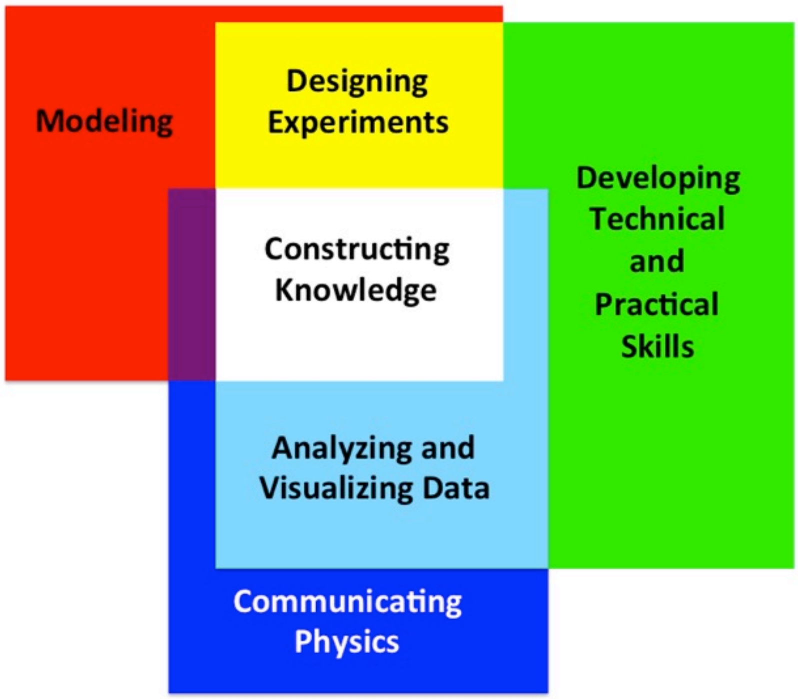
AAPT Recommendations for the Undergraduate Physics Laboratory Curriculum



Report prepared by a Subcommittee of the AAPT Committee on Laboratories
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EXECUTIVE SUMMARY

The Laboratory Goals Subcommittee, a subcommittee of the American Association of Physics Teachers (AAPT) Committee on Laboratories consisting of committee members and friends of the committee, has reviewed the state of the undergraduate physics laboratory curriculum and related physics education research on the physics laboratory and has made recommendations that foster the development of many key 21st century skills and competencies. The undergraduate laboratory is an essential part of the physics curriculum because physics is inherently an experimental science, and there is an increasing awareness of the importance of the laboratory experience in physics instruction. This coincides with an ongoing national focus on authentic and engaging STEM educational experiences. This attention is also reflected in the Next Generation Science Standards.

Physics 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 and skills, including mathematical, computational, experimental, and practical skills; and to develop particular habits of mind. "Thinking like a physicist" and constructing knowledge of our physical universe pervade all of the recommended learning outcomes.

The undergraduate lab curriculum learning outcomes are based on the following focus areas.

- **Constructing knowledge** – collect, analyze, and interpret real data from personal observations of the physical world to develop a physical worldview.
- **Modeling** – develop abstract representations of real systems studied in the laboratory, understand their limitations and uncertainties, and make predictions using models.
- **Designing Experiments** – develop, engineer, and troubleshoot experiments to test models and hypotheses within specific constraints such as cost, time, safety, and available equipment.
- **Developing technical and practical laboratory skills** – become proficient using common test equipment in a range of standard laboratory measurements while being cognizant of device limitations.
- **Analyzing and visualizing data** – analyze and display data using statistical methods and critically interpret the validity and limitations of these data and their uncertainties.
- **Communicating Physics** – present results and ideas with reasoned arguments supported by experimental evidence and utilizing appropriate and authentic written and verbal forms.

The recommended learning outcomes presented in this document are not an exhaustive description of experiments and techniques; rather they are meant to be guidelines for developing lab curricula.

