5

THOUGHTS ABOUT LABS

5.1 INTRODUCTION

A brief history of the *Six Ideas* lab program at Pomona College

A solid laboratory program is an essential part of any introductory physics course. The IUPP project directors strongly wanted each IUPP model curriculum to have an associated lab component. As Dr. Alma Zook (of Pomona College) and I developed the original *Six Ideas* laboratory program, we designed primarily to give students an interesting and engaging lab experience and develop their skills with regard to uncertainty analysis, experimental techniques, and technical writing. We found that our lab program was largely successful in meaning our goals except for the first one: students did not find the lab particularly interesting and considered it a lot of work for little perceived benefit. (Official IUPP evaluations found our lab no different from traditional labs in this regard.) This was in spite of the fact that our own evaluators found the students' writing and analysis skills were noticeably improved by this program over traditional instruction.

There was one IUPP lab program that (according to official evaluations*) *did* seem to engage students' interest and motivate them to learn. This was the program designed by Dwight Neuenschwander and others for the IUPP model *Structures and Interactions*. My colleagues (including Alfred Kwok, Richard Mawhorter, David Tanenbaum, and Susan Melnik as well as Dr. Zook) have worked hard during the past several years to adapt some of Neuenschwander's ideas for our situation. The resulting program has been much more successful.

This chapter will focus on general principles

It is probably impossible to design a detailed laboratory program that would work at every institution. The constraints imposed by the nature of the teaching staff, facilities, lab equipment, and student population vary too widely from institution to institution. I therefore offer the Pomona program only as a case study for how one might develop a reasonably successful lab program based on results emerging from the IUPP process.

An overview of the chapter

I will describe our institutional constraints and goal in **section 5.2**, features of Neuenschwander's program in **section 5.3**, the structure of our lab program in **section 5.4**, a discussion of its advantages and problems in **section 5.5**, and a general list of things that we have learned in **section 5.6**. While I will basically only discuss general principles in this chapter, the the *Lab Reference Manual* and experiment descriptions that we hand out to students are available as PDF files on the *Six Ideas* web site.

5.2 OUR INSTRUCTIONAL GOALS

Basic parameters

Students at Pomona register for a lab section that meets between 1:15 pm to 5:15 pm on a given weekday afternoon. We usually have about 12 weeks of lab during the fall semester and 13 during the spring semester.

Our lab room has six lab stations, and therefore will hold 24 students working in groups of 4 (or paired groups of 2) or 18 students working in groups of 3. We usually run the lab in the latter mode. Each lab session is staffed by a professor and two undergraduate TAs.

The *Six Ideas* lab program at Pomona has four primary educational goals:

*See L. A. Coleman, D. F. Holcomb, and J. S. Rigden, "The Introductory University Physics Project 1987-1995: What has it accomplished?" *Am. J. Phys.* **66**(2), pp. 124-137 (1998).

Our primary educational goals

1. to give students "hands-on" experience with a variety of phenomena,
2. to develop basic laboratory skills (such as appropriate presentation and analysis of graphs, basic uncertainty analysis, and so on),
3. to explore topics better treated in lab than in class (e.g. circuits, optics),
4. to develop students' technical writing skills

In our case, is particularly important that the lab develop students' uncertainty analysis and graphing skills, because the introductory physics course is supposed to satisfy a Pomona College general education requirement in "data analysis." These elements are therefore somewhat more fully emphasized than would be necessary at another institution. Specifically, our lab program seeks to develop the following analysis skills (in roughly sequential order):

Data analysis skills

1. understanding sources of experimental uncertainty and how to quantify it
2. presenting and interpreting simple graphs (with uncertainty bars)
3. using linear regression to determine a slope (and its uncertainty)
4. plotting linear graphs of non-linear relationships
5. understanding the uncertainty of the *mean* of a set of measurements
6. finding the uncertainty of a calculated quantity
7. testing theoretical relationships (taking account of uncertainty)
8. using and interpreting log-log graphs of power-law relationships
9. using and interpreting semi-log graphs of exponential relationships
10. recognizing and eliminating systematic effects

In addition, we wanted to help students learn how to write a coherent five-to-six page lab report in a format similar to a journal article. We teach this during the first semester but students practice this most during the second semester.

