Guidelines for Undergraduate Physics Labs

The undergraduate laboratory is an essential part of the physics curriculum because physics is inherently an experimental science. There are various documents discussing the goals and purpose of the undergraduate lab; however, the last AAPT policy statement on Introductory Lab Goals was approved in 1997.[1] During the last several years, increasing attention has been paid to the importance of the laboratory in physics instruction. The Physics Education Research Community has begun looking at the goals of the advanced undergraduate lab;[2-9] laboratory practices are being incorporated into the new AP Physics 1 and 2 courses for high school students;[10] and there are new high school science standards (Next Generation Science Standards) likely to be implemented in many states in the near future.[11] The Advanced Laboratory Physics Association (ALPhA) has brought focus to the undergraduate laboratory beyond the first year with topical conferences and its laboratory immersions, since its inception in 2007.[12] The topic of the 2010 Gordon Research Conference on Physics Education was on Experimental Research and Laboratories in Physics Education.[13] In the past three years there have been several sessions, including four panels, at AAPT meetings on the pedagogy, goals, and assessment of the instructional labs. There has also been an effort within the AAPT to review the undergraduate curriculum, and this will soon turn into a joint review of the undergraduate curriculum by the AAPT and APS. This is, therefore, an opportune time to review laboratory goals and guidelines for all levels of the undergraduate physics curriculum.

In this laboratory guidelines document, thinking like a physicist and constructing knowledge pervades all of the specific lab goals articulated since the enterprise of physics is the construction of new knowledge. Physics is not just a subject; rather, it is a way of approaching problem solving, which requires direct observation and physical experimentation. Being successful in this endeavor requires one to synthesize and use a broad spectrum of knowledge; mathematical, computational, experimental, and practical skills; and particular habits of mind that might be characterized as thinking like a physicist. While there cannot be either a unique or exhaustive description of this behavior, the laboratory should contain experiences that explicitly support a department's goals for helping students think like physicists as it is locally conceived. Moreover, specific laboratory work often involves a wide variety of technologies, and students should become confident that they can quickly develop a working knowledge of a technology and/or seek appropriate expert technical advice. To this end, J.M. Pimbley wrote: “These days, a physics education … offers the discipline and important tools for tackling new issues. Physics is the liberal arts education for a technological society.”[14]

This document provides five focus points for the undergraduate lab curriculum. The first focus point, Constructing Knowledge, captures some of the overarching goals of the undergraduate lab curriculum while the remaining four focus points -- Modeling, Design, Technical Lab Skills, and Communication – provide concrete recommendations that will (1) train physics majors to think like physicists and perform experimental investigations at an appropriate level for graduate school or a research job in industry, (2) train future physics teachers in essential laboratory skills that they can use to develop rich courses and laboratory experiences for their students, and (3) train the introductory non-physics major to perform experimental investigations from a physicist's perspective which will broaden and strengthen their scientific endeavors in their own diverse fields.

A high-level discussion of each of these focus areas is given first followed by specific recommendations for implementation in undergraduate labs at the introductory and advanced lab levels. Some examples are also given; however, implementation of these recommendations will vary to some extent from one institution to another. Therefore, this document does not list specific equipment or software that the students must use or specific experiments that students must complete.

1. Constructing knowledge[5,6,15,16]

The lab should get students to start thinking like physicists by constructing knowledge without relying on an outside authority. Through laboratory work, students should gain the awareness that they are able to do science and build confidence in their ability to do so. Students should be able to collect, analyze, and interpret real data from personal observations of the physical world as responsible scientists.

While direct instruction can have an appropriate and justifiable use (like teaching the students how to use a measuring device properly), laboratories that consist only of following cookbook instructions or verifying well-known constants do not provide students with experiences that support the student-centered construction of knowledge based on observation. Cookbook instructions do not provide an accurate representation of the experimental process. Activities that verify well-known constants should only be employed as a component of a carefully constructed curriculum. It should be evident to the student how the activity explicitly supports one of the experience categories below.

2. Modeling[1,2,7-9]

Modeling entails developing a "conceptual representation of a real system." A model provides a link between theory and experiment and between a qualitative and quantitative understanding of a system. Models in physics tend to be mathematical in nature, but often have a computational component as well. Simulation and numerical analysis, for example, are important parts of modeling. Modeling should also make explicit the "math-physics-data connection," statistical and systematic error analysis, and understanding sophisticated equipment (i.e. demystifying so-called "black-boxes").

