ABSTRACT

Attempting to foster mastery learning for students in the biological sciences, we incorporated an authentic research-based activity that contained real-world applications. To do this, we redesigned a laboratory component of a junior level, general genetics course. This included lengthening the time for the experiment, incorporating new technology for data analyses, and generating new assessments. These changes led to a more collaborative and interactive environment. Students were given the challenge of inducing a phenotypic change within the model organism, *Paramecium* tetraurelia. This allowed students to design their own experimental approaches. We assessed the students on formative and summative levels to determine if they were accomplishing the learning outcomes. Students demonstrated they were successful in meeting these, which included mastering a set of laboratory skills, designing their own experiment, and incorporating technology needed for data collection and analyses.

Key Words: authentic research; Paramecia; genetics; phenotypic changes; mastery learning.

Introduction

Incorporation of inquiry-based activities into course curriculum has been altering how science is taught in undergraduate science laboratories (AAAS, 2011). Reviews of undergraduate science courses have demonstrated that teaching trends are changing toward the addition of inquiry-based approaches, with most integrating inquiry into science courses with a laboratory component (Ruiz-Primo et al., 2011). However, providing authentic research (AR) based experiences to enhance guided inquiry in the classroom exhibited greater benefits for undergraduate science students in numerous ways. These included students having the opportunity to think like a scientist, having “ownership” of their projects, getting excited about research, pursuing careers in science, and/or entering into science graduate programs (Thiry & Laursen, 2011).

Regardless of the gains shown by students experiencing AR-based approaches, the most recent reviews still showed that over 75 percent of courses still have guided-inquiry activities without an AR component (Beck et al., 2014; Spell et al., 2014; Makarevitch et al., 2015). One reason for this is the lack of consensus about what constitutes AR (Spell et al., 2014). For our purposes, authentic research is not opposed to inquiry-based learning, but is a type of guided inquiry learning aimed at enhancing student autonomy, creativity, meta-cognitive awareness, and self-reliance in the course of learning fundamental laboratory skills, biology content, the principles and practices of scientific research, and the nature of science (NOS). For us, learning biology in the lab becomes authentic when students are encouraged to develop an original hypothesis within parameters, design an experiment to test that hypothesis, collect and interpret data, struggle with initial failures, and modify the hypothesis, designs, and procedures to move forward.

Here, we present a six-week AR laboratory activity embedded into a general genetics undergraduate course. Working in pairs, the students’ research challenge involved inducing a phenotypic change into the single-celled organism, *Paramecium tetraurelia* (Figure 1). Paramecia are ideal models, easily cultured, grown in large numbers, and accessible to microscopic study (Clarke et al., 2002; Elwess & Latourelle, 2004). Additionally, Paramecia raise no ethical issues inherent in animal studies. This organism incorporates the complexity of many larger life forms and is likened to a “swimming neuron” (Hinrichsen & Schultz, 1988).
Student Learning Outcomes (SLO)

By the end of this experiment students will be able to:

1. state a hypothesis
2. design an experimental approach and modify it if needed
3. perform calculations involving solutions, dilutions, and concentrations
4. demonstrate necessary laboratory skills (pipetting, sterile technique, use of microscopes)
5. maintain *Paramecia* cell cultures
6. capture microscopic images and apply the necessary software to measure cells
7. generate graphs for data analyses
8. maintain a laboratory notebook
9. write a formal laboratory report
10. describe and explain basic cell behavior and cell physiology.

These stated SLOs relate to aspects in which students experienced the nature of science (McComas & Olson, 1998). SLOs were assessed using varied forms of measurements (Table 1) focused on scientific knowledge and practices, typically referred to as “course content.” They emphasized characteristic habits of mind, or what it means to approach the world as a scientist. These learning outcomes had more to do with helping students grow from passive students into self-directed learners, from science students into emerging scientists.

Learning Time

The six-week AR part of the laboratory component was implemented in all three once-weekly, 3-hour laboratory sections. Additionally, students had the freedom to access the laboratory facilities throughout the week. Prior to beginning this activity, students were introduced to this model organism during lecture. Additionally, the students were challenged to think about potential chemicals and or conditions to expose the cells to, in order to generate a phenotypic change within the organism. Finally, students were instructed on how to design an experiment complete with a stated hypothesis, dependent and independent variables, and controls.

