A LIVELY ELECTRONIC COMPENDIUM OF RESEARCH, NEWS, RESOURCES, AND OPINION

Astronomy Education Review

Volume 7, Feb 2008 - Dec 2008
Issue 1

Development and Implementation of a Lab Course for Introductory Astronomy

by **Nate McCrady**
UCLA
Emily Rice
UCLA
Received: 11/26/07, Revised: 04/04/08, Posted: 04/25/08

The Astronomy Education Review, Issue 1, Volume 7:13-22, 2008

Abstract

The typical "Astro 101" lecture-based course is passive, and adding well- designed learner-centered labs allows students to experience science as a pattern of thought. In this article, we present an approach to developing an introductory lab course. Identification of goals and student outcomes, particularly skills, and process and attitudinal goals, is a key step. We apply constructivist principles to the lab course and structure content around core concepts to provide cohesion and facilitate knowledge transfer. We discuss the role of the teaching assistant and assessment in a successful implementation of our approach.

1. INTRODUCTION

Several hundred thousand college students take an "Astro 101" course each year, frequently as their only college-level exposure to the physical sciences. These courses are often passive learning environments based on lecture and assigned readings that do not give students exposure to science as a human activity and mode of thought. A lab course offers the opportunity to build student conceptual knowledge and intuition through direct interaction with basic physical phenomena. In addition, the lab setting takes advantage of the strong social aspects of human learning via peer interaction.

At the 2007 Cosmos in the Classroom symposium, it was apparent that there is a strong desire among astronomy educators for a hands-on counterpoint or complement to lecture. Coupled with this desire is significant uncertainty about how to approach the addition of a lab component to the curriculum. We recently developed and implemented a new lab course in conjunction with the one-quarter (10-week) introductory course for nonmajors at UCLA. Because introductory courses vary significantly in length (quarter, semester, or full year) and different instructors have different opinions on the relative importance of specific astronomy content, our specific labs represent only one possible implementation. In this article, we present our approach to development of a lab curriculum based on explicitly defined course goals. We discuss the qualities that define a well-designed lab, based on constructivist principles of learning and using selected examples from our labs. In the final section, we describe how to implement the labs in the classroom.

2. DEVELOPING THE LAB CURRICULUM

A key factor in development of a lab course is understanding the audience: Who are the students, and why are they taking the course? In a typical university introductory astronomy course, the students are non–science majors. In our case at UCLA, the introductory course draws nearly 1,400 students per academic year. These students are primarily freshmen and sophomores, 90% of whom are humanities majors or undeclared. It is important to realize that these students are self-selected to lack the technical background typical among science majors and are frequently lacking in confidence regarding their ability to comprehend science. The students' motivation for taking the course also differs from that of science majors: roughly 90% of our introductory students indicate that they are taking the course to satisfy the physical sciences general education requirement.

Knowledge of the background and motivation of the students guides the identification of goals for the lab course. A useful tool in goal development is the question, "How do I want my students to be different as a result of my course?" Given the hands-on nature of lab courses, the question can be reformulated as "What should my students be able *to do* as a result of completing the lab course?" The answer to this question should include not simply content (i.e., astronomy knowledge) goals but also process and attitudinal goals. In an introductory course, these goals are actually more important than the content goals—nonmajor students are unlikely to have a specific need for astronomy content in other college courses or in the workplace after graduation. In contrast, many skills and attitudes readily developed in an astronomy lab course are widely applicable and represent longer-lasting student outcomes, for example, construction of an argument from evidence, collaboration, estimation, visual representation and interpretation of data, and skepticism. The list of "Goals for Astro 101" developed in American Astronomical Society workshops (Partridge & Greenstein 2003) is divided into content goals and "skills, values, and attitudes" goals. Many of the skills goals listed are much more thoroughly and effectively developed in the hands-on environment of a lab than in a traditional lecture setting. Explicit identification of these non-content-related goals is a key step in developing activities that build student skills with broad application beyond the final exam.

