Labs for the Matter & Interactions curriculum

Robert Beichner, Ruth Chabay, and Bruce Sherwood
Department of Physics, North Carolina State University, Raleigh, North Carolina 27695

(Received 15 September 2009; accepted 30 October 2009)

The Matter & Interactions curriculum for a calculus-based introductory physics course emphasizes the power of a small number of fundamental principles, incorporates the atomic nature of matter throughout, and introduces students to computational modeling. The main goal of the laboratory portion of this curriculum is for students to see fundamental principles in action. From this goal flow subgoals that have led to the development of laboratory activities that include several novel genres.

[DOI: 10.1119/1.3266163]

I. INSTRUCTIONAL ENVIRONMENT

The laboratories at North Carolina State University associated with the Matter and Interactions (M&I) introductory calculus-based physics courses[1] are distinctive in approach and content. Because they have been designed with specific goals in mind, they have particular features that may be useful in connection with other curricula as well.

At North Carolina State there are two environments in which the M&I curriculum is used. In the SCALE-UP studio environment,[2] the class time of 5 h/week is not divided into separate lecture and laboratory meetings, and lecture time is minimized. Students spend most of their time working on hands-on observations ("tangibles"), difficult but interesting problems ("ponderables"), and computational modeling with visualization ("visibles"). The class is organized into collaborating groups of three students. In the more traditional lecture-laboratory M&I environment, there are three lectures per week, along with a 2-h laboratory. As in SCALE-UP, there are formal groups, with each student playing an assigned role. During the laboratory, these teams work on the same three types of activities as SCALE-UP students, matching the experimental, theoretical, and computational aspects of contemporary physics research.

II. GOALS

The goals of the laboratory within the context of the M&I physics curriculum, for both the studio and lecture-laboratory courses, include the following:

- Apply the fundamental principles of physics to a wide variety of situations;
- Relate microscopic properties to relevant macroscopic characteristics;
- Connect computational models to experiments; and
- Use simple error analysis when needed to distinguish between physical models.

These goals lead to most of the differences between M&I laboratories and laboratories associated with more traditional content. Several types of experiments have been developed with the following characteristics:

- Simple experiments and equipment can invoke deep issues;
- Many situations can be data-poor but analysis-rich; and
- A series of related experiments that span the semester can help tie various aspects of the course together.

Specific, non-content-related goals have been developed for the SCALE-UP studio environment; see Ref. 2 for details.

III. DISCUSSION OF THE M&I GOALS

The M&I goals require further elaboration. Consider the first and most important goal that students see in the laboratory, the consequences of the fundamental principles of physics. In mechanics these are the momentum principle (Newton's second law), the energy principle, and the angular momentum principle, plus simple atomic models of matter, especially the ball-and-spring model of solids. In E&M the fundamental principles are Maxwell's equations, the superposition principle, and again atomic models of matter (including the role of electrons in metals).

Many experiments that address this goal are data-poor but analysis-rich. For example, in one experiment students throw a ball straight up and use a stopwatch (usually from their cell phone or wristwatch) and a meter stick to measure the time of flight and the maximum height. They apply the momentum principle to deduce the initial speed, and students are required to show a careful analysis with proper vector momentum notation. Next they apply the energy principle to obtain the initial speed from a different perspective.

Another mechanics experiment involves jumping straight up from a crouched position. Only three quantities are measured: The approximate heights of the center of mass during the crouch, at lift-off from the ground, and at the highest point of the jump. Students must then use the momentum and energy principles to obtain approximate values for the lift-off speed, the change in the jumper's internal energy, and the average force of the floor before lift-off. They also come to grips with the fact that the floor does no work on the jumper in this situation.

A typical E&M experiment involves a transparent cathode ray tube, which is sufficiently expensive that we have just one of them in each laboratory room. The cathode ray tube has electrostatic deflection plates whose voltage can be varied and coils whose current can be varied; the accelerating voltage can also be varied. Students are asked to determine the speed of the electrons by two different methods. Groups request measurements from the teaching assistant and then analyze these measurements to determine the electron speed. Instead of a simplistic worksheet to fill in, students must sort through all the possible observations that could be made to determine the best course of action.

