

# Transforming the advanced lab: Part I - Learning goals

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**Abstract.** Within the physics education research community relatively little attention has been given to laboratory courses, especially at the upper-division undergraduate level. As part of transforming our senior-level Optics and Modern Physics Lab at the University of Colorado Boulder we are developing learning goals, revising curricula, and creating assessments. In this paper, we report on the establishment of our learning goals and a surrounding framework that have emerged from discussions with a wide variety of faculty, from a review of the literature on labs, and from identifying the goals of existing lab courses. Our goals go beyond those of specific physics content and apparatus, allowing instructors to personalize them to their contexts. We report on four broad themes and associated learning goals: Modeling (math-physics-data connection, statistical error analysis, systematic error, modeling of engineered "black boxes"), Design (of experiments, apparatus, programs, troubleshooting), Communication, and Technical Lab Skills (computer-aided data analysis, LabVIEW, test and measurement equipment).

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## INTRODUCTION

At the University of Colorado Boulder (CU), we are transforming our upper-division undergraduate physics lab using the approaches of physics education research. There are at least two compelling reasons to do this. First, ambitious goals for this senior-level course set a target for the rest of our lab curriculum. Second, the advanced lab represents the intersection of three areas that are ripe for more study within PER: lab courses, upper-division courses, and technology.

The advanced lab course has a number of unique opportunities, including sophisticated equipment, extended design projects, and small class sizes. At the same time, these labs can prepare students for opportunities to be had through undergraduate research experiences (mentoring, long-term work on challenging real-world problems, collegial relationships with professionals and peers) [1]. It is natural to ask how we can use these resources to best prepare students to have meaningful research experiences and for graduate school or the workforce.

We are modeling our lab transformation after previous transformations conducted at CU through the Science Education Initiative [2]. First, we establish clear goals, and then develop instructional materials and assessments that mutually align. In this paper we only discuss the first step—learning goals. Subsequent papers will document our instructional materials and assessments.

Our pre-transformed advanced lab course at CU is in many ways typical. For example, the lab is not linked with any lecture courses. There are two one-hour lectures per week associated within the lab course, but

these lectures periods are not explicitly aligned with the activities going on in lab. The existing lab content is broad, ranging from nuclear physics (gamma ray spectroscopy), and particle physics (cosmic ray muon lifetime), to condensed matter physics (scanning tunneling microscope, NMR), AMO physics (saturated absorption spectroscopy, magneto-optical trapping), and physical optics (diffraction, interferometry, polarization). The equipment ranges from basic to highly sophisticated. Students select a subset (4 to 6) of these lab activities to complete during the semester, and they conclude with a five-week final project intended to allow students to demonstrate independence and creativity in the lab. The goals of the guided labs vary, but they typically focus on content mastery, measurement methods, and error analysis. The lab guides have straight-forward procedures and little open-ended decision making. There is little emphasis on applications of physics, but rather a focus on the fundamental ideas of physics. The formal assessments are written lab reports and oral presentations due after completing the lab.

## A FRAMEWORK FOR TRANSFORMING LABS

In the process of transforming our own course at CU, we are creating a framework and accompanying resources for instructors to modify and/or develop lab exercises that move beyond a traditional advanced lab course. Such a framework must start with clear learning goals stating what students should be able to do by the end of the course. The learning goals are designed to span the

skill set used by professional physicists. Course structure and individual labs need to be aligned with these goals. Equally importantly, assessment should move beyond written lab reports as the primary (summative) form of assessment [3]. Pre-post assessments need to be developed to gauge learning and measure the effectiveness of the transformation. Formative assessments should be integrated into the lab guides to provide constant feedback so students can take control of their own learning. The assessments should span the range of cognitive skills and avoid the tendency of many labs to focus on lower Bloom's-level skills [4].

Our transformation seeks not to radically change the existing physics content nor the apparatus. The first reason for limited change is to keep the cost of the transformation as low as possible. The second is that the physics content and apparatus are highly dependent on institutional resources and interests of the instructors. Research on the dissemination and sustainability of educational innovations indicates curricula that support instructors in adapting materials to their own purposes, such as the Modeling Instruction program, are more likely to be adopted and sustained [5, 6]. We are focusing on scientific reasoning, communication, and general purpose lab apparatus that can be adapted in a variety of ways by the faculty at CU and by an active and growing community of advanced lab instructors who are part of the Advanced Lab Physics Association (ALPhA). In this paper, we focus on learning goals. Other parts of the framework, such as assessments and curricular materials, will be shared as they are developed.