### Procedures

**Materials**

Students were provided a bacterial culture of *Klebsiella pneumonia*, regular wheat media, and a stock of *Paramecia tetraurelia* (Elwess & Latourelle, 2004; Carolina Biological can also supply the media and cells). Yeast can be used as a food source for the *Paramecia* in place of *Klebsiella*. Additionally, students were provided a list of available chemicals within the teaching laboratory and informed they could bring in products (with instructors’ approval). Protective goggles and gloves were provided.

**Student Instructions**

Each team (two students) was presented with the challenge of inducing a sustained and measurable phenotypic change in *Paramecia tetraurelia*. With this challenge came the responsibility of designing

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**Table 1. Activities implemented as part of the authentic research component.**

<table>
<thead>
<tr>
<th>Activity</th>
<th>Assessment</th>
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<tbody>
<tr>
<td>Experimental Design Worksheet (SLO#1 &amp; #2), due 1st week</td>
<td>Graded with feedback</td>
</tr>
<tr>
<td>Revised Experimental Design (SLO#1 &amp; #2), due 3rd week</td>
<td>Graded; based on analysis of original experimental data</td>
</tr>
<tr>
<td>Laboratory Safety: Proper and safe disposal of cell cultures and chemicals</td>
<td>Instructor observation</td>
</tr>
<tr>
<td>Capturing and measuring cells using microscopes with cameras (SLO#6), due 2nd week</td>
<td>Assignment: photos of cells with measurements</td>
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<tr>
<td>Maintaining a laboratory notebook (SLO#8), collected 6th week</td>
<td>Graded with feedback</td>
</tr>
<tr>
<td>Generated graphs (with error bars) from collected data (SLO#7), collected during 6th week</td>
<td>Graded with feedback</td>
</tr>
<tr>
<td>Formal Laboratory Report (SLO#9 &amp; #10), collected two weeks after completion of activity</td>
<td>Graded with feedback; Summative Assessment</td>
</tr>
<tr>
<td>Maintenance of Cell Cultures (SLO#5)</td>
<td>Instructor observation</td>
</tr>
<tr>
<td>Laboratory Skills: Pipeting; Use of digital microscopes and cameras; Calculations of solutions, dilutions, and concentrations (SLO#3 &amp; #4)</td>
<td>Skills Performance Assessment</td>
</tr>
</tbody>
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**Figure 1.** *Paramecia* taken under 400x magnification; ruler in photo represents a 100-µm scale. Image courtesy of Jin Sil Pyo.
and implementing their experiment, while maintaining cell cultures and finally collecting and analyzing data.

Designing and implementing the experiment was ongoing and subject to changes in implementation. Students had to present a hypothesis, suggest independent and dependent variables, provide levels for the independent variable, identify the dependent variable, and attend to controlled factors as well as the actual control. Many of these items were subject to changes over the course of the research.

*Paramecia* cultures were maintained as stated in Elwess and Latourelle (2004). Each team was required to submit their experimental design to their instructors prior to starting their preliminary investigation (week one).

**First Week.** If the experimental design was approved, the teams could set up their initial experiments. Their primary challenge was determining the concentration range and exposure time for their chosen agent (see Table 2). Students determined workable concentrations through trial and error and by searching primary literature. Students set up the varying concentrations using 12-well tissue culture plates (Figure 2); concentrations were in triplicate. This approach reinforced the students’ understanding of solutions, dilutions, and concentrations.

Each student had a laptop computer and a microscope (dissecting, compound, and inverted) available. Every microscope had a means to digitally capture images (Figure 3); the students were instructed on how to measure cell lengths, widths, and area as a possible data analysis tool. Over the next four weeks, they were assigned individual components of a laboratory report: Introduction (week 1), Methods (week 3), Results (week 6), and References (week 1) (Table 1). Focusing on only one component at a time allowed for sustained work in relevant cognitive skills (description, interpretation, analysis, synthesis, and so on). In their introductions, students provided reference information on *Paramecia* and their agent of choice. We did not assign the discussion section, as we wanted to see how well the students could formulate this in their final report. Each component was graded and returned with feedback.