Also in E&M students measure the distance dependence of the magnetic field of a long straight wire by the varying deflection of a compass needle away from North as the distance between the wire and compass is varied. They have seen a derivation of the $1/r$ field of a long straight wire, but the derivation can be very abstract until they actually place a wire at various distances above a compass. It also raises the question: "How long does a wire have to be to be 'long'?" Again using the deflection of a compass needle away from North, students measure the pattern and distance dependence of the magnetic field near a current-carrying coil and near a bar magnet.

From the compass deflection at a measured distance from a bar magnet, students can determine the magnetic dipole moment of the magnet.[3] They measure the mass of the magnet and calculate the approximate number of atoms in the magnet, assuming it is made of iron. They can then compare their macroscopic measurement of the magnetic dipole moment to the prediction of a very simple microscopic model in which each atom contributes a field corresponding to one Bohr magneton. These values differ by about a factor of 2, and after a semester and a half of working with sometimes rough approximations, they can understand that this value is in very good agreement given the simplicity of the model. This measurement and calculation is a good example of making macro-micro connections in E&M.

Except for the transparent cathode ray tube, these experiments are not only data-poor and analysis-rich, but they also are in the category of simple equipment used to get at deep issues. We believe it is important to address a notion that might arise from the use of fancy laboratory equipment that physics applies only to special situations in special rooms with special equipment (and maybe you have to wear a white laboratory coat).

A. Error analysis

In experiments such as most of the ones we have described, we judge that it would be intrusive and distracting from the main goal to ask for error analyses. It isn't that we couldn't fashion a good learning activity out of determining the approximate errors in the derived quantities, at least for the mechanics experiments (in introductory E&M laboratories, error analysis typically plays no role). The issue is that there are many possible competing goals for the laboratory, and we must make conscious choices to focus on the most important goals. There is a place for error analysis, but we need to be thoughtful about when to emphasize this aspect of the laboratory experience because it can take a lot of time, which might better be spent in the service of higher goals.

A traditional mechanics laboratory activity is a measurement of the magnitude g of the Earth's gravitational field or other well-known quantities with error analysis. We suggest that in its usual form, such experiments are not a good match to the goals of the introductory course, nor are they good examples of using error analysis. A measurement of a well-known quantity, necessarily much less accurate than the established value, strikes many students as pointless ("but I already know the value of g"), and it takes much explaining to try to make clear the subtle distinction between the estimated accuracy of the experiment and the difference between the students' value and $9.8\ \mathrm{m/s^2}$.

An authentic use of error analysis is to distinguish between competing models. This use arises naturally in an E&M experiment that addresses the following question: You charge a large (1 F) capacitor through a high-resistance resistor and through a low-resistance resistor. In which case does the capacitor end up with more charge? Students see that in the first case, the charging takes longer but with a smaller current, whereas in the second case, the charging takes less time but the current is larger. Before making more measurements, students are asked to make a prediction. An experimental way to check the prediction is to discharge the capacitor through the high-resistance resistor and measure the discharge time. The two discharge times are not exactly the same, and it is natural for students to seize on the difference even if it is small, especially if the sign of the difference confirms their prediction. Here is where error analysis plays a crucial and authentic role. Repeated measurements give an indication of expected fluctuations, and error bars on the two kinds of measurement show that within the error estimates, it appears that the charge is the same.

Fig. 1. Small aluminum blocks, $\approx 2\times 2\times 4\ \mathrm{cm}^3$, are used to hold student nametags and are also used for experimentation.

B. More examples of the use of simple equipment

A SCALE-UP "tangible" asks students to determine the mass and size of an aluminum atom by measuring the mass and volume of a block of aluminum metal (shown in Fig. 1) and using Avogadro's number (which is at least familiar to them from chemistry courses). This exercise could be purely theoretical, invoking the known density of the metal. But actually handling the material and visualizing (for simplicity) a cubic lattice of atoms make the activity concrete and instructive. The same small blocks are utilized later in the course as students estimate the power output of their palms when tightly grasping a block to warm it from room temperature to skin temperature.