Recommendations

- Learning outcomes for the introductory laboratory experience are intended for both majors and non-majors.
- The advanced laboratory experiences should build upon the introductory laboratory experiences.
- Learning outcomes may be implemented throughout the curriculum, within dedicated laboratory courses or within physics courses that integrate laboratory experiences.

- The learning outcomes are general enough that they are universally accessible; however the implementation will vary by institution depending on available resources and student populations.
- The laboratory should contain experiences that support a department's specific pedagogical goals.
- Institutions that have the expertise or resources to go above and beyond these recommendations are encouraged to do so in order to provide their students an even richer laboratory experience.

Successful implementation of these learning outcomes has clear societal benefits. The physics laboratory prepares responsible scientists and fosters both a deeper understanding of natural physical processes and the development of a variety of highly transferrable 21st century skills. The laboratory also provides a link to skills and habits that are valuable for innovation and entrepreneurship. The laboratory allows students to understand how fundamental physical ideas enable most modern technologies and therefore to appreciate the role that physicists can play in developing practical solutions to societal problems.

I. INTRODUCTION

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 goals and learning in introductory and advanced undergraduate lab courses;[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 K-12 science standards (Next Generation Science Standards), likely to be implemented in many states in the near future, which emphasize a broad spectrum of experimental and laboratory practices.[11] Since its inception in 2007, the Advanced Laboratory Physics Association (ALPhA) has brought focus to the undergraduate laboratory beyond the first year with topical conferences in 2009 and 2012 and dozens of faculty development opportunities through its laboratory immersions program.[12] The topic of the 2010 Gordon Research Conference on Physics Education was on Experimental Research and Laboratories in Physics Education.[13] Since 2011, there have been several sessions, including four panels, at AAPT meetings on the pedagogy, goals, and assessment of the instructional labs. In 2012, President's Council of Advisors on Science and Technology (PCAST) called for "advocat[ing] and provid[ing] support for replacing standard laboratory courses with discovery-based research courses" in their report *Engage to Excel: Producing One Million Additional College Graduates with Degrees in Science, Technology, Engineering, and Mathematics*.[14] Also, in 2012, the AAPT's Undergraduate Curriculum Task Force was charged to review the undergraduate physics curriculum, and the AAPT and APS established the Joint Task Force on Undergraduate Physics Programs (J-TUPP) in 2014 to examine what "skills and knowledge… the next generation of undergraduate physics degree holders [should] possess to be well prepared for a diverse set of careers."[15] This is, therefore, an opportune time to review laboratory goals and guidelines for all levels of the undergraduate physics curriculum. To this end, the AAPT Committee on Laboratories formed a Subcommittee consisting of members and friends of the Committee on Laboratories, who teach a range of student populations from non-majors to introductory laboratory students to advanced laboratory students at a range of institutions, including two-year colleges, primarily undergraduate institutions, masters-granting institutions, and Research 1 universities. This subcommittee has reviewed the state of the undergraduate physics laboratory curriculum and related physics education research on the physics laboratory and has made recommendations that foster the development of many key 21st century skills and competencies.

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 scientific discovery, which requires personal observation and physical experimentation. Being successful in this endeavor requires one to synthesize and use a broad spectrum of knowledge and skills, including mathematical, computational, experimental, and practical skills, and to develop 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. They should also understand how fundamental physical ideas enable most of the technologies used by 21st century societies and therefore appreciate the role that physicists can play in developing practical applications of physics. Further, physics has interdisciplinary applications, and plays an important role in modeling, measuring, and analyzing natural processes ranging from cellular biology to climate dynamics. To this end, J.M. Pimbley wrote: "These days, a physics education … offers the discipline [training] and important tools for tackling new issues. Physics is the liberal arts education for a technological society."[16]

II. LEARNING OUTCOME FOCUS AREAS

The learning outcomes for and experiences in the undergraduate physics laboratory curriculum are organized into six focus areas. The first focus area, Constructing Knowledge, captures some of the overarching goals of the undergraduate lab curriculum while the remaining five focus areas -- Modeling, Design, Technical and Practical Laboratory Skills, Data Analysis and Visualization, and Communication – contain concrete recommendations that will:

a) prepare majors in physics and other physical sciences to think like physicists and perform experimental investigations at an appropriate level for graduate school, research laboratories, jobs in industry, or other public or private sector STEM careers.
b) prepare future teachers in essential laboratory skills that they can use to develop rich courses and laboratory experiences for their students.
c) introduce non-physics majors to experimental investigations from a physicist's perspective, which will broaden their appreciation of the interdisciplinary nature of science and strengthen their readiness to participate in a highly technical 21st century.

