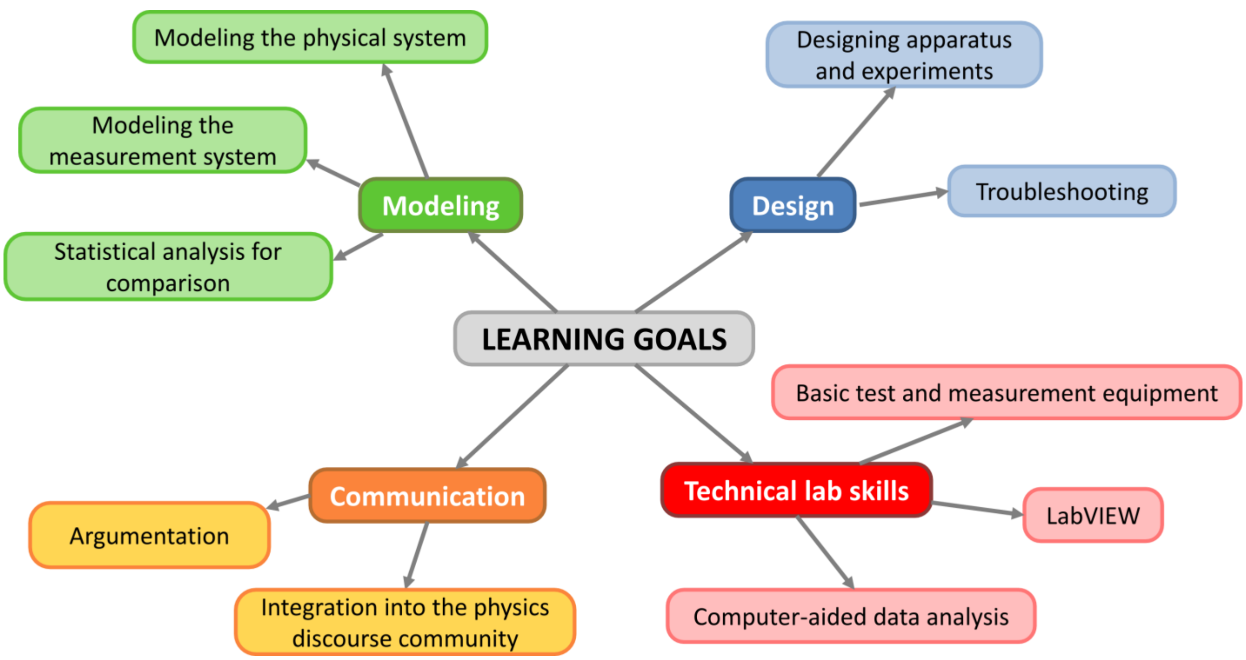
Detailed Learning Goals for the Advanced Lab

Advanced Lab learning goals were developed at University of Colorado Boulder through interviews and group meetings with 22 faculty members from a range of physics sub-disciplines. Additional input came from classroom observations of the advanced lab course, literature on laboratory education in STEM fields, and from the wider physics lab course community.

The diagram below organizes the learning goals into four main categories: modeling, design, communication, and technical lab skills. For successful implementation, a well-defined learning goal should have a specific observable outcome. Each of the course-level goals shown in the learning goals diagram needs to be broken down into action-oriented practices that can be assessed.



Modeling

Modeling the physical system

- **Understanding the main physics ideas**
    - Identify the system, interactions, and environment.
    - Identify the fundamental principles that are used to build the model.
    - Identify the simplifying assumptions. What is being ignored?
- **Developing a predictive model**
    - Use the main physics ideas to develop a predictive model. In general, this step is optional in the lab context because lecture courses provide opportunities for model development.
    - Use words, diagrams, graphs , and mathematics to communicate the model.
    - Write a mathematical expressions for the model

    - For any mathematical symbols, be able to describe the physical meaning (constants, operators, variable), including how they are measured and the appropriate units.
- **Using a predictive model**
    - Use computational and/or analytic representations of the predictive model to generate anticipated results before conducting the experiment.
    - Justify the choice of all model parameters as reasonable for the system being modeled.
    - Make predictions that can be compared with data as it is acquired during the experiment.
    - Use the predictive model to perform a fit of the data.
- **Articulating the limitations of the model**
    - Identify all the relevant model limitations including idealizations in the specific details (e.g., a point particle, massless string) and approximations in the fundamental principles (e.g., Newtonian vs relativistic mechanics).
    - Identify what ratio of quantities must be small in order for the simplification to be valid.
    - Quantitatively check, by measurement if necessary, that the system parameters are in a regime where the simplifications are valid.
- **Revision of models** If a prediction with measurements shows the model is inadequate to predict the data
    - Generalize the predictive model to include missing elements that were intentionally or unintentionally omitted. This may require computational modeling, or approximation techniques to include the previously neglected effect.
    - Redesign the physical system so that a particular simplification is valid.
    - Compare the above two options and decide the better course of action based on which is more feasible, efficient, or will better answer the scientific research question.