## Methodology

We began establishing learning goals by interviewing 15 faculty. During interviews, some questions were unguided such as: "*What is the purpose of a good lab course?*" Some questions explicitly addressed learning goals such as: "*What is the goal of communication in the course?*" Other questions implicitly addressed learning goals: "*What abilities do you look for when hiring an undergraduate researcher, or a new graduate student?*" A draft set of learning goals was then given to the faculty and was discussed at two working group meetings (9 faculty per meeting) in order to establish a set of consensus goals. Altogether, 21 faculty were involved in the process (8 AMO, 3 Condensed Matter, 3 High Energy Particle, 2 Plasma, 3 PER, and 2 Mechanical Engineering). We also built upon existing statements from the AAPT regarding the introductory physics laboratory [7], and also upon goal statements from the advanced lab community [8].

Four broad categories of learning goals emerged from

the literature review, interviews, and discussions: *Modeling, Design, Communication, and Technical Lab Skills*. The learning goals are an ambitious change from our previous course, meaning that it is unlikely that students will master them in one course. However, they set the bar for where we want physics majors to be when they complete their degree, and hopefully, over time, the earlier lab courses will align to create a more cohesive lab curriculum.

## LEARNING GOALS

### Modeling

Modeling, and more specifically, Modeling Instruction, was developed as a way to explicitly incorporate the thought processes of professional physicists into the undergraduate physics curriculum [9]. Despite an initial hope that "...modeling theory should appear obvious to physicists..." [9] it has found its greatest adherents in a thriving community of high school teachers through the Modeling Instruction program. Only recently has the introductory college-level curriculum begun to incorporate modeling [10].

A model is a conceptual representation of a real system, and in physics the most common and powerful representation is usually mathematical. The common traits among models are (1) they are simplified versions of objects and their interactions, (2) they have predictive power, and (3) they have a limited range of applicability [11]. A synthesis of our learning goals has showed that modeling can serve as a unifying principle for a variety of learning goals common to the traditional physics laboratory courses. In addition, modeling makes explicit the nature of science. Four sub-goals fall under the theme of Modeling.

**Math-Physics-Data connection:** Throughout our upper-division course transformations at CU, faculty have stated that students should be fluent in translating mathematical representations into physical problems and vice versa. In the theoretical courses, this was called the "Math-Physics connection." Additionally, in a lab class we require that students are fluent in translating between their noisy and incomplete data and both the mathematical representation and the physical system being studied. Additional support for this learning goal came from many faculty who believe that the best labs are quantitative and rich with physics content, creating a natural opportunity for connecting the mathematical models, data, and the physical system.

**Statistical error analysis:** The importance of comparing data with theory is one universal feature of physics lab courses. The statistical procedures are codified in

widely used textbooks on error and data analysis [12], and the PER community has devoted attention to the matter [13, 14]. Error analysis at CU starts in the introductory physics lab, yet some students struggle with the basics in the advanced lab. Error analysis at CU has also neglected certain related topics such as analysis of distributions and time-series measurements. Also, error analysis and statistical analysis have rarely been used to solve authentic problems where the analysis itself impacts a decision. Error analysis, in the context of modeling, then becomes one part of the process of developing, testing, and refining models.

**Systematic error analysis:** An understanding of systematic error or "systematics" (i.e., a repeatable deviation in the measurement from an idealized model) was identified by faculty as an attribute of sophisticated student reasoning. Yet, in the pre-transformed class, systematic error is rarely explicitly brought up. Conveniently, systematic error is one of the most natural places for modeling in the advanced lab. For example, when source of the systematic error is the measurement device, the model of the measurement tool is too simple or incorrect. The process of improving the model of the measurement device is commonly called "calibration." If the systematic error source is not in the measurement device, but rather the system itself, we can either try to construct a more ideal apparatus, or extend the theoretical model of the system to include these non-idealities. Either way, an explicit focus on modeling changes systematic error from being an often neglected sibling of statistical error analysis into a natural and prominent part of the modeling process.

