and rejoin. This view is depicted in the "classical theory" shown below. Outline a set of experiments that would allow you to conclude that chiasma formation does NOT depend on any change in association of sister chromatids with each other. Your experiments should be designed to distinguish between the classical theory and the chiasmatype theory as shown. Be certain to state the predicted outcomes of your experiments if the classical theory is true and if the chiasmatype theory is true, (and be certain that the predicted outcomes are in fact different!).

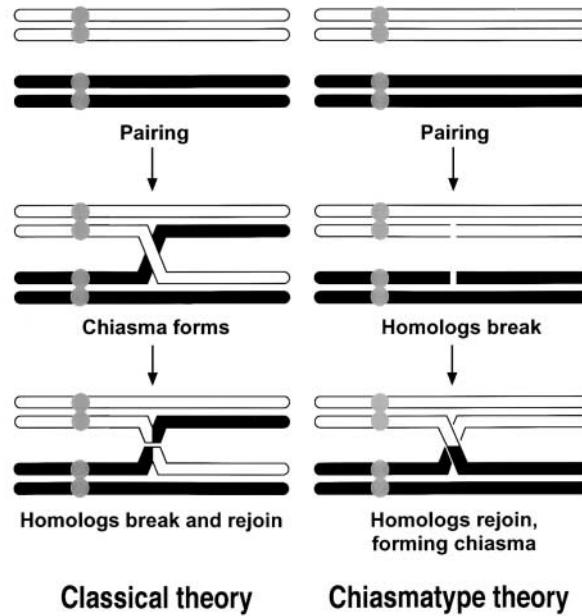


FIGURE 2.—Sample course project. Students worked in groups outside of class and presented their results to their peers during recitation sections, in addition to turning in a written report.

elimination of the nonproductive ones. The benefits of teachers experiencing the collaborative process while introducing students to collaborative learning have been clearly described (BRUFFEE 1993). TA proficiency in this method of instruction varies, just as it does in a more conventional recitation structure in which TAs present solutions to the assigned problems. However, the collaborative approach to planning the discussion appears to benefit the less-experienced TAs in particular, since they are able to see how the more experienced TAs respond to a wide variety of possible answers, rather than feeling uncomfortable when their own rehearsed explanations are "interrupted" by student questions that they had not anticipated.

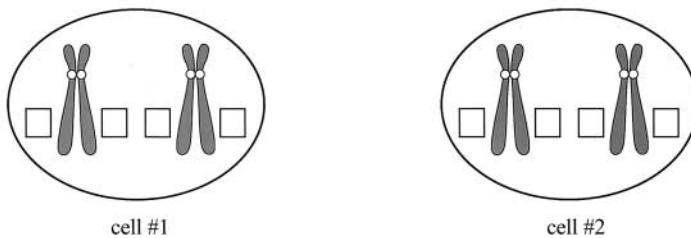
The recitation assignments are a mix of the assignments previously discussed in class as well as old exam questions and class projects. Two class projects have been particularly successful and would be adaptable to many courses. The first uses a simple and attractive Mendelian genetics simulator (Flower Breeder, site license obtained from dyann@schmidel.com). The simulator allows students to "pick" wildflowers, outcross and self-cross these, and store desired "strains" in a collection box. The students are asked a guided series of questions using the simulator. They "discover" epistatic relationships and design a series of testcrosses to confirm the relationships. The students work on the assignments in groups outside of class and then present their strategies during recitation (half of the groups make presentations

on this topic). The second project uses ambiguities or errors in the textbook as a basis for experimental design (see Figure 2). Most textbooks fail to depict the proper behavior of sister chromatids during meiosis, especially in the small diagrams of chromosomes (see, for example, ALBERTS *et al.* 2002, pp. 1131 and 1132; KLUG and CUMMINGS 2003, p. 205; RUSSELL 2002, pp. 20 and 22) or they fail to distinguish between sister chromatids and homologous chromatids in these small diagrams (see, for example, GRIFFITHS *et al.* 2000, p. 71). These errors serve to reinforce the erroneous assumptions that many students have concerning meiotic chromosome behavior, which make a true understanding of the process impossible for them to attain. Accordingly, the students are given a diagram similar to that shown in Figure 2 and asked to design experiments that would allow these "models" to be distinguished. Since they have already studied evidence underlying the semiconservative replication of chromosomes, many realize that [<sup>3</sup>H]thymidine or BUdR labeling can be used to distinguish sister chromatids from each other and thus determine if sister-sister associations persist both before and after crossing over as predicted by the chiasma-type model. Others with more biochemical sophistication point to the different consequences of perturbing particular steps in crossing over. The remaining groups make presentations during recitation on this topic, and the most creative approaches are also discussed in class. Students benefit at several stages during this inquiry module. They profit

## 1. Exam question on Meiosis

The boxes in the following diagram indicate particular loci. Use as many of the following symbols as you need (and as often as you need) to make it clear that cell #1 is a HAPLOID cell and cell #2 is a HETEROZYGOUS DIPLOID cell by filling in the boxes in the diagram.