Of course, each lab must cover some topic, so the question is, how does one choose the specific astronomy content? A useful approach is to identify core concepts applicable throughout astronomy. Astronomy is applied physics, so these core concepts are often physical: gravity, motion and orbits, energy, light and color, and so on. Table 1 outlines the core concepts and specific content of our one-quarter lab course as an example. Selection of a few core concepts for the labs facilitates "spiral learning," whereby the concepts are revisited repeatedly, building on them as the students gain confidence and experience (Bruner 1960). Physics education research indicates that students develop their understanding of a concept in stages (McDermott 1991) and that learning is highly contextualized. Students are more likely to develop an abstract understanding of a concept after exposure in multiple contexts (Bransford, Brown, & Cocking 2000). Returning to the core concepts in different contexts and at increasing levels of complexity reduces contextualization, helping students separate a concept from the specific circumstances in which it is presented.

Table 1. Labs in Use in the UCLA Introductory Astronomy Course		
Lab	**Title**	**Core Concepts and Specific Content**
1	Quantitative Skills Review	Scientific notation; working with exponents; manipulating ratios and units of measure Core concepts: ratios
2	Night Sky Motions (planetarium)	Interpretation of motions of the night sky as a function of the Earth's orbit, rotation, and seasons, planetary orbits, and observer latitude Core concepts: orbital motion
3	Light and Telescopes	Ray behavior of light; focusing light with lenses and mirrors; investigating a simple spyglass telescope Core concepts: light
4	Light and Color	Emission, absorption. transmission, and reflection of light; the composition of white light; continuous vs. line spectra; the function of filters; spectroscopy of arclamps and sunlight Core concepts: light and color
5	Gravity and Extrasolar Planets	Mass balance and center of mass; reflex motion of stars; interpretation of radial velocity curves; and application of Kepler's laws of planetary orbits Core concepts: gravity, orbital motion, ratios
6	Stars and the H-R Diagram	Star colors, surface temperatures, and Wien's law; the relationship between radius, surface temperature, and luminosity; apparent brightness as a function of distance; using the H-R diagram to infer the basic properties of stars Core concepts: light and color, ratios, plot interpretation
7	Black Holes and the Galactic Center	Escape speed, event horizons, and gravitational redshift; indirect evidence of supermassive black hole in the Galactic Center; gravitational time dilation Core concepts: light and color, gravity, orbital motion
8	Structure and Motion of Spiral Galaxies	Circular motion; solid body rotation; Keplerian rotation curves and evidence of dark matter in galaxies; appearance of galaxies in different colored filters and interpretation in terms of star formation Core concepts: gravity, orbital motion, light and color, plot interpretation

9	Expansion of the Universe	Galaxy redshift measurements and interpretation; why expansion leads to a Hubble law; how age of the Universe depends on acceleration of Universe; interpretation of age of Universe from plots of its expansion history Core concepts: light and color, plot interpretation

Another advantage of the spiral approach is that it ties the various labs together as a cohesive body of knowledge. Nonmajor students often view science courses in a linear manner, as a series of sequential, unrelated activities to complete. Students tend to compartmentalize labs; they see no relation between the labs and lecture, and simply finish a lab and forget it. The spiral learning approach facilitates student development of more complete conceptual understanding. Repeated exposure reminds students of what they have already encountered in a particular concept and provides new contexts to deepen and extend their understanding. In particular, the opportunity for students to apply prior knowledge opens the way for the higher-level thinking skill of synthesis: construction of new knowledge from multiple conceptual sources.

Gravity is a good example of a core concept in introductory astronomy. Although it is a familiar everyday phenomenon for students, their understanding is very likely to be poor and incomplete (Kavanagh & Sneider 2007). Gravity can be approached in many specific contexts in an introductory course. Examples include Newton's third law, Newton's law of universal gravity, planetary and satellite orbits, free fall, reflex motion due to extrasolar planets, ocean and planetary tides, star formation, stellar evolution, general relativity and curved spacetime, escape velocity and black holes, expansion, and the geometry of the universe. Each of these topics is suitable for student exploration in a lab or tutorial setting, and the core concept of gravity can thus be built on in multiple labs over the course.