3. **Design**[1,3-6, 8]
   Guided inquiry or properly scaffolded open-inquiry-based labs better promote scientific reasoning than cookbook labs. Students should be capable of posing scientific questions and should be able to develop and engineer experiments to test models and hypotheses, often with certain constraints such as cost, time, and available equipment. And students should be able to troubleshoot systems using a logical, problem-solving approach. The hands-on experience of constructing an experimental set-up or apparatus and of troubleshooting it is a very important part of a laboratory experience.

4. **Technical lab skills**[1,8]
   Students should learn to make measurements using basic test equipment, correctly record these measurements, and to determine the appropriate equipment to use for particular measurements. Students should be able to use computers to acquire and to analyze data and should be able to critically interpret the validity and limitations of the data displayed. Students should develop practical laboratory skills throughout the undergraduate experience.

5. **Communication**[8,17]
   Communication is a process that involves creating and presenting results and ideas to others who are listening or reading, interpreting, and evaluating. Laboratory courses are excellent places to develop scientific communication skills, though scientific communication should be fostered throughout the curriculum as well. Students should learn to present reasoned arguments backed up by experimental evidence. Those arguments should include elements such as plots, tables, numerical results with uncertainties, and diagrams. Further, the overall format any style of presentation should be in forms authentic to the discipline: technical reports and journal-style articles, conference-style oral presentations, and scientific posters. Intrapersonal communication skills should also be developed in the lab through teamwork and collaboration.

Recommendations

Recommendations for student learning outcomes and experiences in the lab are given here for introductory and advanced lab levels. The outcomes and experiences defined at the introductory level are intended for majors and non-majors in their introductory physics sequences. It is expected that advanced lab courses will meet and reinforce the recommendations for the introductory labs and add (and reinforce whenever possible) the next layer of skills. "Advanced lab" is defined as any lab beyond the introductory lab sequence, not just for labs titled "Advanced Lab." All of these recommendations need not be built into every laboratory course. Rather, the laboratory curriculum over the course of the major should include all of these recommendations at some point. The laboratory curriculum should be a spiral or scaffolded curriculum such that students develop and reinforce their skills throughout their undergraduate years, building from the introductory labs through the advanced lab curriculum. The recommendations for Constructing Knowledge are goals to strive for and build toward throughout the entire laboratory curriculum. Some of these recommendations can be introduced in the introductory sequence, but it may not be possible to build all of these recommendations into a non-majors introductory sequence. The recommendations for the other four focus points are broken into introductory and advanced lab recommendations in tables below. Some examples and discussion are also given in the table for these recommendations.

1. Constructing Knowledge	**Recommendation**	**Discussion/Examples**
The lab should get students to start thinking like physicists by constructing knowledge that does not rely on an outside authority. Through laboratory work, students should gain the awareness that they are able to do science and build confidence in their ability to do so. Students should be able to collect, analyze, and interpret real data from personal observations of the physical world as responsible scientists.	Students should be able to generate questions that they would like to explore, determine which questions can be answered through the development of appropriate experiments, and understand the limits of experimentation. When questions are poorly designed or not testable, students should be able to revise them.	Students should be provided multiple instances during the four year curriculum where they clearly see the entire cycle from asking a question to deciding between alternate explanations or models based on observation. When results are inconclusive, students should be given opportunities to revise either their question or their experiment. This may be done either individually or in groups.
	Students should be able to devise falsifiable models or hypotheses covering observable features of nature.	
	Students should be able to describe experimental observations clearly, accurately, and succinctly and identify the most important physics concepts in an experiment.	
	Students should be able to construct arguments and identify trends based on experimentally controlled observations.	
	Students should be able to transfer knowledge between different contexts, recognize connections between different concepts, and reason by induction to produce generalizations.	For example, while students may learn to use an oscilloscope in one setting, they should be able to apply their working knowledge of oscilloscopes in various contexts in order to make a range of measurements.