A high-level discussion of each of these focus areas is given in this section, with specific recommendations for implementation in undergraduate labs at the introductory and advanced levels given in the tables in Section V. 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, software, or pedagogical approaches that must be used or specific experiments that students must complete.

- **Constructing knowledge**[5,6,17-20]
  Through laboratory work, students should gain the awareness that they are able to do science; that is, students should be able to collect, analyze, and interpret real measured data in an ethical manner as responsible scientists and draw meaningful conclusions from personal observations of the physical world. The laboratory curriculum should get students to start thinking like physicists by constructing knowledge that does not rely on an outside authority, should explicitly make them aware that they can construct knowledge in this way, and should build confidence in their ability to do so.

- **Modeling**[1,2,8-9]
  Modeling entails developing an abstract representation of a real system being studied in the laboratory. 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 and/or computational in nature. Students should be able develop models to represent physical systems, including their measurement devices; implement models using computers as appropriate; use models to predict the outcomes of experiments; and interpret their laboratory results in the context of models they have developed. Students should also be able to recognize a model's limitations, including considerations of uncertainties in measurements and the limitations of measurement devices.

- **Designing Experiments**[1,3-6, 8, 21-23]
  Students should be able to pose scientific questions, develop and engineer experiments to answer questions they pose, and test models and hypotheses, considering certain constraints such as quality of data desired, cost, time, available equipment, and safety concerns. Also, 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. Students should emerge with demonstrable skills in executing technical projects from conception to completion.

- **Developing technical and practical laboratory skills**[1,8]
  Students should be exposed to a range of standard laboratory measurements. They should learn to make measurements using standard equipment and accurately record their measurements and observations. Students should understand the limitations of their measuring devices and how to choose the appropriate equipment to use for particular measurements. Students should be able to use computers to acquire data and should develop other practical laboratory skills throughout the undergraduate experience. Students should gain experience in safely using specialized tools, materials, and devices when building and running experiments.

- **Analyzing and Visualizing Data** [6,7,24,25]
  Data analysis is a critical part of the experimental process since "observations are useless until they have been interpreted."[26] Students should be able to use statistical methods to analyze data and should be able to critically interpret the validity and limitations of the data displayed. Students should be able to choose appropriate plotting methods to represent their data and should be able to fit their data and extract physical quantities from fit parameters. Students should also be able to quantify uncertainties in the data and propagate these uncertainties through calculations. Students should be able to compare their experimental results to mathematical models, computational models, or simulations. Students should encounter an expanding range of data analysis and evaluation tools appropriate to their program of study.

- **Communicating Physics**[8,27]
  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 ethical scientific communication should be fostered throughout the curriculum as well. Students should learn to present reasoned arguments supported by experimental evidence. Those arguments should include elements such as plots, tables, numerical results with uncertainties, and diagrams. Further, the

overall format and style of presentation should use forms authentic to the discipline, such as technical reports, journal-style articles, and conference-style poster and oral presentations. Interpersonal communication skills should also be developed in the lab through teamwork and collaboration. While not the only place in the curriculum to do so, the laboratory is an important place to foster or reinforce teamwork and collaboration skills.