An example of a single concept covered in multiple contexts from our lab course is light and color. Students begin to investigate light and color through experimentation with a white light source and a set of color filters. Subsequent labs develop the concept through spectroscopy of the Sun and arclamps, the colors and temperature of stars, and star formation indicators based on the colors in images of galaxies. A separate line of inquiry builds student understanding of light and color through investigation of the redshifts due to gravitational stretching of spacetime in the vicinity of black holes (as detected by observing a laser clock), and expansion of the universe (as detected by the recession velocities of galaxies).

The topic of extrasolar planets provides an excellent opportunity for a lab that brings together many of the core concepts in introductory astronomy. The spectroscopic detection method in particular is a straightforward application of some fundamental concepts: Kepler's laws of planetary motion, center of mass, Newton's third law and law of universal gravity, spectral lines in stars, and measurement of redshift. The detection plots of stellar reflex motion from journal articles provide students with actual data from which they can learn about time series plots, periodic motion, and superposition. Extrasolar planets are an example of specific content that draws on multiple concepts, providing a rich topic for lab courses.

3. QUALITIES OF A WELL-DESIGNED LAB

The constructivist view of learning is that new knowledge is built from existing knowledge (Bransford et al. 2000, Chapter 1 and references). Students enter the classroom with preexisting mental models, often incomplete and self-contradictory (Redish 1994). For meaningful learning—that is, learning that may be transferred to new contexts—to occur, the students' preconceptions must be engaged. Many common misconceptions in astronomy are well known (e.g., Comins 2001) and can be directly addressed with the "elicit/confront/resolve" approach of McDermott (1991). Students are led to commit to their existing conception, via prediction or explanation, and then led to confront the inadequacy of their mental model through their own observations. Research has demonstrated that the resulting cognitive conflict (i.e., "my understanding does not match my evidence") is effective in deconstructing incorrect mental models and moving students toward conceptual understanding (e.g., Thacker et al. 1994).

This approach, variously labeled as "learner-centered" or "inquiry-based," stands in distinct contrast to traditional methods of instruction in science labs. In the latter, students read a brief description of a phenomenon and are then presented with a series of tasks to perform, not unlike a recipe in a cookbook. The emphasis in this approach is on the generation of a result (not unlike cooking), with the intent of demonstrating some topic from lecture. Students in traditional science labs often fail to see the relevance of the assignment and view it as simply a set of tasks to finish. As noted by McDermott (1991), "very little inductive thinking is involved; the reasoning is almost entirely deductive; the student is not actively engaged in the process of abstraction and generalization." (304). Students strive to attain the "correct" response and experience frustration and confusion when they encounter difficulty.

A well-designed lab draws on an education research-based understanding of how people learn. It should uncover inadequate student conceptions and provide experiences that change those conceptions (Weimer 2002). Such a lab will elicit and directly engage student misconceptions and then guide students in construction of a new, more scientific understanding of a concept. In comparison with introductory physics, there is a real paucity of well-developed learner-centered lab activities for introductory astronomy. As noted earlier, astronomy is applied physics, and some existing introductory physics labs can be readily used or adapted. The *Physics by Inquiry* workbooks (McDermott and the PER Group 1996) are an excellent set of interactive conceptual lab activities for topics like gravity, light, and spectroscopy. The CAPER team's *Lecture Tutorials for Introductory Astronomy* (Prather et al. 2007) is a rich source of well-developed conceptual astronomy material and may be adapted to a hands-on laboratory setting.

While developing our lab course, we discovered that there are presently very few conceptual lab activities for astronomical topics beyond naked-eye astronomy and the Solar System. In particular, topics typically covered in the late stages of a one-term introductory course are significantly underrepresented: stellar evolution, galaxy structure, and cosmology. Given this situation, we should discuss some considerations for those who undertake development of a lab activity.

A useful technique for actively engaging students in lab is to mimic the scientific process. A typical model is "observe, model, predict, test, evaluate." Students are first led to make observations of phenomena to develop intuition and familiarity with the concept at hand. Next, they are asked to make predictions for new or modified situations, based on their current conception. The role of the predictions is the same in the labs as it is in science: to provide a reality check on understanding of the concept. Students then test their prediction via experiment, or, in the case of pencil-and-paper labs, following through their logic to make comparisons with existing data. The prediction step is critical because it forces students to commit to their mental model. Any misconceptions can thus be exposed by observation and addressed in the lab. Data or observations that contradict an incorrect or incomplete model place the student in cognitive conflict and provide the "teachable moment" wherein a new mental model can be constructed.