		Introductory Level		*Advanced Level*	
2. Modeling Modeling entails developing a "conceptual representation of a real system." A model provides a link between theory and experiment and between a qualitative and quantitative understanding of a system. Models in physics tend to be mathematical in nature but often have a computational component as well. Simulation and numerical analysis, for example, are important parts of modeling. Modeling should also make explicit the "math-physics-data connection," statistical and systematic error analysis, and understanding sophisticated equipment (i.e. demystifying so-called "black-boxes").		**Recommendations**	**Examples**	**Recommendations**	**Examples**
	Conceptual Framework	Students should be able to choose the appropriate conceptual framework for the (physical) situation being modeled.	Students can use Newton's Laws or energy conservation as a conceptual framework to describe the motion of an object sliding down an incline.	Students should be able to choose the appropriate conceptual framework for the (physical) situation being modeled.	A particular interpretation of quantum mechanics might motivate a single photon experiment or the interpretation of the results.
		Students should be able to switch between model representations.	Such representations include verbal and written descriptions, analytical (mathematical) models, computational models, physical constructions	Students should be able to switch between model representations and apply multiple model representations to a given investigation.	In a non-linear dynamics experiment, students should be able to provide a theoretical model and construct a computer model of the system being investigated experimentally.
	Assumptions and Simplification	Students should understand the assumptions, limitations, and simplifications inherent in their model and the errors that might be introduced by these.	A student modeling an object's motion without friction should be able to identify that friction has been neglected and what the consequences of making this simplification are.	Students should understand the assumptions, limitations, and simplifications inherent in their model and the errors that might be introduced by these.	

		Students should be aware that instruments need to be calibrated for proper use.		Students should calibrate their apparatus or ensure that their apparatus/ instrumentation is calibrated.	Students might use calibration standards to ensure an instrument is working as expected.
				Students should understand the instrumentation used in an experimental investigation, including any systematic errors or biases that might be introduced by these.	
	Units and Estimation	Students should be able to estimate using appropriate units both inputs to and outputs from a model of a system.	A student should have some understanding of what a quantity means physically (*e.g.* what it means for a length to be 1 cm, 1 m, or 1 km) and a sense of scale in order to determine if a physical quantity is reasonable given the system being modeled.)	Students should be able to estimate using appropriate units both inputs to and outputs from a model of a system.	A student might provide a back-of-the-envelope or order of magnitude estimate of the expected results of an experiment and do a preliminary analysis of the data to see if results seem reasonable before doing a full run.

		Introductory Level		*Advanced Level*	
3. Design		**Recommendations**	**Examples**	**Recommendations**	**Examples**
Guided inquiry or properly scaffolded open-inquiry-based labs better promote scientific reasoning than cookbook labs. Students should be capable of posing scientific questions and should be able to develop and engineer experiments to test models and hypotheses, often with certain constraints such as cost, time, and available equipment. And students should be able to troubleshoot systems using a logical, problem-solving approach. The hands-on experience of constructing an experimental set-up or apparatus and of troubleshooting it is a very important part of a laboratory experience.	*Experimental design*	Students should design a procedure to test a model or hypothesis or make a measurement of something unknown, accounting for the types, amount, range, and accuracy of data needed to give reproducible and accurate results.	The student may be given an open-ended question (or have to ask a question about a concept covered in class) and design an experiment to test their hypothesis given the equipment available from the instructor.	Students should define the scope of a project or refine a question such that it can be answered feasibly given the available resources or define the scope of a problem to be investigated.	The students are given some autonomy to ask a question (relevant to the course), develop a hypothesis, and design an experiment to test their hypothesis.
				Students should plan/design an experimental investigation, taking into account the types, amount, and accuracy of data needed to give reproducible and accurate results.	Students running a counting experiment might consider the source activity and the $\sqrt{N}$ statistical error associated with a counting experiment to determine how long to collect data.
				Students should read the literature to hone ideas for their experimental design.	Students can use the literature to refine a question or improve an experimental design.

	Apparatus construction and testing	Students should have a hands-on opportunity to construct and/or set up an apparatus, and then make measurements and collect data using that apparatus to test a model or hypothesis.		Students should design and construct an apparatus to carry out an experimental investigation given various constraints (time, cost, available materials, etc).	
	Design assessment and improvement	Students should do basic troubleshooting.	Examples may include ensuring apparatus are properly leveled or balances / sensors are zeroed	Students should take an iterative, logical approach to troubleshooting their apparatus and refining their measurements and apparatus design.	This may include troubleshooting electronics, ensuring proper alignment of optics, or correcting for vacuum leaks.
		Students should understand the limitations of their experimental design, including potential sources of error.		Students should understand the limitations of their experimental design, including potential sources of systematic error.	If a particular light detector has a wavelength dependent efficiency, students should understand and account for this when measuring a spectrum.