Modeling the measurement system

Just like it is important to understand the physical system and how it is modeled, experimental physicists also must understand their measurement tools. Understanding is important for a few reasons: it makes the results more trustworthy, it can be used to optimize the measurement or to show it is feasible (important for tough new measurements), it is needed to process the data in a way that can be compared with theoretical predictions, or for easier visualization. *Understanding* measurement equipment can then be defined as an exercise in modeling (i.e., *describing*, *using*, *testing*, and *refining* models).

Understanding a measurement tool is very similar to understanding a physical system. It includes understanding the main physics ideas that govern its operation, having a mathematical description of the idealized behavior, articulating the performance limitations, and calibrating (refining) the model of its operation. Despite these similarities, there are a few ways measurement models often differ.

- Measurement devices are often “black boxes” and so the most basic model will be often an “input-output” model. Students will create an model that specifies an input quantity, an output quantity, and a transfer function that connects the input and output.
- Aspects of the model definition or limitations often come from the manufacturer’s data sheet, so students should use the data sheet to identify the numerical values of model parameters and the limitations of idealized device behavior.
- Use words, graphs, and mathematics to describe how the “derived quantities” relate to the raw data.

Statistical analysis for comparison

Statistical analysis, broadly speaking, has two uses. The first is to estimate the quality of the measured data, especially, how reproducible is the data in question. The second is to compare the measured data with the predictions from a model.

- **Estimating the quality of data**
  - Estimate the uncertainty in measured quantities.
    - Describe how the uncertainty was estimated and justify what that approach gives a reliable estimate of the uncertainty (e.g., $\sqrt{n}$ theoretical estimate from counting statistics, from repeated measurements, from the resolution of the measurement tools)
    - Decide if the uncertainty changes throughout the experiment, and if it does, estimate it appropriately.
    - Quantitatively describe how the measurement uncertainty could be improved with multiple measurements, i.e., if I wanted to improve my accuracy to $X\%$, then I would need to average N trials.
  - Estimate uncertainty in derived quantities.
  - Calculate the propagated error in derived quantities.
    - Use error propagation to identify the largest sources of error in the experiment.
  - Represent uncertainty…
    - Graphically as error bars.
    - Graphically, as a distribution of results like a histogram.
    - Numerically using appropriate significant digits.
  - Distinguish between systematic and random error sources in the measured data or derived quantities.
- **Understanding the methods of statistics.** Given a particular statistical method (calculating an average, doing a nonlinear least-squares fit, a χ^2 test)
  - Explain why the method is used, what information it gives, and how it is interpreted.
  - Explain the rules for carrying out the method.
  - Give examples of the typical kind of data to use the method for.
  - Use the method to analyze and interpret actual data.
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- **Comparison of data with predictions**
  - **Decide.** Students should be able to develop a list of options for comparing measurements and predictions (e.g., is it best to predict the raw data? process data so it is easier to compare with a general theory or compare across experiments? Is there a standard in the field?)
    - Appraise a list of the relative merits of the options and defend a particular choice for presenting the analysis.
  - **Graphical.** Making plots of theoretical predictions and data with correct labels, legends, and annotations.
  - **Use fits based on a model**
    - Obtain best fit parameters.
    - Obtain errors in best fit parameters.
    - Interpret errors in best fit parameters.
    - Compare the fit with expectation to determine if the best fit is likely converged to the optimal set of fit parameters (particularly important for nonlinear model fitting).
    - Plot residuals and use the plot to determine the presence of systematic error sources.
    - Compare the size of the residuals to the estimated random error in the measurements.

- χ^2 Compare the measured data and predictions using χ^2 to estimate the likelihood of a discrepancy being due to random fluctuations, or something else.
    - Students should be able to explain why $\chi^2 \ll 1$ indicates that the uncertainty has probably been overestimated.