**Second through Fifth Weeks.** Students focused on refining concentrations and lengths of exposure. During this time, students checked cells, took pictures, collected data, and set up another trial, adjusting concentrations as needed. Furthermore, laboratory skills were assessed while students were performing their lab protocols within the regular lab class.

**Sixth Week.** Final data collection and analysis was conducted (Figure 4), along with the proper disposal of cell cultures and chemicals. Formal laboratory reports were due two weeks later.

### Faculty Instructions

Since there were three separate laboratory sections, the course instructor dedicated one lecture session with all students present to describe the model organisms (*Paramecia*), the specifics of this research-based experience, and the intended learning outcomes.
Safety Issues
There were two possible safety issues. The first was the use of *Klebsiella pneumoniae* within the wheat media cultures. *Klebsiella pneumoniae* can cause pneumonia if ingested. The students were required to use protective gloves when handling all plates and flasks containing this bacterium. Prior to the start of lab and at the conclusion, students were to wipe down their bench space with bleach (which was provided) and wash their hands with antibacterial soap. Finally, once the students were through with any containers holding *Klebsiella*, they were to put bleach in the container; instructors properly disposed of containers. Since students were given the freedom to select an agent, there was the potential of some chemicals having hazard concerns. In accordance with the Globally Harmonized System (GHS), students were directed how to determine the health effects, flammability, reactivity, and special hazards. They labeled chemicals using the NFPA 704 Diamond.

Sample Data
One team collected poison ivy and isolated urushiol (oily resin) to use as their test agent. (All safety precautions were in place: use of disposable gowns, gloves, and goggles, and isolation done in a biological hood). Figure 5 demonstrates results, which showed the length and width of the cells significantly longer and wider at 15 percent concentrations. This was based on measuring at least 10 cells at each concentration.

Suggestions for Determining Student Learning
Formative assessment of activities and assignments included feedback on the accuracy of student work, as well as to analyze whether the tasks and directions were understood. Instructors periodically reviewed each student’s performance regarding data collection, laboratory skill sets and safety, and written materials, including lab reports. Feedback to the student may have been one or all of the following types: descriptive, corrective, and evaluative (Witte, 2012). Using the *descriptive assessment* model allowed the instructors to review and explain students’ performances and how tasks were completed (Table 1), using laboratory skills as an example. As an illustration, instructors modeled correct use of pipettes. Instructors discussed with students’ their mistakes in pipetting as observed; some students quickly determined what changes to make, while others needed a more corrective assessment.

In general, instructors provided *corrective assessments* to help students identify desirable changes to complete tasks (see Table 1). As an example, students were expected to produce a formal laboratory report. Instructors provided expectations in mini-lecture format for written components of the final formal laboratory report.
focusing on conventions for scientific writing. Students produced drafts of each section, which instructors reviewed, graded, and assessed. Instructors noted common mistakes so that the next time the learning experience is used, a written checklist of items to be addressed in the writing will be generated for the students.

Evaluative assessment provided a rubric “standard” of performance and allowed students to review their progress (see Table 1. Laboratory skills). Again, use of pipettes was observed during each laboratory setting, but with 24 students, it was easy to miss incorrect usage. In the future, instructors will add opportunities to evaluative performance of skills relevant to SLO#4 earlier in the experiment.

Just as assessments of student work and practices should be designed to drive their learning, all assessments of teaching can and should drive instruction. Instructors can evaluate any activities and assignments that students complete in order to review and revise instruction for the future. Instructors can be more effective when they use student performances to guide their instruction (Heritage, 2007; Stiggins & Dufour, 2009). Therefore, in recent versions of this activity, instructors have been much more intentional in assessing the quality of students’ experimental outcomes (see Figure 5, e.g.) and student performances on lab skills (see Figure 6, e.g.) to make adjustments to instruction mid-course.

But one of the biggest changes from the four- to the six-week version of the activity is the use of the student comments and assessments of their own learning and experiences (Tables 3 and 4). Such surveys conducted at the ends of the course can guide course design and instruction in subsequent iterations. Soliciting student comments and reflections during the semester, however, can prove extremely helpful in making adjustments on the fly and meeting particular classes of students where they are. Such formative assessment is designed to review and improve student learning as it occurs by helping students to revise misconceptions and validate prior knowledge, as well as assisting instructors in providing meaningful adjustments (Wood, 2009). Students come to classes with prior knowledge and misconceptions that affect interpretations of the newly presented information. For example, during the analysis stage of the learning experience, not every student was clear on the difference between dependent and independent variables, so this had to be reinforced in every version of their experimental design. And this was reinforced with each generate graph of their data.