5.3 A "LAB BEFORE LECTURE" STRUCTURE

A description of Dwight Neuenschwander's lab program

Dwight Neuenschwander and co-workers developed a very creative lab program for his IUPP model course entitled *Structures and Interactions*. Results from the IUPP evaluation team indicated that this lab program was more successful (particularly with regard to student attitudes) than both traditional lab programs and other IUPP programs (including the *Six Ideas* program). These results make this model worth considering.

This lab program was constructed so that a selected set of ideas are developed in lab *before* they are developed in lecture. This means that labs and lectures are closely linked and that all labs are by their very nature discovery-based labs.

The actual lab exercises were structured as follows. Students are divided up into teams of three or four and are given only brief written instructions (that primarily describe the purpose or goal of the lab) and similarly brief oral instructions focus on introducing the equipment that they might use. The teams are then left to design the experiment on their own. After the teams struggle with this for 20 minutes or so, the lab staff-members begin to circulate, discussing with each team their approach to the problem, offering suggestions, and asking searching questions. In the process, the instructors guide each team toward a fruitful way of doing and analyzing the experiment, but this arises of discussion with the students rather than being provided to them in advance.

When a team thinks that they have completed their work, they bring their work to a lab staffer for a checkout interview. The staffer asks questions that probe the quality of their work. If they are unable to answer some of these questions, the staffer may send them back to their lab station to explore the answers. Students are assigned a *team* grade based on their performance in this checkout interview and whether or not they had to be sent back to their lab station to improve their work. No written work is assigned or graded: students are done with the lab when their evaluating instructor finally allows them to leave.

IUPP evaluation results for this lab program

Evaluations indicated that students appreciated a number of things about this lab design. Students liked the grading system, partly because it did not require

any written work, and partly because (as some admitted in an internal IUPP report I saw) it was pretty easy to snow the lab TA during the checkout interview. In their published IUPP report [*Am. J. Phys.* **66**(2), 1998], Coleman, Holcomb, and Rigden describe the response of a number of students that formal lab reports "make the lab seem really terrible and not as fun to go to," as one put it.

But Neuenschwander's lab was not popular simply because it involved less perceived busywork. Students genuinely appreciated the discovery aspect of the lab program, and they *especially* liked the fact that the lab and class were so tightly coordinated. Students in the Neuenschwander lab program were much more likely to claim that the labs were valuable and contributed to their learning compared to comparison groups in traditional lab programs.

5.4 POMONA'S CURRENT LAB STRUCTURE

The "lab before lecture" aspect is difficult to emulate

Unfortunately, the lab program at Pomona has been traditionally fairly disconnected from the class, and (because it is hard to develop good new labs from scratch) this has put some constraints on more closely linking the class and lab. The requirement that we teach data analysis in a logically coherent and sequential manner makes this even harder, because it is hard to find the right experiment that simultaneously involves the right data analysis skill *and* helps students make discoveries about an important topic discussed the following week of class. Therefore, in spite of the strong payoff for better class-lab integration, we have not done this nearly as well as we would like yet.

We have been more successful in adapting individual labs to make them more oriented toward "discovery" and in adapting the checkout-interview approach to evaluation (with some modifications to avoid potential problems). We currently structure the lab as follows.

The structure of our labs

Each lab has a specific, easily-stated *goal* described on a single sheet of paper handed out at the beginning of lab. Students work in teams of *three* to design an experiment to accomplish that goal with the available equipment. Students are graded as a *team* on the basis of the quality of responses to questions posed during a checkout interview.

The TA Guide

Before each lab, each lab assistant is given a TA's Guide that describes in some detail the educational goals of the lab, at least one approach to accomplishing the stated goal, pitfalls that students might encounter, questions to ask during the checkout interview, and how to grade responses to those questions. The last two items is important because it enables checkout interviewers to be more consistent and objective in their evaluation of team performance. The TAs are also given several copies of a grade worksheet for recording team grades.