A key process goal for our labs is that students gain experience with the technique of arguing from evidence, a skill that is not intuitive for many non–science majors. We use a Socratic approach whereby students are led through their investigations of a concept by a series of questions. Questions are structured such that students may test their working understanding (i.e., mental model) of a concept directly with the equipment or data available to them in the lab room. The lab questions are designed to induce the students to provide observational or experimental support for their assertions. In practice, we have found that this approach engages the students, on occasion leading to animated disagreements that are settled by direct experiment among peers.

One way for students to engage with material and build their skills in arguing from evidence is by interpreting real astronomical data. Actual images or data partially digested in the form of plots provide a link between content discussed in lecture or reading assignments, and the activities in the lab. Examples from our labs include interpretation of the radial extent of galaxies in images versus plots of their rotation curves; comparisons of the properties of stars based on their location in an H-R diagram; and identification of the periods of extrasolar planets from plots of stellar reflex motions. Images and actual data provide new contexts for the concepts under investigation and place students in position to build the same chains of basic reasoning that astronomers use. In addition, student use of real data works toward the attitudinal goal that science is comprehensible.

With regard to mathematical content, assessment should focus on the students' reasoning rather than their calculations. Although even introductory students can often perform algorithmic exercises, they are unable to evaluate or interpret the results. A better approach is to ask students to reason about relationships between physical variables (Slater & Adams 2003, pp. 11–12), draw comparisons, or interpret simple ratios. The reasoning and argument from evidence is the key factor, and assessment should focus on the argument and the conclusions rather than the arithmetic. We will return to the topic of assessment in the section on implementation.

The tendency of introductory science students to compartmentalize (i.e., "this is true in science class") may be addressed by tying the scientific concepts to student experiences. By building from familiar phenomena to the underlying scientific concepts or physical principles, we combat compartmentalization and establish the relevance of the topic. As an example, a lab on orbital motion within a galaxy begins with discussion of rotation of a familiar object, such as a compact disc or Frisbee. As students investigate the velocity and motion of hypothetical ants at various distances from the center of the spinning disc, they gain experience with the underlying scientific principles in an easily recognizable situation. This provides the foundation for transfer of the new knowledge regarding rotational motion to an abstract setting, such as stars in a galaxy. Students can reason by analogy with the familiar case, allowing them to leverage and extend their existing knowledge.

4. IMPLEMENTING A LAB COURSE

Context and learning environment are important factors in promotion of student conceptual understanding. The lab setting is the one place in an introductory course where students are fully, actively engaged in their own learning (Redish 1996). In a "discovery lab" setting, wherein small groups interact directly with data, instruments, and one another, students build their own conceptual understanding through guided observation of phenomena. The discovery lab approach shifts the focus from solely the specific content of the lab to a balance between content and process, "between science as knowledge and science as a way of knowing" (McDermott 1991, 305). This balance of content and process is tied directly to the broader goals of an introductory science course for nonmajors.

In our course, students work on the labs collaboratively in small groups. Educational research has demonstrated the benefits of collaborative learning, including goal-directed reasoning, increased search of solution space, formulation of explanatory arguments, and metacognitive aspects such as monitoring of the process and awareness of constraints (e.g., Vye et al. 1997). In our experience, a lab group size of three appears to be optimum: large enough to facilitate peer learning interactions, and small enough that all students interact with the materials and each other. Each group is provided with all the required equipment or data; we avoid a "lab stations" set-up that could lead to compartmentalization of phenomena or concepts. Instead, concepts are developed sequentially through the mentioned science model: observe, model, predict, test, evaluate.