		Students should reflect on their results, consider how their experimental design (apparatus, data collection methods, etc) might have impacted the results, and suggest ways to improve their design.	At the introductory level, students might not have the time in lab to re-design and re-run an experiment, but it is worthwhile for them to think about possible refinements.	Students should reflect on their results and have an opportunity to improve their design.	
	Collaboration	Students should work together in small groups to design and construct an experiment.	Students should begin to collaborate in small groups to effectively design and construct an experiment.	Students should work together in small groups to design and construct an experiment.	Students can divide pieces of a project among themselves, but students should see and understand every part of the design and experimentation process.

		Introductory Level		*Advanced Level*	
4. Technical Lab Skills		**Recommendations**	**Examples**	**Recommendations**	**Examples**
Students should learn to make measurements using basic test equipment, correctly record these measurements, and to determine the appropriate equipment to use for particular measurements. Students should be able to use computers to acquire and to analyze data and should be able to critically interpret the validity and limitations of the data displayed. Students should develop practical laboratory skills throughout the undergraduate experience.	*Measuring devices and apparatus*	Students should be able to use measuring devices and apparatus to make measurements consistent with the content covered in class	During the course of an introductory lab, students should, minimally, be able to measure time, distance, mass, temperature, voltage, and current.	Students should be able to understand the measuring devices and apparatus and make measurements appropriate to the content of the course	In an optics lab, students should make relevant optics measurements (eg beam quality and characterization) and constructing optical systems (e.g. interferometers, quantum optics/single photon experiments)
		Students should be able to understand the limitations of measuring devices and choose an appropriate device for making the measurement.	When making a length measurement, students can select an appropriate device (e.g. ruler, caliper, or micrometer).	Students should be able to use and understand the limitations of measuring devices and sensors.	An example would be determining the optimal device for light collection based on wavelength of light: InGaAs photodiode, Silicon photodiode, PMT, NaI crystal, etc.
		Students should make measurements with various analog and digital devices and determine errors on those measurements.	Students should understand that every measuring device has an associated uncertainty.	Students should make several different types of standard laboratory measurements.	These could include: 1) Counting measurement (e.g., photons or particles) 2) Small signal measurement (e.g, using lock-in amps or

					interferometry) 3) Resonance measurement (e.g., atomic or NMR) 4) Time-series measurement (e.g., power spectral density) 5) Precision measurement (e.g., precision well beyond the typical laboratory uncertainty of ~1%)
	Computation skills	Students should use a computer to do basic data analysis.	Students should be able to make plots and tables as well as perform basic curve fitting and statistics (e.g. mean and standard deviation) using a computer.	Students should use a computer to do sophisticated data analysis.	Students should be able to make plots and tables, do curve-fitting, do basic statistical analysis proficiently, and do some higher-level statistical analyses (e.g. Poisson statistics, correlations, Baysian analysis, design of experiment, confidence intervals).
				Students should use a computer to interface to experimental apparatus for data acquisition.	Examples may include using commercial software and data collection tools to interface with an

					apparatus.
	Practical skills	Students should begin developing some practical, hands-on lab skills.	An example would be constructing and analyzing simple circuits.	Students should have the opportunity to develop some practical, hands-on lab skills.	Examples may include soldering, machining, building and/or troubleshooting a vacuum system, aligning optics, computer interfacing to system for automation and/or data acquisition.

		Introductory Level		*Advanced Level*	
5. Communication Communication is a process that involves creating and presenting results and ideas to others who are listening or reading, interpreting, and evaluating. Laboratory courses are excellent places to develop scientific communication skills, though scientific communication should be fostered throughout the curriculum as well. Students should learn to present reasoned arguments backed up by experimental evidence. Those arguments should include elements such as plots, tables,		**Recommendations**	**Examples**	**Recommendations**	**Examples**
	Creation/ Presentation	Students should develop clearly stated scientific arguments that proceed from a clearly stated question to the presentation of evidence, the evaluation of that evidence, and the conclusions.	Students should be able to use their data to generate claims and back up the stated conclusions.	Students should develop clearly stated scientific arguments that proceed from a clearly stated question to the presentation of evidence, the evaluation of that evidence, and the conclusions.	
		Students should make scientific arguments using a number of standard elements of technical communication.	Students should: i. Use technical vocabulary appropriate for the physics content and apparatus used in the introductory lab. ii. State measurement and analysis data with significant digits and uncertainty. iii. Present data in	Students should make scientific arguments using a number of standard elements of technical communication.	Students should: i. Use technical vocabulary appropriate for the physics content and apparatus used in the advanced lab. ii. State measurement and analysis data with significant digits and uncertainty. iii. Present data in