Design

Designing apparatus and experiments and carrying out experiments

A complete experiment includes all that is in the modeling category: making prediction, taking measurements, and doing a comparison. In addition, it adds aspects related to a broader view of scientific inquiry, engineering design, and troubleshooting technical problems in the lab. There are also key metacognitive strategies that are valuable when carrying out an experiment.

- **"Testable research questions"**
  - Write a well-defined testable research question that
    - specifies the independent, dependent, and control variables.
    - And sufficiently operationalizes all variables so that they can be measured.
  - Example:
    - General question: *"How does the shape of the aperture affect the diffraction pattern?"*
    - Testable research question: *"How does the width of a parallel slit affect the 1D intensity distribution in the diffraction pattern."*
- **Wise design**
  - Explain how the experiment that they design and carry out can be used to answer the testable research question.
    - Describe other experiments that could perform a similar test and justify why this one is most appropriate.
  - Use predictions about the physical system to set requirements for the apparatus (e.g., resolution, noise, and dynamic range of the measurement tools.)
  - Use the requirements as design goals for the apparatus and experiment. Don't overshoot the requirements unless it is extremely easy to accomplish.
  - Evaluate practical and/or efficiency considerations and use them to constrain the design.
  - Given any particular setting in the experiment (e.g., sample rate, gain setting, length of interferometer arms) students should be able to defend their choice as better or why it is one of a range of equally reasonable settings.
  - In general student should be in the habit of asking and answering the following questions:
    - Is that experiment/apparatus good enough?
    - What counts as "good enough"?
    - How can I tell if my system is good enough (short of running the whole experiment)?
- **Calibration** Students should be able to define a model of the measurement system and take measurements in a simple test case to evaluate the model, and perhaps refine it. This process is usually called "calibration".
- **The quick check**…Continually be in the habit of doing a "quick check" experiment prior to taking a long set of data, so that they can be sure the apparatus is working as expected and it is worth taking the time for the data.

- **Plotting of data.** Students should plot data during the experimental setup in order to continually compare with predictions and evaluate the data.
- **Lab notebooks**
  - Students will use their lab notebook to record their thinking
    - At the start of each day to set an agenda and plan for the day's activities.
    - While they are solving problems, debugging, modifying their setup, designing apparatus
    - At the end of the day to summarize key results and a to-do list for next time and a list of unanswered questions.
  - Students will use their lab notebook to record the following kinds of things.
    - Diagrams of the setup
    - Relevant settings on equipment.
    - Location of saved data
    - Tables of hand recorded data with units
  - Students will use their lab notebook to present preliminary results
    - Plots of data should be generated while doing a lab, and as results are plotted, they should be printed and taped into lab notebooks.
  - Students will be able to use their lab notebook to answer questions about data from many weeks prior, once their memory has faded.

Troubleshooting

Troubleshooting should be viewed as a condensed version of the scientific process. Students should bring to bear all their skills in modeling and experimental design while troubleshooting. In particular, they should consider their system, make predictions about what it does, measure what it actually does, decide if the difference is significant enough to investigate further and/or identify a particular component as the culprit and then fix it.

- Divide the system in to a set of linked subsystems and understand the operation of the components sufficiently so they can describe the subsystems build up to the whole.
- Students should make predictions about the expected behavior of a well-functioning subsystem.
- Devise an experimental test of the subsystem and compare with predictions to determine if the subsystem is functioning properly.
- The sequence of tests should be orderly so that the student will converge on the trouble spot.
- The process should be efficient, not duplicating tests, and should use their past experience and other knowledge to decide if certain issues might be more likely than others.
- Lab notebooks should be used for recording and interpreting troubleshooting results.

Communication

Argumentation

This argumentation, broadly speaking is the process of convincing an audience of a claim using supporting evidence and reasoning, and by considering other alternative claims as less well-supported. However in physics, argumentation sometimes takes a slightly narrower form. It is reasonable to say that physicists "understand" a physical system when they possess both a quantitative predictive model and measurement tools to quantitatively investigate it in the laboratory. The goal of the argument is to convince the reader that an appropriate and accurate predictive model can be used to describe a set of reliable quantitative data about an interesting physical system.