The symbols: A B D E F G H J a b d e f g h j



*Comment: The exam question is a simplified variant of the class assignment.*

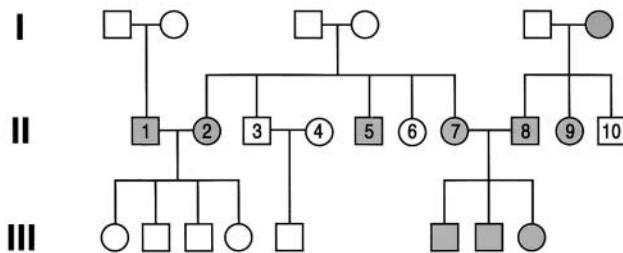
## 2. Exam question on Mendelian Genetics

Imagine that you are a plant breeder and you have determined that plants heterozygous simultaneously at 4 particular loci exhibit vigorous growth. Plants with all other genotypes exhibit ordinary growth. If you were to cross two plants that exhibit vigorous growth, what proportion of the offspring would exhibit vigorous growth?

*Comment: The exam question is a slightly more complicated variant of the class assignment.*

## 3. Exam question on Pedigrees

Examine the following pedigree that represents a family with hereditary hearing loss. Choose some symbols and state the genotypes of individuals II-1, II-2, II-7 and II-8 that are consistent with their phenotypes, their parents' phenotypes, and their children's' phenotypes.



*Comment: This is a complicated variant of the class assignment, since students do not expect that pedigrees can also illustrate complementation.*

## 4. Exam question on Experimental Design

Imagine that you had crossed two haploid strains ( $Ab \times aB$ ) of the fungus *Neurospora crassa*. You recovered 100 random meiotic progeny, and half had the phenotype  $Ab$  and half had the phenotype  $aB$ . List two possible explanations for your failure to recover any spores with the  $AB$  or the  $ab$  phenotypes. Explain how you could distinguish between your two possible explanations.

*Comment: Following their experience with experimental design in the course, most students propose experiments that would distinguish between tight linkage and inversion heterozygosities.*

from approaching something that seems far too sophisticated for them at first and from eliminating less-productive approaches along the way. They realize that conclusions derive from evidence and that interpretations of biological phenomena can change over time. They realize not only that they are entitled to question textbook conclusions, but also that their understanding can deepen as a result.

**Evaluation of the methods:** Taken collectively, these methods have resulted in interactive classes in which students come to class prepared to contribute. They experience the nonlinear nature of scientific reasoning, and the important role that argument plays in scientific explanations. They learn to use what they know to make

predictions about what they do not yet understand (FISHER 2000). Their individual presence in the class is important, thus helping to justify the fact that each hour of class time involves nearly 200 hr of student time. The instructor can direct the class in ways that maximize student comprehension, rather than relying only on exams to monitor student understanding. It was also important that the in-class exams evaluate the students' inquiry skills, since they are a major component of the course. Accordingly, the exams include sections in which students must use diagrams to explain phenomena, make predictions, and propose alternative explanations. Portions of exam questions, together with comments concerning their relationship to the questions

FIGURE 3.—Sample exam questions. Only the portions of each question that were designed to test students' skills at conceptualization and inquiry are shown here.

discussed in class, are shown in Figure 3. Several practical strategies have been implemented to ensure that evaluating student performance on such exams does not pose an undue burden on the graders. Students are given a blank sheet to do their outlining and strategizing. The space for their answers on the exam is limited by boxes. Prior to the actual grading, the exams are skimmed and answer keys are modified to include all acceptable answers.

In the short term, overall student satisfaction with the course and the instructor did not change significantly during the period when increasing emphasis was placed on student inquiry (the means from the 1996–2002 course evaluations range from 3.7 to 4.0 on a five-point scale). Also, student performance on the exams did not change significantly during this time (the means range from 75 to 81% on the midterm and from 65 to 71% on the cumulative final).