numerical results with uncertainties, and diagrams. Further, the overall format any style of presentations should be in forms authentic to the discipline: technical memos and/or reports and journal-style articles, conference-style oral presentations, and scientific posters. Intrapersonal communication skills should also be developed in the lab through teamwork and collaboration.			tables and plots. iv. Make basic sketches/ diagrams of the apparatus/system		tables and plots. iv. Use a variety of plot formats and styles relevant to their experiments (lin-lin, log-lin, polar, Bode, etc.) v. Make basic scientific diagrams or schematics of apparatus.
		Students should be able to communicate their results effectively in oral and written forms that can smoothly transition to more authentic forms of scientific communication in advanced labs.		Students should be able to communicate their results effectively in forms authentic to the discipline.	Students should be able to write technical memos and/or reports for a research group, basic journal-style articles, short oral presentations, and poster presentations.
		Students should begin using a lab notebook to record significant aspects of their experiment.	Things like a description/sketch of the apparatus, procedure, data, and analysis are appropriate for a beginning student to include in a notebook.	Lab notebooks should be of sufficient quality for beginning PhD-level research.	The format of notebook entries, the handling of mistakes, and the use of the notebook should be more sophisticated and authentic to the discipline than in

					introductory labs.
	Interpretation and Evaluation	Students should be able to identify the claims, theoretical background, experimental evidence, and logical connections that link their own argument together.		Students should be able to identify the claims, theoretical background, experimental evidence, and logical connections that link their own argument together.	
		Students should be able to interpret a number of standard components of technical communication, including vocabulary, numerical results with uncertainty, tables, and figures.		Students should be able to interpret a number of standard components of technical communication, including advanced vocabulary, numerical results with uncertainty, tables, plots, and figures.	
		Students should be able to evaluate their own presentations for both the quality of the scientific arguments and the style.		Students should be able to evaluate and critique their own work, which includes evaluation of the quality of the scientific argument and overall	

				presentation style.	
		Students should be able use their lab notebook as a record for explaining the details of their work in any written summaries.		Students should be able to evaluate the work of others and provide constructive feedback that could be used to improve the quality of their peers' scientific investigations and presentations.	Students could participate in a simulated peer review process.
				Students should be able use their lab notebook as a tool for organizing more complex experimental investigations and for recording experimental details that will be referred to in oral or written presentations.	
	Collaboration	Students should be able to effectively plan and carry out experiments and discuss ideas in small groups as part of the overall		Students should be able to effectively plan and carry out experiments and discuss ideas in small groups as part of the overall scientific	

		scientific process.		process.	

As mentioned above, these recommendations represent the minimum exposure to laboratory skills and habits that an undergraduate physics student should develop during the course of the physics major. How these recommendations are implemented will vary from institution to institution depending on things like resources available; however, they are general enough that they are universally accessible. Universities that have the expertise or resources to go above and beyond these recommendations are encouraged to do so in order to provide their majors an even richer laboratory experience. In the end, there are several reasons for embedding these recommendations in the laboratory curriculum. They give non-physics majors exposure to thinking like a physicist and introduce them to the skills and methods of physics, which are transferrable to their own disciplines. Moreover, implementing these recommendations will improve the training of the next generation of physicists and prepare them well for graduate school and for employment in the technology job sector and many other employment sectors. Students will come out of the physics major with the ability to think like a physicist and construct knowledge and will have a variety of highly transferrable skills.

This document was prepared by a subcommittee of the AAPT Committee on Labs:
Nancy Beverly (Mercy College); Duane Deardorff (University of North Carolina); Richard Dietz (University of Northern Colorado); Melissa Eblen-Zayas (Carlton College); Robert Hobbs (Bellevue College); Dean Hudek (Brown University); Joseph Kozminski, Chair (Lewis University); Heather Lewandowski (University of Colorado); Steve Lindaas (Minnesota State University Moorhead); Ann Reagan (IEC Services); Randy Tagg (University of Colorado Denver); Jeremiah Williams (Wittenberg University); Benjamin Zwickl (Rochester Institute of Technology)

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