III. ADDRESSING INTRODUCTORY AND ADVANCED LABORATORY EXPERIENCES

Specific recommendations for student learning outcomes and experiences are given in the tables in Section V for both introductory and advanced lab levels. The introductory-level outcomes and experiences are intended for majors and non-majors in their introductory physics sequences. It is expected that advanced laboratory courses will meet and reinforce the recommendations for the introductory laboratories and add, and reinforce whenever possible, the next layer of skills. "Advanced lab" is defined as any laboratory experience beyond the introductory laboratory sequence, not only laboratory courses 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 spiraled or scaffolded such that students develop and reinforce their skills throughout their undergraduate years, building from the introductory laboratory courses through the advanced laboratory courses. For instance, some of the recommendations for Constructing Knowledge, should be introduced in the introductory sequence; however, these recommendations should permeate the entire laboratory curriculum. Some of the recommendations for Constructing Knowledge may be introduced in non-major laboratory courses and sequences as well. The recommendations for the other five focus areas are broken into separate introductory and advanced laboratory recommendations, with some examples, in tables in Section V.

IV. IMPLEMENTATION OF THE RECOMMENDATIONS

How these recommendations are implemented will vary from institution to institution depending on local conditions like resources available and student population; however, they are general enough that they are universally accessible. Some of these skills may also be developed within the physics curriculum outside traditional laboratory courses. For example, an experimental component may be integrated into traditional theory courses so that students are able to make a connection between theory and experiment. In fact, a report on high school laboratories from the National Research Council indicates that merging laboratory activities with concepts developed concurrently in a course can lead to a deeper understanding of the ideas,[28] and the 2002 AAPT publication *Guidelines for Two Year College Physics Programs* states that "the integrated lecture-lab format… can be successful in improving student learning." [29] Moreover, many introductory physics courses are now structured in an integrated-laboratory format.[30-32]

It is important to embed the introductory-level recommendations into the laboratory curriculum for students taking physics courses at all levels and through all delivery platforms. For example, even online laboratory courses should include some hands-on laboratory activities and measurement of real data.[30,33,34] The specific recommendations implemented and the extent to which they are implemented depends on the level of the course and the student population. Exposing non-physics majors to thinking like a physicist and introducing them to the skills and methods of physics will provide them skills and thought processes transferrable to their own disciplines.

For an undergraduate physics major, these recommendations represent the minimum set of laboratory skills and habits that the student should develop during the course of the physics major. 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. Implementing these recommendations will improve the preparation of the next generation of physicists and prepare them well for graduate school, for employment in the technology job sector, for jobs in education and public outreach at all levels, and for jobs in many other employment sectors,[35] as well as prepare them to be the next generation of innovators and entrepreneurs.[36,37] Students will come out of the physics major with the ability to think like a physicist and construct knowledge, and they will have a variety of highly transferrable skills.

V. LEARNING OUTCOME RECOMMENDATIONS FOR THE UNDERGRADUATE LABORATORY CURRICULUM

Constructing Knowledge	Recommendation	Discussion/Examples
Through laboratory work, students should gain the awareness that they are able to do science; that is, students should be able to collect, analyze, and interpret real measured data in an ethical manner as responsible scientists and draw meaningful conclusions from personal observations of the physical world. The laboratory curriculum should get students to start thinking like physicists by constructing knowledge that does not rely on an outside authority, should explicitly make them aware that they can construct knowledge in this way, and build confidence in their ability to do so.	Students should be able to generate scientific 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 individually or in groups.
	Students should be able to devise falsifiable models or hypotheses to explain observable features of nature.	Students could be provided examples of and practice making declarative statements that are substantive, unambiguous, and therefore easily falsifiable. e.g. "Light travels in straight lines." or "All coins will slow at the same rate when sliding across fresh clean paper."
	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.	A student is able to synthesize all of the information present, including the results and the uncertainties, and make a cogent, data-driven conclusion.