Discussion

Field Testing

We first tested this research experience as a four-week process, but student feedback suggested they would be better served if this experience was a six week project, and we agreed (Elwess & Latourelle, 2004). We asked the students for their feedback on this six week experience. Specifically, students were asked to anonymously provide one sentence to summarize their experience (Table 4). Comments from the students, which were overwhelmingly positive.

Evidence of Student Learning

Evidence of student learning was seen on multiple levels, including performance on each of the laboratory skills components (Figure 6), with over 84 percent of the students passing each skill. We asked students to assess how well they achieved some goals of the course (Table 3). In the future, this survey should align more closely to the stated SLOs. That being said, the overall average ranged from 4.23 to 4.77 on a 1–5 Likert scale. Finally, 17 teams (out of 36) were successful in showing phenotypic changes with supporting data, but as we emphasized throughout this experience, it is not about the destination but the journey.

Student Assessment of Their Learning

In the seventh week of the semester, a consultant from the Center for Teaching Excellence, the College’s faculty development center, visited each of the three lab sections to conduct a mid-term assessment of

| Table 3. Survey results on a scale of 1–5, with 1 = absolutely not and 5 = yes, greatly. |
|---------------------------------------------------------------|------------------|
| Statements                                                                 | Average, N = 58 |
| This research experience improved my pipetting skills. (SLO#4)             | 4.49 ± 0.76      |
| This research experience improved my ability to calculate solutions and dilutions. (SLO#3) | 4.23 ± 0.86      |
| This research experience introduced me to new technology/software (microscopes, Moticams, ImageJ). (SLO#4) | 4.77 ± 0.46      |
| I am confident that I can take a microscopic image of a cell and measure it accurately. (SLO#6)    | 4.76 ± 0.46      |
| I valued having ownership of my own research project. (NOS)                 | 4.60 ± 0.75      |
| This research experience improved my ability to design and carry out an experimental approach. (SLO#2) | 4.58 ± 0.56      |

Figure 6. Results of all the laboratory skills assessment including the formal laboratory report. The numbers represent the percentage of students (N = 70) who achieved a C (73%) or higher for each skill. Image courtesy of Nancy L. Elwess.
teaching. The Midterm Survey and Student Focus Group provided an opportunity to get feedback from students about their experiences in the class. Without instructors present, the consultant informed students of the purpose of the visit, and that participation would be voluntary and anonymous. Students were asked to respond individually in writing to four questions:

1. What in this course is helping you to learn most effectively?
2. At this point in the semester, is there anything that has been taught that is still unclear or confusing to you?
3. Do you feel that the feedback you receive on your course work and through class discussions helps you with your learning?
4. Are there any changes you would make to help you get more out of the class?

After students had taken 7–8 minutes to write out responses, the consultant engaged the class in a 10-minute discussion about how the class was going for them. A report highlighting both the written and oral comments was subsequently prepared by the consultant and shared with the instructors.

From student comments on both the written survey and the focus group, a number of themes emerged. Interestingly, students identified big-picture aspects of the course, and how they connected not only to the skills-based or intellectual dimensions of learning, but also to the affective dimensions of their experiences in the lab.

1. Students reported enhanced reflectivity about, and greater autonomy over their own learning. This was particularly apparent when aspects of the experiment did not succeed. Students wrote that the following was helping them:
   - “Hands-on participation. Learning how to execute an experiment and then being allowed the freedom to design our own experiments and learn from our results.”
   - “Having your own experiment and designing it instead of doing what’s given.”

2. Students reported that they were thinking and acting less like a science student and more like a scientist:
   - “The course is helping me learn how to set up and successfully test a hypothesis for an experiment.”
   - “I like how applicable the course is. We don’t just learn the concept/theory; we are able to do problems, maps, equations, and even apply it in lab → ‘real life’ aspect makes it easier to learn.”
   - “The hands-on experiments really help. I feel that doing the experiments independently with some help here and there is helping to boost my confidence as a scientist.”