In another experiment, students discover that ripping a strip of invisible tape off another leaves both tapes significantly charged electrically. An interesting experiment using this simple equipment is to determine approximately how much charge is on a piece of tape by observing static equilibrium between electric and gravitational forces. (The mass of a specific length of tape is measured with an electronic balance.) This experiment feels authentic because students have no idea of even the order of magnitude of what the result should be. Students are asked to identify the approximations and assumptions made in their analyses. Follow-up analysis includes determining what fraction of surface sites has an excess charge. The result shows that these charges are very far apart on an atomic scale so that the surface charge distribution on an electrostatically charged insulator cannot be thought of as uniform unless you are many atomic diameters away from the surface.

These two experiments incorporate multiple goals in that they involve simple equipment, make macro/micro connections, and are data-poor and analysis-rich.

A kit of simple equipment has been designed, which permits doing serious "desktop" experiments in electrostatics, circuits, and magnetism. This kit is at the core of many of the E&M experiments. The kit includes invisible tape, batteries, bulbs, a compass, a 1 F capacitor, thick and thin Nichrome wires, a bar magnet, and clip leads.[4]

C. Series of activities

A key experiment early in the mechanics semester has students hang weights on the end of a long thin wire to determine Young's modulus and observe the static and dynamic behavior of macroscopic spring-mass systems. These experiences are the foundation for understanding a simple ball-and-spring model of solids to explain a wide range of phenomena through macro/micro connections. Students are shown how to use Young's modulus to determine the effective strength of the interatomic bond modeled as a spring. This strength is used to predict the speed of sound in a metal using a simple ball-and-spring computational model. Mechanics and thermal physics are integrated throughout the mechanics semester, and late in the semester in a section on statistical mechanics, their experimental result for the strength of the interatomic bond is used to predict the temperature dependence of the specific heat capacity of aluminum and lead, which agrees with published data.

The measurement of Young's modulus is deliberately simple and relatively crude because the goal is to vivify the theory, not to become bogged down in minutiae. The equipment (see Figs. 2 and 3) was designed so that a 2 kg mass stretches a wire by an easily observed several millimeters. There exist various kinds of apparatus for measuring Young's modulus accurately, typically involving extremely small stretches hardly visible to the student, but accuracy is not the point here. The point is that students should see and experience the phenomena that the theory attempts to explain and use.

Another example of a series of activities spanning much of the semester is the students' increasingly refined and extended computational models of gravitational motion. First a simple calculation of the vector gravitational force $-(Gm_1m_2/r^2)\hat{r}$ is accomplished for basic astronomical situations. Later they use this force to model the motion of a spacecraft coasting near the Earth, and they observe different trajectories depending on the initial conditions. Later they add in the effects of the Moon in a simplified model where Earth and Moon are fixed and observe a far richer set of possible trajectories and high sensitivity to initial conditions. This sequence has the flavor of a multiweek project.

D. Connections to computational models

As noted, many of the student activities in SCALE-UP and the laboratory component of the lecture-laboratory course incorporate computational modeling.[5] The laboratory is a natural place for such work to take place, as both experiment and computational modeling complement theory in contemporary physics. In addition to computational modeling *per se*, there are also activities that link computational modeling and experiment.