	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.
	Students should be able to conduct experiments, perform analysis, and disseminate results in a professional and ethical manner as responsible scientists.	Students should be made aware of responsible/ethical scientific practices through case studies or formal Responsible Conduct in Research (RCR) training. Students should not engage in "fabrication, falsification, or plagiarism."[20]

Modeling		*Introductory Level*		*Advanced Level*	
		Recommendations	**Examples**	**Recommendations**	**Examples**
Modeling entails developing an abstract representation of a real system being studied in the laboratory. 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 and/or computational in nature. Students should be able develop models to represent physical systems, including their measurement devices; implement models using computers as appropriate; use models to predict the outcomes of experiments; and interpret their laboratory results in the context of models they have developed. Students should also be able to recognize a model's limitations, including considerations of uncertainties in measurements and the limitations of measurement devices.	*Conceptual Framework*	Students should be able to choose the appropriate conceptual framework for the physical situation being modeled.	Students can use energy conservation or Newton's Laws 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. Students should begin to apply multiple model representations to a given investigation.	Such representations include verbal and written descriptions, analytical (mathematical) models, computational models, physical constructions, and graphical / diagrammatic models.	Students should be able to switch between model representations and apply multiple model representations to the complete analysis of a given investigation.	In a non-linear dynamics experiment, students should be able to develop 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 uncertainties 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 uncertainties that might be introduced by these.	The interpretation of measured changes in polarization of light reflected from surfaces (including thin films) depends on the underlying models of the materials used.

		Students should be aware that instruments need to be calibrated for proper use.	Scaling a video is a calibration (scaling in this case) of pixels to a unit of length. In this case, students should be aware that additional scaling is needed if the reference object used for scaling is behind or in front of the plane containing the action.	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.	Students can model their measurement devices to better understand them, thereby demystifying so-called "black boxes." For example, they could determine if AC voltage measurements are "true RMS" and what the frequency limits are to a particular instrument's ability to measure AC signals.

	Units and Estimation	Students should be able to estimate, using appropriate units, both input parameters to and output values from a model of a system.	Students 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 input parameters to and output values from a model of a system.	Students 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 making fine-grained measurements. For example, students can estimate the current that would be produced by a silicon photodiode detector used to monitor changes in intensity of a small laser.

Designing Experiments		*Introductory Level*		*Advanced Level*	
Students should be able to pose scientific questions, develop and engineer experiments to answer questions they pose, and test models and hypotheses, considering certain constraints such as quality of data desired, cost, time, available equipment, and safety concerns. Also, 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. Students should emerge with demonstrable skills in executing technical projects from conception to completion.		**Recommendations**	**Examples**	**Recommendations**	**Examples**
	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.	Students may be given an open-ended question like: "Here is a bottle of mineral oil. What is the most precise value of density for the oil that you can experimentally obtain?" or "What can make waves travel faster (slower) on a string, considering source and/or string properties?"	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 be able to read the literature to refine a question or improve an experimental design.	Students could be asked to write a short design proposal with a literature review before proceeding with the construction of their experiment.
				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.	Students may propose expanding on an experimental result presented in an *American Journal of Physics* article using resources available at her/his institution.

	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 can set up air tracks and force tables or align the lasers, optical elements, and protractors in a refraction experiment.	Students should design and construct an apparatus to carry out an experimental investigation given various constraints (time, cost, available materials, etc.).	Students could design and build a simple circuit to determine Planck's constant using different colored LEDs in an intermediate lab or could construct optical tweezers to measure the trapping force in a more advanced lab setting.
	Design assessment and improvement	Students should do basic troubleshooting.	Students could ensure that air tracks are properly leveled or that balances / sensors are zeroed	Students should take an iterative, logical approach to troubleshooting their apparatus and refining their measurements and apparatus design.	Students could troubleshoot electronics, ensure proper alignment of optics, or detect and correct vacuum leaks.
		Students should understand the limitations of their experimental design, including potential sources of error.	When doing a projectile motion experiment, students should realize that air resistance is a source of error, or that a spring launcher does not have the same muzzle velocity when fired vertically as when fired horizontally.	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 be able to think synthetically and apply physics principles in designing experiments and/or developing practical applications of physics.	An application example is Chester Carlson's invention of electrostatic printing based on his undergraduate physics education and a good reading of the literature on photoconductive materials.
		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 and write up/present possible refinements.	Students should reflect on their results and have an opportunity to improve their design.	In a capstone project, when a group encounters unexpectedly poor performance, the students have to determine what went wrong and modify their design accordingly.
	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.