One crucial part of thinking and acting “like a scientist” is social—working with and learning from peers in a crowded and busy laboratory. Most students said that they learned a lot from their fellow students, and that they liked this. They appreciated learning both the social and technical skills necessary for professional work in the sciences. Related to thinking and practicing “like a scientist” is autonomy, or ownership of one’s own learning and development, especially setting up next steps for solving problems. Specifically, students become better at identifying what they did not know and figuring out how to obtain that knowledge or information.

Enhancing this section of the course from four to six weeks might seem like a minor adjustment, but it had enormous consequences for this iterative, trial-and-error process, and for student autonomy, resilience, and learning. In the four-week activity, students felt rushed and frustrated when their experiments had to be adjusted, or when their Paramecium died and they had to begin this part of the experiment again. Though the four-week activity was

<table>
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<th>Table 4. Selected student comments on authentic research experience.</th>
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<tr>
<td>“I was finally a scientist; failure, progress, ideas, observations; all from an experiment I designed.” (NOS)</td>
</tr>
<tr>
<td>“It was a great experience because we had the freedom to design our experiment and learn by redesigning and repeating the process.” (SLO#2)</td>
</tr>
<tr>
<td>“It was learning to ride a bike called research but with training wheels.” (NOS)</td>
</tr>
<tr>
<td>“This was a great opportunity; the manifestation of the scientific process in our own hands was so beneficial because we really got to immerse ourselves in research of our own creation.” (NOS)</td>
</tr>
<tr>
<td>“I didn’t like the experiment; it would have been more beneficial if we had more guidance.”</td>
</tr>
<tr>
<td>“I thought it was a wonderful opportunity to use new technology to hone our laboratory skills and learn invaluable research methods.” (SLO#4 &amp; #6)</td>
</tr>
<tr>
<td>“I thought it required too much time outside of lab.” (NOS)</td>
</tr>
<tr>
<td>“Loved doing hands-on research that I designed. It is making me consider a future in research.” (NOS)</td>
</tr>
<tr>
<td>“This experiment required a lot of time, but that was my fault since I designed the experiment.” (SLO#2; NOS)</td>
</tr>
<tr>
<td>“I really liked how we had full independence to design our experiment; it made the research experience authentic.” (SLO#2)</td>
</tr>
<tr>
<td>“By far the best way to get students writing efficient lab reports.” (SLO#9)</td>
</tr>
<tr>
<td>“This experience pushed us out of our comfort zones and test[ed] our lab skills in a way that increased our understanding in essential laboratory concepts.” (SLO#4)</td>
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designed as a guided inquiry activity in which “students investigate a teacher-presented question using student designed/selected procedures” (Banchi & Bell, 2008), it concluded for many students without a completed experiment, which meant that they did not discover the answers to their questions. Instructors had to "fill in the gaps" or provide the generic interpretations of anticipated experimental outcomes that should, ideally, have come from data generated by the experiment, just so that lab reports could be completed.

This, unfortunately, echoes the worst lessons of “cookbook lab courses” and short-circuits the AR opportunity. Biological processes have their own schedule and cannot be rushed. Similarly, scientific investigation has its own schedule, and is fundamentally iterative, and the six-week time frame better supports this. Whether because of contamination, improper use of equipment, an under- or overdose of the test agent, or other features of the “real world” that make their way into the laboratory experience (budget issues, personnel challenges, etc.), experiments rarely proceed smoothly from hypothesis to useful data. As the comments indicated, students appreciated the opportunity to wrestle with “failure,” and adjust hypotheses and procedures.

This might entail researching the literature, brainstorming with peers, designing proof-of-concept micro-experiments, or talking through hypotheses, assumptions, and practices with the instructor to discover some new angle of attack. Autonomy was enhanced in this course as compared with traditional courses because in the latter case, the instructor typically alerts the students to the boundaries of their knowledge and helps them design the protocols for getting the information they need to continue the experiment. Yet here students explicitly credited the freedom to create relevant and interesting hypotheses, and design and execute experiments to test them with the chance to overcome the attendant “failures” of the experiments by making adjustments.