We have made the choice to emphasize simple materials and equipment in the labs. Because our students are self-selected non–science majors, it is important to limit the amount of abstraction present. We attempt to stay as close to the phenomenon or concept as possible, without complicated "black boxes" performing feats of apparent magic. For example, rather than use spectrometers and arclamp tubes, our spectroscopy lab begins with flashlights, colored theater gel "filters," and glass prisms. Only after building up to the behavior of grating slides do we introduce arclamps, and finally a simple cardboard tube spectroscope. The emphasis of the labs is on reasoning from evidence and the universality of physical laws, so it is important to keep the concepts rooted in familiar items. An additional advantage is the low capital cost of the labs. Our initial setup cost at UCLA was on the order of a few dollars per student, with very low annual maintenance costs. The simplicity and familiarity of the equipment provides additional relevance to the students and helps reduce problems of contextualization (i.e., "this is how nature behaves only in science labs").

The role of the teaching assistant (TA) or lab proctor is somewhat different in our labs than in traditional labs. In a traditional cookbook-style lab, the TAs spend considerable time maintaining equipment and interpreting lab directions for students obsessed with generating "the right answer." Because our labs are aimed at a more self-directed investigation of concepts, the TA’s task is to roam the lab room observing student conversations, breaking in to engage in Socratic dialogue with groups that are either moving quickly or struggling with the concepts (see discussion in Brogt 2007). In our large public university setting, this has led to an interesting observation regarding the effect of class size. As a general rule, a smaller number of students is better, providing more interaction between the students and the TA. However, in our larger classes, limited availability of TA attention often leads to increased peer interaction. Tired of waiting for the TA to arrive, the students return to discussion and frequently arrive at the answer to their question without additional assistance. This effect was unexpected, and although our experience is anecdotal, it is worth considering that there is an optimal level of TA–student interaction somewhere below "as much as possible."

The TA-as-facilitator approach requires deep conceptual understanding on the part of the TAs. This cannot be taken as a given, even in the typical case in which the TAs are graduate astronomy students. The conceptual focus of the labs stands in contrast to their own astronomy training in many cases, which has its traditional focus on problem-solving and mathematical modeling. TA preparation is thus critical to the success of the conceptual lab approach. Our TAs work through each upcoming lab in weekly instructor meetings, exactly as the students will. In general, the TAs display some of the same misconceptions as the students and often have the same difficulties on the labs. It is indispensable that the TAs work through the labs themselves in small groups just as the students will. In this way, the TAs develop their own conceptual understanding, can anticipate student difficulties, and can develop questions to ask the students in the Socratic dialogue.

Assessment and grading drives student learning because the assessment practices of a course tell students what to learn and how deeply to learn it (Brissenden et al. 2002). It is therefore critical that the assessment techniques applied to the labs match the goals for the lab course. The traditional approach to lab grading of assigning arbitrary point values to correct responses emphasizes to students the ultimate importance of generating correct responses. This situation fosters the undesirable yet common student misconception of science as a collection of facts and answers. If the goals of the lab are more process- and skill oriented, assessment should focus more on the processes and the skills. For example, if development of visual representation skills is a goal, students should be called on to make drawings, schematics, or sketches, and the related assessment should evaluate the qualities of these works. Because the goal is learning with understanding, as evidenced by the ability to transfer new knowledge to novel contexts, students should be called on to express their understanding in their own words.

Finally, students should be provided grading impunity for "incorrect" predictions; the point is for them to commit to their conceptions as a self-check on their understanding. Grading the predictions would lead to after-the-fact "predictions" that are antithetical to the scientific process. Students need the freedom to be wrong as a stepping stone from their preexisting conceptions to a more scientific understanding. Assessment guides student behavior: grading the student’s account of his or her path to understanding emphasizes the importance of the process and reinforces the idea that science is a way of thinking.

5. CONCLUSIONS AND FUTURE WORK

The introductory astronomy course at UCLA is a one-quarter (10-week) course. The logistics of grading student work in a 200+ student course limit us to nine labs, and as such, we have to make serious choices about what material to include. Other universities present the survey astronomy course over a 15-week semester or even as a full-year course. The approach we have presented in this article is applicable to any of these schedules. The spiral learning approach would bear significant fruit over a longer course because students would be able to build to fairly sophisticated conceptual understandings through additional exposures to core concepts.