	Project management			Students should be able to plan and guide complex technical projects from initial formulation through construction and testing to completion and reporting.	A team working on a senior lab project to measure Cerenkov radiation can set various technical milestones, identify resource needs, estimate a timeline, allocate a division of effort, and document their progress and can adapt and refine their process as the project encounters new challenges.

Developing Technical and Practical Laboratory Skills		*Introductory Level*		*Advanced Level*	
Students should be exposed to a range of standard laboratory measurements. They should learn to make measurements using standard equipment and accurately record their measurements and observations. Students should understand the limitations of their measuring devices and how to choose the appropriate equipment to use for particular measurements. Students should be able to use computers to acquire data and should develop other practical laboratory skills throughout the undergraduate experience. Students should gain experience in safely using specialized tools, materials, and devices when building and running experiments.		**Recommendations**	**Examples**	**Recommendations**	**Examples**
	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, potential difference, and current.	Students should be able to understand the measuring devices and apparatus and make measurements appropriate to the content of the course.	In Optics Lab, students should make relevant optics measurements (e.g. beam quality and characterization) and construct optical systems (e.g. interferometers, quantum optics/single photon experiments)
		Students should be able to understand the limitations and associated uncertainties of measuring devices and choose an appropriate device for making the measurement.	When making a length measurement, students choose an appropriate device (e.g. ruler, caliper, or micrometer).	Students should be able to use and understand the limitations of measuring devices and sensors.	Students could determine the optimal device for light collection based on wavelength of light: InGaAs photodiode, Silicon photodiode, PMT, NaI crystal, etc.
		Students should make measurements, including uncertainties, with various analog and digital devices.	Students can look up the uncertainty of a multimeter reading on a particular setting in the manual or online specifications.	Students should make several different types of common laboratory measurements.	These *could* include: 1) Counting measurement (e.g., photons or particles) 2) Small signal measurement (e.g., using lock-in amplifiers or interferometry) 3) Resonance measurement (e.g.,

					atomic or NMR) 4) Spectral measurement (e.g., time-series measurement) 5) Precision measurement (e.g., precision well beyond the typical laboratory uncertainty of ~1%)
	Practical skills	Students should begin developing some practical, hands-on lab skills.	Students can construct and analyze simple circuits, level or align apparatus, arrange clamps or supports that are suitable to the weights or stresses involved all with some thought to the possible impact these choices may have on data collection.	Students should develop some practical, hands-on lab skills.	Students could learn soldering, machining, building and/or troubleshooting a vacuum system, aligning optics, or setting up a motor-driven mechanical drive train for moving a probe.
		Students should be able to use now-common data gathering tools like video to extract physical data.	Students could use video motion tracking software to evaluate a model of an athlete's high jump.	Students should use a computer to interface to experimental apparatus for data acquisition.	Students could use commercial software and data collection tools to interface with an apparatus.

		Students should be able to record and organize their observations, data, and results in preparation for keeping a laboratory notebook.	Introductory students could record a description/ sketch of the apparatus, the measurement procedure, data, and analysis.	Students should maintain laboratory notebooks of sufficient quality for beginning graduate-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.
		Students should see examples in the laboratory that connect physics to real world applications, including consumer devices, biomedical systems, and industrial processes.	Students could study the physics of familiar systems such as thermal energy transfer in coffee cooling, the behavior of light bulbs in electrical circuits, motion and forces involved in a human jump, or the optics of telescopes, microscopes, or corrective lenses. Students could also be exposed to the physics of more complex systems like thermal energy transfer in a bread maker or the use of charges and electric fields to analyze biological samples in gel electrophoresis.	Students should be able to identify fundamental physics that is used in advanced commercial instrumentation and quantitatively describe system performance criteria.	Students can determine the expected drop charge and deflection given the drop potential and electric field specifications in a flow cytometer.