Weekly TA meetings

Since our lab assistants are generally undergraduates, we have found it *very* helpful to hold a 2-hour meeting before the lab begins each week so that the lab assistants can go through the lab exactly as if they were students in the course. This not only makes them thoroughly familiar with the lab but helps them experience what the the process is like for the students (as well as exposing bugs and possible pitfalls).

Helpers and graders

During each lab session, a certain lab staffer is designated as a given team's **grader**; this is the person that conducts the checkout interview. A *different* staffer is designated as the team's **helper** (sometimes we call this person the team's "guardian angel"). The helper's job is to respond to questions, pose leading questions, protect students' safety, nudge them to do the right things, and generally be helpful without telling the team what to do. The helper (who has seen the TA's Guide) knows the questions that the grader will ask, and can therefore help the team prepare for the interviews. Helpers also look to see that each student pulls his or her weight. Both roles rotate among the lab staff during the semester so that each team is evaluated fairly. (In an 18-student lab with three staff, this means that each staff person is a helper for two student teams and a grader for two teams.)

We have found that separating these roles is *very* important. It enables the undergraduate graders to be tougher and more demanding, and reduces the likelihood that they will be snowed. It also reduces possible sources of conflict of interest and trust. The team can completely trust their helper to be as helpful as possible (without doing the work for them), and the team will understand why the grader needs to have everything explained carefully and can expect the grader to be tougher and more demanding than their gentle helper.

Some labs have pre-lab exercises that must be completed before students come to lab. When the lab begins, each team's grader will evaluate the pre-lab work, recording their scores directly the grade sheet.

Student roles

During each lab, each team designates a member to be responsible for each of the following roles.

1. The **Recorder** is responsible for keeping a careful record of lab procedures, observations, and measurements in his or her lab notebook. This will serve as the team's record of the lab.
2. The **Procedure Supervisor** is responsible for understanding the group-developed procedure, making sure that it is followed, and generally keeping the group on task and working efficiently.
3. The **Skeptic** is responsible for worrying about what the grader will think and anticipating questions he or she will ask, for making sure that uncertainties are analyzed carefully and work is done correctly, for making sure that everyone completely understands the lab completely, and for thinking about safety issues.

The team should rotate these roles so that everyone gets a chance to experience each role.

Procedure and checkout interviews

The team asks their helper for a ***procedure interview*** when, after playing with the equipment and talking (but before taking data), the team thinks that it has devised a workable procedure for addressing the lab's goal. The helper will ask the team some questions to make sure that the procedure is realistic and that the team has anticipated possible problems. The team asks for a ***checkout interview*** when it has accomplished the lab's goal and feels that each team member fully understand the lab and what the results mean. The grader then looks at the Recorder's notebook and asks specific team members questions designated in the TA's Guide (which are keyed to the team roles) so as to explore the team's understanding of the lab. He or she also asks the team to reflect on how they could have done the lab better, both with regard to lab procedure and to working together as a group.

Grading the checkout interview

The checkout interview grade depends on the quality of the answers provided by *whoever the grader asks*. (The TA's Guide generally specifies which person should answer each question.) A student should *not* respond to a question unless the grader asks that person directly (even if he or she knows the answer). This helps ensure that each team member not only takes responsibility for his or her role but also for helping *everyone* in the group understand the lab fully.

At the end of the interview, the grader will assign a score out of 20 points (including any pre-lab points). The grader should some feedback about how well the team did and offer suggestions for future improvement. The grader then gives the completed grade sheet with the recorded score to the lab instructor before the end of the lab.

Special labs with writing assignments

One lab during the first semester (traditionally, the "simple pendulum" lab) and *two* labs during the second semester are treated differently. For these labs, (1) teams can assign the roles as they see fit (rather than following the strict rotation), (2) the team's *helper* conducts the checkout interview (to give the team feedback) but does not grade them, and (3) students are instead graded *individually* on first and final editions of a ***full lab report*** describing the lab. We generally create the lab syllabus so these labs happen during the second half of the se-

mester, but not right at the end (as students are usually struggling with other papers at the end of a semester). Students are also given a detailed description, with examples, of how a full lab report should be written.