As noted, there are good sources of well-designed learner-centered lab and tutorial activities for basic physics. In astronomy, the situation is not as well developed. Excellent conceptual materials have been created for traditional topics such as night sky motion, lunar phases, and planetary orbits. Far less developed are more modern astronomy topics, such as black holes, extrasolar planets, star formation, galactic structure, astrobiology, and the origins and expansion of the universe. There is real need for development of learner-centered conceptual material for these topics. Our nonmajor students are the ultimate consumers of modern astronomical advances, and it is a disservice to the community to allow their conceptual understanding to stop at the borders of the Solar System.

Acknowledgments

The authors wish to thank Professors Wolfgang Brandner, Ian McLean, and Shoko Sakai for allowing us to implement our new labs in their courses at UCLA. We also thank the numerous teaching assistants and graders who provided the time, effort, and enthusiasm necessary for detailed feedback during initial development of the labs. This material is based on work supported by the National Science Foundation under Grant No. 0502649. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

References

Bransford, J. D., Brown, A. L., & Cocking, R. R., (Eds.) 2000, *How People Learn: Brain, Mind, Experience, and School*, Washington, DC: National Academy Press.

Brissenden, G., Slater, T. F., & Mathieu, R. D. 2002, "The Role of Assessment in the Development of the College Introductory Astronomy Course," *Astronomy Education Review*, 1(1), 1. http://aer.noao.edu/cgi-bin/article.pl?id=1.

Brogt, E. 2007, "A Theoretical Background on a Successful Implementation of Lecture-Tutorials," *Astronomy Education Review*, 6(1), 50. http://aer.noao.edu/cgi-bin/article.pl?id=243.

Bruner, J. 1960, *The Process of Education*, Cambridge, MA: Harvard University Press.

Comins, N. F. 2001, *Heavenly Errors*, New York: Columbia University Press.

Kavanagh, C., & Sneider, C. 2007, "Learning about Gravity I: Free Fall: A Guide for Teachers and Curriculum Developers," *Astronomy Education Review*, 5(2), 21. http://aer.noao.edu/cgi-bin/article.pl?id=220.

McDermott, L. C. 1991, "Millikan Lecture 1990: What We Teach and What Is Learned—Closing the Gap," *American Journal of Physics*, 59(4), 301.

McDermott, L. C., & the PER Group at the University of Washington 1996, *Physics by Inquiry* (Vols. I & II), New York: Wiley.

Partridge, B., & Greenstein, G. 2003, "Goals for ‘Astro 101’: Report on Workshops for Department Leaders," *Astronomy Education Review*, 2(2), 46. http://aer.noao.edu/cgi-bin/article.pl?id=64.

Prather, E. E., Slater, T. F., Adams, J. P., & Brissenden, G. 2007, *Lecture-Tutorials for Introductory Astronomy* (2nd. ed.), San Francisco: Addison-Wesley.

Redish, E. F. 1994, "Implications of Cognitive Studies for Teaching Physics," *American Journal of Physics*, 62(9), 796.

Redish, E. F. 1996, "New Models of Physics Instruction Based on Physics Education Research," in *Deutsche Physikalishe Gesellschaft, Didaktik der Physik* (Vol. 60), K. H. Lotze (Editor), Jena, Germany: Physik-Verlag, 51.

Slater, T. F., & Adams, J. P. 2003, *Learner-Centered Astronomy Teaching: Strategies for Astro 101*, Upper Saddle River, NJ: Prentice Hall.

Thacker, B., Kim, E., Trefz, K., & Lea, S. M. 1994, "Comparing Problem Solving Performance of Physics Students in Inquiry-Based and Traditional Introductory Physics Courses," *American Journal of Physics*, 62(7), 627.

Vye, N. J., Goldman, S. R., Voss, J. F., Hmelo, C., & Williams, S. 1997, "Complex Mathematical Problem Solving by Individuals and Dyads," *Cognition and Instruction*, 15(4), 435.

Weimer, M. 2002, *Learner-Centered Teaching*, San Francisco: Jossey-Bass.