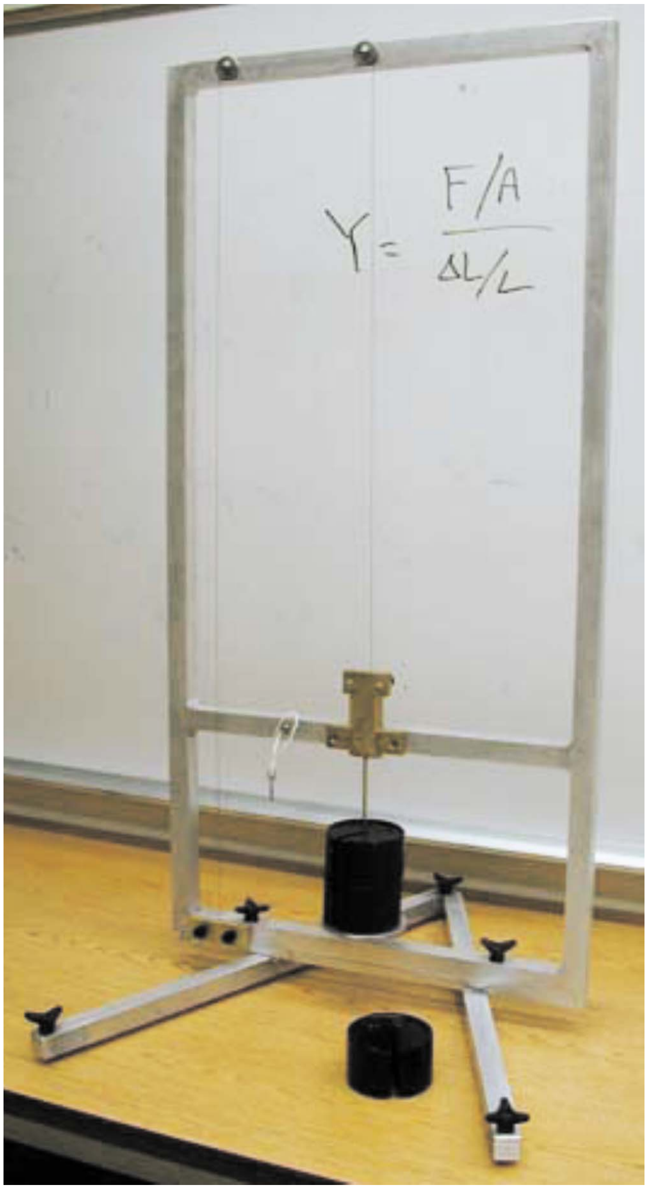

Fig. 2. Our locally built Young's modulus apparatus allows students to directly measure how much a metal wire stretches when a known load is applied. The wire can be seen as a thin vertical line in the center of the apparatus, across pulleys on the left half of the top of the frame, and down the left side.

As an example, students make measurements of the motion of a fan cart using a sonar detector and then model this motion in a computer program using the measured mass of the fan cart and the initial momentum. They adjust the net force to reproduce the motion observed in the experiment.

In another case students make measurements of the force constant of a spring, the mass of an object hanging from the spring, and the period of the motion. They then write a program to numerically integrate the motion of a mass hanging from the spring, using the measured mass and spring constant. They have the program generate a graph of the motion