Analyzing and Visualizing Data		*Introductory Level*		*Advanced Level*	
Data analysis is a critical part of the experimental process since "observations are useless until they have been interpreted."[26] Students should be able to use statistical methods to analyze data and should be able to critically interpret the validity and limitations of the data displayed. Students should be able to choose appropriate plotting methods to represent their data and should be able to fit their data and extract physical quantities from fit parameters. Students should also be able to quantify uncertainties in the data and propagate these uncertainties through calculations. Students should be able to compare their experimental results to mathematical models, computational models, or simulations. Students should encounter an expanding range of data analysis and evaluation tools appropriate to their program of study.		**Recommendations**	**Examples**	**Recommendations**	**Examples**
	Analytical skills	Students should use a computer to do basic data analysis.	Students should be able to do basic statistical analysis; e.g., mean and standard deviation).	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, Bayesian analysis, confidence intervals).
		Students should be able to plot their data appropriately and extract information from their plots.	Students should perform basic curve fitting and relate the fit parameters to physical quantities.	Students should be able to represent their data using methods relevant to their experiment and extract information from their plots.	Students may use a variety of plot formats (log-log, log-lin, polar, Bode, contour, etc.) and linearizing their data. Students should be able do curve fitting and relate the fit parameters to physical quantities.
		Students should quantify the uncertainties of their results in a reasonable way.	Students might use the weakest link rule,[6] GUM-compliant methods,[7] or other methods deemed appropriate.	Students should be able to perform uncertainty analysis using professional standards.	Students should use GUM[24] or NIST[25] standards or other approved uncertainty analysis standards.

		Students should know how to use and interpret methods for data visualization in some well-known situations.	Students could relate false-color representations of temperature sensed by infrared cameras to numerical data without being confused by actual visual appearance.	Students should be exposed to methods and algorithms for processing spatial data sets and should extend the interpretation of data sets by using advanced analysis tools.	Students could locally filter digital image data to provide smoothing or edge enhancement. Students could use contour plotting software to relate field data to underlying models or to make predictions, e.g. of likely locations of discharge breakdown around a sharp electrode.

Communicating Physics		***Introductory Level***		***Advanced Level***	
		Recommendations	**Examples**	**Recommendations**	**Examples**
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 ethical scientific communication should be fostered throughout the curriculum as well. Students should learn to present reasoned arguments supported by experimental evidence. Those arguments should include elements such as plots, tables, numerical results with uncertainties, and diagrams. Further, the overall format and style of presentation should use forms authentic to the discipline such as technical reports,	*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 data-driven / evidence-based 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 data-driven/ evidence-based 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 tables and plots. iv. Make basic sketches/ diagrams of the apparatus/system.	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 tables and plots. iv. Make scientific diagrams or schematics of the apparatus/system.

journal-style articles, and conference-style poster and oral presentations. Interpersonal communication skills should also be developed in the lab through teamwork and collaboration. While not the only place in the curriculum, the laboratory is an important place to foster or reinforce teamwork and collaboration skills.		Students should be able to communicate their results ethically and effectively in oral and/or written forms that can smoothly transition to more authentic forms of scientific communication in advanced labs.	Students should begin using methods of scientific writing and presentation, but not necessarily at the level of journal-style articles and conference presentations. Students should not plagiarize or be intentionally misleading in disseminating their results.	Students should be able to communicate their results ethically and effectively in forms authentic to the discipline.	Students should be able to write technical memos and/or reports for a research group, journal-style articles, short oral presentations, and poster presentations. Students should not plagiarize or be intentionally misleading in disseminating their results.
	Interpretation and Evaluation	Students should be able to identify the claims, theoretical background, experimental evidence, and logical connections that hold their own argument together.		Students should be able to identify the claims, theoretical background, experimental evidence, and logical connections that hold 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 plots.		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 critique their own presentations for both the quality of the scientific arguments and the style.	Students should be able to evaluate and edit their own work based on a given rubric.	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 to evaluate and edit their own work based on a more advanced rubric or on journal submission guidelines.
				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 local peer review process.
		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 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 scientific process.		Students should be able to effectively plan and carry out experiments and discuss ideas in small groups as part of the overall scientific process.	

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