One of the most crucial aspects of fostering student autonomy and encouraging mastery learning (see “Student Opinions,” below) is the nature and tone of the guidance provided by instructors. Students often asked instructors to anticipate the outcome of their experiment, such as, “Should I try glyphosate? How much?” Rather than responding directly, instructors guided their inquiry with questions like, “What is the first step in determining a starting concentration to induce phenotypic changes?” This kind of “detective work” models for students how scientists develop and test a hypothesis.

Initially, many students resisted and showed frustration at what they thought was obstinance, laziness, disregard for the student, or even ignorance on the part of the instructor. Student may not recognize this discursive practice as teaching. This is where clear SLOs are helpful both for teachers and students. Reminding students (and ourselves) that by the end of the course, students will be able to (for example) “state a hypothesis for their experiment” (SLO#1) and “design an experimental approach and be able to modify it if needed” (SLO#2) emphasizes that these are the cognitive skills students should be practicing. Whether they show phenotypic variations with their selected agent is less important than learning these fundamental investigative skills. By focusing on the mastery of skills and dispositions, students feel less anxiety about meeting any particular performance metrics for their own sake. As instructors, it was exciting to see students mature, from depending on constant guidance to realizing they have ownership of their experiments. This entails a responsibility to adjust hypotheses and modify experimental approaches. As students reworked their experiments, they were evolving into scientists.

Student Opinions

To appreciate the importance of students’ ownership of their learning, it was helpful to distinguish between performance and mastery learning.

Mastery goals focus on the learning process with an emphasis on individual improvement, gaining new skills, and challenge. Performance goals are defined as a concern with outcomes such as grades, rather than process, and with one’s ability, especially in comparison to others. There is considerable evidence that motivation and learning are facilitated in settings that promote mastery rather than performance goals. (Karabenick & Collins-Eaglin, 1997)

When students described the Paramecia experiment, they used the language of mastery rather than performance. The following end-of-semester student comments were typical:

- “I was finally a scientist, failure, progress, ideas, observation was all of my work.”
- “I liked being able to design the experiment and being responsible for how much work went [into] it. It was frustrating when they kept dying, though.”
- “I was able to take the rains [sic] and understand what I was doing.”

Students learn more deeply when they are able to connect abstract ideas and content to themselves and their goals. “Conditions that support mastery goals are challenging tasks, a high degree of student choice and control, a focus on individual improvement and individual evaluation . . . , and opportunities for students to work together on assignments” (Karabenick & Collins-Eaglin, 1997). Students in this course reported that the Paramecia project encouraged all of these:

- “It was a great experience because we had a lot of freedom to design our experiment and learn by trying again.”
- “I thought that the experience of the ‘Inducing Mutations in Paramecia’ was very beneficial to broadening our lab skills and critical thinking.”

Note the focus on choice and control, and appreciation of the scientific process in the first comment, and individual improvement in the second. Only one student explicitly mentioned in writing the benefits of learning through peers, the lab partner model.

- “Constant interaction between instructors, TAs, and peers [is working well for me in this course].”

In the focus group discussion, however, most students said they learned a lot from their fellow students, and they liked this.

It bears noting that some of the most used words or word roots in students’ written comments included “fun” or “enjoy” (12 out of 51 comments), “own” (as in “our own experiment” or “on my own”) (14/51), “create,” “creative,” “creativity” (6/51), and “real” (as in “real-life” or “real researcher”) (6/51). These feelings of ownership, control, creativity, enjoyment, and relevance provided intrinsic motivations, and were crucial to mastery learning (Ambrose et al., 2010, p. 75).
Students seemed to recognize the value of the learning outcomes and how those SLOs supported mastery of the cognitive and practical skills of scientific research. As a result of the authentic research activity in this course, students are better prepared for majors in any scientific discipline and for future work in labs as scientific researchers.

References


NANCY L. ELWESS is a Distinguished Teaching Professor in the Department of Biological Science, elwessnl@plattsburgh.edu. EACH can be reached at State University of New York Plattsburgh, 101 Broad St, Plattsburgh, NY 12901. MICHAEL MURPHY was Assistant Director, Center for Teaching Excellence, SUNY Plattsburgh at the time of writing. Currently he can be reached at the Schreyer Institute for Teaching Excellence, Penn State University, University Park, PA 16802.