The revision cycle for the lab reports

The first edition of each lab report is due at the beginning of lab the week after the corresponding lab. The following week, each student has a half-hour interview with that student's grader, who will give the initial draft a grade (out of 20 points) and make suggestions about how you can improve your work for the final edition. The final edition is due at the beginning of lab a week after the interview and is graded by the same grader on a 40-point scale. The first edition is graded mostly on effort, while the second edition is based on quality. We have found it useful to give the students a copy of the grading sheet that the graders use (though perhaps with some details obscured). We have also found it very important that the grader project what final grade the first edition would earn if submitted unchanged as the second edition.

See the web site for more details

This gives a broad outline of the lab structure, but the fine details of implementation can often make a tremendous difference. Moreover, I have not described the specific labs or how we have tried to achieve our goal of teaching good lab analysis skills. If you are interested in learning about Pomona's lab program in more detail, please refer to the materials posted on the Six Ideas web site. These materials include the experiment descriptions we give to students, the *Lab Reference Manual* that students read to learn about data analysis skills, and the TA Guides for the various labs.

5.5 STRENGTHS AND WEAKNESSES

Strengths of this lab structure

This lab program has a number of advantages over a traditional lab structure while addressing some of the problems of Neuenschwander's system.

1. **Students do much less tedious writing** than in a traditional lab where students have to hand in a lab report or lab notebook. This alone makes students much happier about the lab! (This also reduces the tedious grading work that lab staffers must do.)
2. **However, students still do *some* writing.** This helps address our goal that students learn technical writing skills.
3. **The writing involves a revision cycle.** Having the revision cycle has proved to be much more valuable in teaching good writing and report style than having multiple writing assignments.
4. **The lab is more discovery-oriented** than a typical "cookbook" lab, yet the procedure interview and the presence of a designated helper means that students will not end up going too far astray. This makes the lab more interesting to students and helps them practice experiment design skills.
5. **Checkout grading is more objective.** The combination of having a TA's Guide that spells out checkout-interview questions and splitting the roles of helper and grader has helped make the grading process more reliable and objective.
6. **The grading system reinforces peer instruction.** The fact that each team gets a group grade based on the performance of individual members means that there is a strong incentive for team members to help each other understand the lab.
7. **Undergraduates can be good TAs in this system.** The weekly TA meeting has greatly improved the quality of help from TAs. (I think that even if I had graduate TAs available, such a meeting would be valuable.) The reduction in writing to grade also helps TAs focus on doing a better job of grading the written work that *is* required.

Remaining problems with our lab program

There do remain some problems with this struucture that we would still like to address.

1. **The grading scheme does not really distinguish weak students from strong students.** Students accept team grades as long as everyone's final grades are reasonably good. We have therefore generally treated the grade as a recognition of effort and as a goad to collaborative learning rather than a tool for distinguishing poor students from good students. Most of the interview scores we give end up in the 16 to 20-point range.
2. **Grading is still not perfectly objective.** In spite of the TA Guide, student TAs still find it tough to grade peers as harshly as professors will, even when a team's performance is pretty poor.
3. **There often is a crunch at checkout time.** The workload for TAs is fairly light until near the end of the lab. Then the two teams a TA is helping often want help preparing for the checkout interview at the same time the two teams the TA is grading are asking for checkout interviews. We have found that it helps to allow teams to get pre-checkout help from a TA who is not their helper, but we have also thought about importing extra graders during this crunch time, because if teams are left waiting too long, morale can really suffer. Another possiblity would be to stagger starting times by an hour or so, so that fewer groups finish at the same time.

We also still do not have the level of coordination between the class and lab that we would like, and some of the individual labs in our current program are weak and/or run too long. But other than these problems, we have found that this system works much better for us than anything else we have previously tried.