**Modeling "black boxes":** There is no escaping sophisticated experimental equipment in the lab. Common examples include photodiodes, lasers, oscilloscopes, multi-channel analyzers, lock-in amplifiers, and LabVIEW. The benefits of black boxes to students and researchers are unquestioned, but they increase the separation between the physical system and the student. Faculty are concerned that when the separation between the student and the physical phenomena is too large, the lab experience becomes meaningless. Such concerns are not new and are sometimes explicitly addressed in the introductory physics lab [15]. However, we think modeling guides this process of deconstructing black boxes in a very clear way. For example, just as models of natural systems are testable, students should be able to test and refine their models of a black box.

## Design

Our current lab course has many "cookbook" labs that lead students through a specific procedure, which begins with the construction of the apparatus and ends with a

statement about what quantities and plots should be presented in the lab report. Faculty are concerned "cookbook" labs keep students focused on lower-order cognitive processes during the lab. By incorporating design, we plan to engage students more frequently in this higher cognitive level process usually categorized under "synthesis" or "create" in the Bloom's taxonomy. Research indicates that incorporating design activities keeps students on-task and working at a higher cognitive level during the lab [16].

The first sub-goal within design is that student should be able to design experiments to test a model or a hypothesis. This is very similar to a variety of inquiry-based labs, which allow students some role in determining the procedure and apparatus needed to do the experiment [16]. The second sub-goal is engineering design. In engineering design, we apply our understanding of physics to design a product that meets a particular application within certain constraints (e.g., cost, time). The third sub-goal is troubleshooting—the ubiquitous process of tracking down and solving problems in an experiment or engineered device. Students already engage in troubleshooting because in any lab something inevitably doesn't work as expected. Our goal is to turn this from a haphazard process into a more systematic, expert-like approach.

## Communication

Discussions surrounding communication in the lab course showed that many faculty believe scientific writing and communication are some of the most valuable skills learned as a physics major. At the same time, faculty acknowledge student writing does not typically meet their expectations; it is time consuming for students to produce; and it is time consuming to grade. Research indicates that writing skills learned in a freshman writing course are difficult to transfer [17], leading to poor writing in lab courses. After all, the communication in the lab course is about a specific subject matter, uses technical vocabulary, and is in genres specific to the physics community. All of these must be mastered to become a good scientific communicator [17]. In response to these concerns and evidence from the literature, two sub-themes emerged for communication in the advanced lab course.

The first is *argumentation*. Faculty believe that, though students spend considerable time writing lab reports, their writing often lacks a coherent and convincing argument. In response, our learning goals for the transformed course emphasize good scientific argumentation, which can be defined as the supporting of *claims* with *evidence* through *reasoning* [18]. Argumentation has seen increasing emphasis throughout science education because it makes the process of scientific reasoning more explicit

[19].

The second sub-theme is *integrating students into the discourse of the physics community*, which can be summarized by *authenticity*, *audience*, and *alignment* [20]. Authenticity, applied to lab courses, means the communication should represent authentic forms for the discipline. Audience means that for genuine communication to take place the readers or hearers should not merely be graders, but should be actively trying to make sense of the presentation. Alignment means the communication activities should line up with the purposes of the lab, and need not have the same form for all parts of all lab courses.

### Technical Lab Skills

The faculty agreed on setting course-wide learning goals for all students for three technical lab skills: (1) using computers for data analysis, (2) using LabVIEW for computerized measurement and automation, and (3) using basic test and measurement equipment like oscilloscopes and photodiodes. Although faculty believe there are many other relevant technical lab skills, such as alignment of optical systems, they are more specialized and will be restricted to particular lab activities where they are relevant, but not for all students in the course.

### CONCLUSIONS

Through discussions with faculty and a review of the literature, a set of learning goals was developed for the advanced undergraduate physics lab course at the University of Colorado Boulder. While the learning goals fit well with many of the traditional aims of the undergraduate physics lab, the broad themes of Modeling, Design, Communication, and Technical Lab Skills bring the advanced lab closer to the innovative reform efforts seen at the introductory level. Over the next two years, a revised advanced lab course with assessments will be implemented based on these learning goals. The framework developed here is designed to encourage sustainability and innovation in labs at CU and enable transfer to other institutions seeking to modify labs.

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