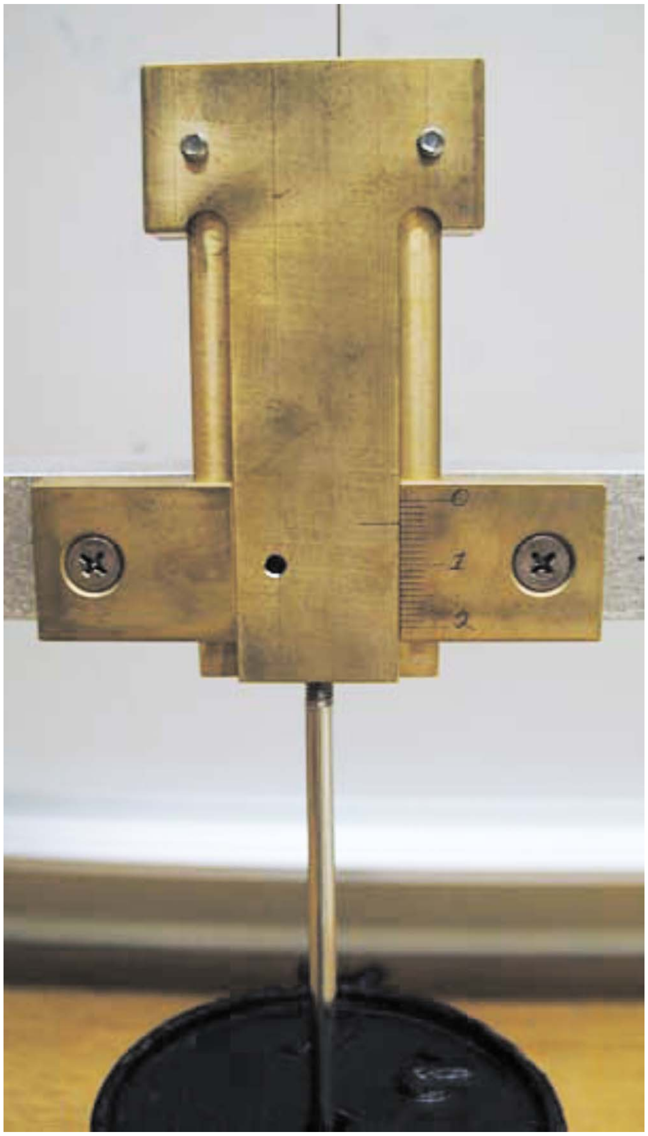

Fig. 3. A close-up view of the brass scale used to measure the stretch of the wire in the Young's modulus apparatus. The vertical piece is attached to the wire and slides through a slot in the horizontal piece, on which are millimeter markings.

and compare the period seen in the graph with the observed period. (In the course, students are also introduced to the analytical solution for a one-dimensional oscillator.) Figure 4 shows student output of an extension of this model of the experimental apparatus to nonplanar three-dimensional oscillations of the hanging mass. This three-dimensional model is further extended to include graphs of kinetic energy, spring potential energy, gravitational potential energy, and total energy. An advanced project involves adding air resistance or sliding friction.

IV. LABORATORY REPORTS

We do not have students write long formal laboratory reports. We want them to focus on the key issues, not to spend time describing the equipment, for example. We do monitor their group work during the laboratory, and we ask follow-up questions in homework and on tests.

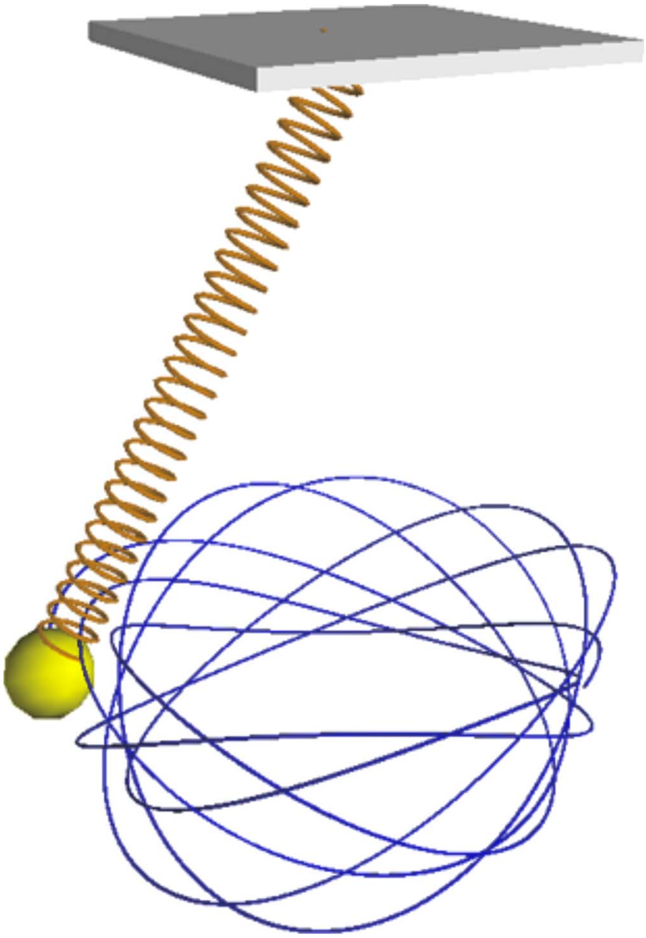

Fig. 4. Output of a student's VPYTHON program illustrating nonplanar oscillations.

For the computational modeling done in the laboratory, each group turns in their program, which is run by the teaching assistant to assign a grade. Because the output of these VPYTHON (Ref. 6) programs is a three-dimensional visualization, grading is rapid since it is almost impossible for an incorrect program to produce correct 3D motion. There are also accompanying WEBASSIGN (Ref. 7) problems, which ask students questions that require running their program with stipulated parameters.