5.6 SOME LAB DESIGN WISDOM

Things we have learned from a decade of trying to improve our lab program

Our experience at Pomona and the results discussed in the IUPP evaluation also suggest the following general principles as helpful guidelines for someone designing a lab program.

(1) **Develop a "written tradition" for lab staffers** (instead of relying on an oral tradition). Since both undergraduate TAs and faculty lab instructors rotate in and out of the labs in unpredictable ways, we have found that the quality of instruction improved greatly when we made a detailed "written tradition" of information about the labs available to all lab staff. This TA's Guide included descriptions of common conceptual problems, things that students generally do wrong, instructional strategies that have worked, safety issues, and other strategies for making the lab go more smoothly. As mentioned before, we found it very valuable to hold weekly staff meetings during the year to discuss the labs just completed and possible changes and/or additions to the TA's Guide (as well as to look ahead to the next lab). The result (over a period of five years or so) has been much better lab instruction and better and cleaner labs. This is probably the single most useful thing we learned during our reform work at Pomona!

(2) **Think clearly about your goals for the lab.** Our lab program demonstrates that it really *is* possible to create a lab program that improves selected laboratory skills. Think carefully about what *you* want students to take away from the lab. If such reflection reveals skills that are especially important to you, then think about how you can create labs that specifically develop these skills. Conscious development of such labs can really pay off.

(3) **Select only your most important goals for development**. It is very easy in thinking about goals to write down a huge list of things that you would like students to be able to do. A two-semester lab program only allows time to develop a handful of skills well. Prioritize your goals, and make *sure* that your lab program develops the four or five most important in depth. Don't

let your ambition to teach students everything make the labs so complicated and challenging that the students don't have time to learn *anything* well.

(4) **Don't try to "cover" too much in a given lab.** A given lab exercise should focus on a *single* physical idea in conjuction (perhaps) with a *single* skill or lab analysis concept. We felt that students would best learn an idea when it is highlighted for their attention: if graphing skills *and* propagation of uncertainty *and* linear regression are all presented for the first time in one project lab, students are not going to be able to give each skill enough attention.

(5) **Connect labs to the class** (as much as possible). One of the clearest findings of the IUPP evaluation group was that students really appreciate (and report better learning) if labs are connected in a vital way to the class material. This is therefore worth doing to the extent possible.

(6) **Don't make students verify; let them discover.** A number of faculty groups (including the IUPP Laboratory Group early in the IUPP process) have recommended this approach to labs, educational research tends to support this (see also the positive results concerning the Neuenschwander lab described above), and our experience shows that students enjoy this approach much more. At the same time, our experience is that while it is easy to create "verify" labs, it is hard to design really good "discover" labs. We all have an almost ingrained desire to have students see that what we are talking about in class really works, and though this is perhaps better done with demonstrations, many lab programs are designed around the opposite of this principle.

(7) **Describe labs in appropriate detail.** If students are given too little information about a given lab (particularly if there is no well-developed "written tradition" about it among the lab staff) they feel helpless and frustrated and are angry when they are graded on things they didn't know were important. Too much information lets them to get through the lab without thinking (and they will deride the labs in evaluations as being too "cookbooky"). Achieving an appropriate balance is tricky, but doing it well is very important. This balance probably should probably shift during the year to encourage students (once they have some skills) to become more self-reliant. Our goal (now that we have set up a good "written tradition" is to keep lab descriptions to a single side of a sheet of paper.

(8) **Don't be too ambitious about reform.** When we began to reform the lab program at Pomona, we almost completely replaced our entire set of experiments and our entire approach to the lab in one fell swoop. What can I say? We were young. We were innocent. Then we were exhausted. Moreover, our rapid-fire approach to inventing new labs meant that a number of labs did not work very well and were frustrating or confusing to students. My earnest advice to eager reformers is that one can do a *good* job developing maybe two new labs a summer if one is doing something else, and *maybe* three or four if that is one's sole objective for an empty summer. Plan ahead for what you would like to do and then work through your plan deliberately and carefully over a period of years. You and your students will be much happier.