It is clear that students continue to be challenged by the course. The open-ended course evaluations administered in all courses in the Biology Department provide some insights into the aspects that were both difficult and satisfactory for the students. For a few, applying what they have just learned to making new predictions was very difficult “because the information wasn’t yet concrete in our minds.” Others found the emphasis on the figures and the need to find the relevant information to be disturbing (“Seriously, where were the notes?”). These students appeared to be unable to make the transition between viewing genetic information as something absolute that they were in class to receive [what ERICKSON and STROMMER (1991), in summarizing the work of Perry, Belenky, Kurfiss, and others, have defined as “received knowledge”] and the more sophisticated view of genetics demanded by the course, which relies on methods and evidence (“procedural knowledge”). From the course evaluation comments, it appeared that some students were able to make such a transition during the brief period of the course (“The class assignments were a great idea. I learned more in class than I thought I was going to at first.” “Assignments before class helped me have some understanding and bring in questions for the class period.” “Some of the questions in class are hard to understand but this helps the learning process.” “A lot was learned and each piece of knowledge built on the last.”). It was also clear that many students were already comfortable with procedural knowledge and welcomed the approach (“I gained a lot more information in class than most other lectures can help me attain.” “In-class discussion and problem solving was especially helpful for me.” “Her exams were unique and superb in forcing the student to think and process the information as a real scientist would.”). Although the student comments were wide ranging, none concerned the structured conversations *per se*. Apparently these appeared to be a natural part of the discus-

sion process from the students’ perspectives and not worth singling out for particular comment.

Student satisfaction and grades are important short-term guides to student success in a course. It was important that these measures did not decrease even though unfamiliar demands were placed on so many of the students. Other indicators were also important measures of the effectiveness of the course modifications. For example, when the figures and associated questions were first assigned, the papers were collected at the end of class to ensure that students had come to class as prepared as possible. This proved to be both cumbersome and unnecessary. By structuring the questions so that most students could answer at least part of the assignment, both the value of the advance preparation and the subsequent class discussion were apparent to the students. Without the advance preparation, it is very hard to follow what goes on in class. With the advance preparation, the class discussions both reinforce what the student has concluded and provide insights into issues that they could not resolve on their own. Student compliance is monitored by the instructor and the TAs by simply observing the students as they exchange papers, and the fact that it is not an issue is an important short-term indicator of the value that students place on the inquiry-based approach. Also, the recitation projects, which are done collaboratively and are only a very minor fraction of the course grade, are taken very seriously by the students, especially since they are required to present their results to their peers. The high quality of the presentations is an important overall indicator of student effort and achievement in creative work during the course. In addition, many students remain in contact in subsequent semesters. In recent years, former students served as peer facilitators or supplemental instruction leaders for the course. These students led online discussion forums and chat rooms or supervised voluntary study groups, and they received either pass-fail credit as teaching interns or financial compensation. The current students felt very free to talk about the course to the undergraduates who were not involved in assigning course grades, while the facilitators provided valuable insights to both the students and the instructor concerning the longer-term value of the inquiry approach. Also, students often write about the course in subsequent years, when some of the longer-term benefits can be perceived. “I have to admit I was a bit daunted by the difficulty of the course. However, it turned out to be one of the best classes of my college career for not only was I challenged intellectually, but also I was taught a new, exciting way of thinking and problem solving. Your class challenged me to use my background knowledge to solve new, unfamiliar problems. At the time it was a bit frustrating for I had never really been asked to perform such a challenging task. I have now learned to approach exams from a totally different perspective, not attempting to know exactly what will be

asked but rather learning how to solve any problem that may be given using only my fundamental knowledge."

## DISCUSSION

I conclude that incremental changes to empower student inquiry in a large lecture course are both possible and beneficial to the students, teaching assistants, and instructors. The revised course has resulted in a change of attitude among the students, because they recognize their responsibilities to evaluate scientific information both individually and collectively. The large size of the classes did not impede the changes. In fact, it may have facilitated them, since the instructor could not know each student personally as is possible in a small class and thus could not influence their thinking in as direct a fashion. The students had to learn to rely on each other and ultimately developed confidence in their own abilities to make scientific arguments.

In a large research university, there are many avenues for student inquiry to occur and to be reinforced. The challenge is to assist students in making the transition, as early as possible in their undergraduate experiences, from relying on conclusions that they read or hear to trusting their own abilities to understand how the conclusions were reached and to evaluate the underlying evidence. While it is reasonable to expect that students will develop at different rates, it also appears that the essential change in habits from simply receiving information to engaging in inquiry can be encouraged. BAXTER MAGOLDA (1999) has identified several elements that appear to help students to make this transition, including instructor-student discussions (talking *with* students rather than talking *at* students), providing time for students to formulate their ideas prior to class discussions, and emphasizing the ways in which the discipline is continuing to change. These elements are features of Biology 50 and appear to assist at least some students in learning to rely more on their own reasoning as the course progresses. It is clear that many undergraduates engage in research and other creative work as students. Whether widespread modification of courses to introduce more inquiry at all levels, particularly in introductory courses, would result in broader participation, more sophisticated achievements, and/or a deeper understanding of science remains a topic for future study.

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