V. APPROACH

In the SCALE-UP context there are communication-oriented goals in addition to the lab-oriented goals we have described, and they flavor the students' entire laboratory experience. Students should be able to express their understanding in written and oral forms by explaining their reasoning to peers, demonstrate their knowledge and understanding of physics in written assignments, discuss experimental observations and findings, present a well-reasoned argument supported by observations and physical evidence, evaluate oral arguments both their own and those espoused by others, function well in a group, and evaluate the functioning of their group.

These goals are different than what is often seen in traditional physics courses and stem from the philosophy of the SCALE-UP approach. Aspects of these goals are also found in the laboratory component of the lecture/laboratory M&I curriculum. In both contexts we have relied heavily on the design of formal groups and group roles done at the University of Minnesota.[8] Teams of three students are assigned by an algorithm in WEBASSIGN. These students work together for several weeks before being reassigned to a different team. For any given day of a laboratory or SCALE-UP class meeting, each student is given a specific role: Manager, skeptic, or recorder. The students and teaching assistants receive training in how to ensure fruitful team collaboration. Details of teammate assignment as well as how we conduct our training, including videos of successful and unsuccessful groups, are available in Ref. 2. WEBASSIGN further supports collaboration by allowing only the recorder to submit materials for the group.

VI. ADDITIONAL RESOURCES

We call your attention to additional resources besides the M&I (Ref. 1) and SCALE-UP (Ref. 2) websites we have mentioned. Students use VPYTHON to do computational modeling in which navigable 3D animations are side effects of computations.[6] A collection of computational modeling activities used in Spring 2007 in the lecture/laboratory curriculum is available.[9] There is ongoing work to improve instruction in computational modeling. A recent development is the creation of short instructional videos on VPYTHON that may be more useful than written instructions.[10]

ACKNOWLEDGMENTS

Robert Morse, Priscilla Laws, and Mel Steinberg stimulated our thinking about experiments that involve simple equipment. These developments were supported in part by the FIPSE program of the U.S. Department of Education through Grant Nos. PB116B71905 and P116B000659 and by the National Science Foundation through Grant Nos. MDR-8953367, USE-9156105, DUE-9554843, DUE-9752313, DUE-9972420, DUE-9981107, DUE-0127050, DUE-0237132, DUE-0320608, and DUE-0618504.

---

[1] Ruth Chabay and Bruce Sherwood, *Matter & Interactions*, 2nd ed. (Wiley, Hoboken, NJ, 2007) See ⟨matterandinterations.org⟩.

[2] You will need to request permission to access the instructional materials available on the SCALE-UP website ⟨scaleup.ncsu.edu⟩. SCALE-UP ⟨scaleup.ncsu.edu/groups/members/wiki/e355b/NCSU_Physics_Goals.html⟩ are listed in detail.

[3] Brandon Lunk and Robert Beichner, "Exploring magnetic fields with a compass" (submitted).

[4] E&M kit procurement information is available at ⟨matterandinteractions.org⟩, and a commercial version is available from Pasco, ⟨www.pasco.com⟩, item EM-8675.

[5] R. Chabay and B. Sherwood, "Computational physics in the introductory calculus-based course," Am. J. Phys. **76**(4), 307–313 (2008).

[6] At ⟨vpython.org⟩ you can download VPYTHON installers at no cost for Windows, Macintosh, and Linux.

[7] See ⟨www.webassign.net⟩.

[8] P. Heller, R. Keith, and S. Anderson, "Teaching problem solving through cooperative grouping. Part 1: Group versus individual problem solving," Am. J. Phys. **60**(7), 627–636 (1992); P. Heller and M. Hollabaugh, "Teaching problem solving through cooperative grouping. Part 2: Designing problems and structuring groups," *ibid.* **60**(7), 637–644 (1992). Also see ⟨www.co-operation.org⟩.

[9] You will need to request a password to open the zip file of computational modeling activities from ⟨compadre.org/portal/items/detail.cfm?ID=5692⟩.

[10] See ⟨youtube.com/vpythonvideos⟩.