- **Because Physics arguments almost always receive significant support from quantitative predictive models, it is important to convince the audience your predictive model is appropriate and accurate** (see Modeling the physical system)
  - Students should be able to explain the basic physics ideas in a model.
  - Explain the limitations in the model and why it is appropriate to use here (a bad example would be "because the data looked like this functional form")
  - Use graphs, diagrams, and equations to show how the model is used to make predictions.
  - Make predictions that can be compared with measurements.
- **Description of the experiment**:
  - State the testable research question.
  - Describe the experiment and justify how it can be used to answer the research experiment.
  - Identify the independent, dependent, and controlled quantities.
  - Identify any unknown parameters in the measurement or predictions. Explain why these are unknown and why it is reasonable for these to vary in a fit.
  - Describe how the parameters in the apparatus or measurement were optimally chosen, or at least justify why the data is sufficient to not warrant further optimization.
- **Make a case the data is believable, convincing, accurate, and interesting**
  - Demonstrate the sufficiency of the data by measuring all important quantities needed as inputs for the predictive morel or for the data analysis.
  - Take data that is sufficiently complete to capture the important physics phenomena.
  - Explain the basic physics ideas governing the measurement tools.
  - Explain quantitatively the ideal behavior of the tools and discuss the limitations.
    - Demonstrate the instruments were within being used in appropriate ways.
  - Explain any further data processing to the raw data prior to comparison with predictions, including equations when necessary.
  - Quantify the quality of the data using statistics.
    - Describe the sampling method and how is was chosen to optimize the quality of the measured data (e.g., was it sampled to capture the interesting features, averaged to improve signal to noise, or was the scope just happened to be on that setting.)
    - Describe how the uncertainty is estimated.
    - Describe how the uncertainty is used in the comparison.
    - Demonstrate the repeatability of any surprising findings.
- **Presentation of data and prediction in compelling ways**
  - Presented data should be sufficient to support any claims, and it should be made clear why the data is relevant to making the claims.
  - Decide when it is appropriate to tables or graphs to present results.
  - Label all data and include units.
  - Label and scale graph axes appropriately.
  - Write informative and complete captions.
- **Analysis and conclusions**
  - If the agreement is good, it should be demonstrated using statistics such as the χ^2 goodness-of-fit test.
  - Discrepancies between should be quantitatively evaluated using graphical and statistical methods.

    - Propose alternative explanations for the data.
    - Argue for a refined model, modified apparatus, or other changes based on the previous analysis.
        - If possible, carry out the refinement and make new predictions or take new data to test if the level of agreement between the model and measurements improves.
- **Final projects** will include the additional aspects of argumentation because of the increasing level of student-initiative offered in the final project.
    - Explain why this topic is interesting to you.
    - Do a literature search and identify and read relevant background papers.
    - Synthesize the literature and explain why it is interesting to the scientific community.
    - Convert a topic of interest into a testable research questions.
    - Cite relevant prior work in such a way that it is clear what idea from the prior work is being used or built upon. (In contrast to just listing a set of references at the end which are not cited throughout argument)
    - Use the background literature to
        - Inform the development of quantitative models
        - Inform the design of the experiment.

Communicating in authentic forms in the discipline

The oral presentation and written paper should be exercises in argumentation as described in detail above. In addition to those considerations we include the following:

- **Oral Presentations**
    - Present a well-organized argument using a slide show with oral explanations.
    - Emphasize the biggest ideas during the 10-15 minute time limit + questions.
    - Use good PowerPoint style and oral presentation style.
    - Evaluate their own work and that of their peers in the categories of argumentation and style using established rubrics for the course.
- **Written papers**
    - Present a well-organized argument using a written report.
    - Write sentences that are well constructed.
    - Use standard writing conventions for grammar, punctuation, and spelling.
- **Posters** are not going to be part of the course, though they are authentic.

Technical lab skills

Computer-aided data analysis

- **Making predictions.** Use analytical and computational modeling tools from lecture courses (e.g., numerically solving an ODE) to make predictions.
    - Numerical solving of different equations.
- **Data analysis:** Use Mathematica or similar computational packages to implement any of the standard statistical tests described in learning goals for “Using statistical analysis…”
- In addition, the following skills are key

- Handling data
  - Import common data file types (CSV, txt, binary)
    - Identify file structure and delimiter by opening the file in a text editor like Microsoft Notepad.
  - Import header information
  - Apply basic array operations to manipulate data (e.g., transpose, selecting subsets, pick a column, pick a row, element, other subset)
- Plotting
  - Plot data
  - Plot functions (mathematical expressions for the predictions).
  - Use all the different axes (linear, log-linear, log-log, polar)
  - Make 3D plots using surface, contour, and image/array plots
  - Add error bars to plots
  - Add and format labels, legends, and annotations
  - Combine plots of data with fits or theory.
  - Use standard formatting techniques for prettier plots (e.g., line colors, markers, font sizes)
- Fitting
  - Carry out linear and nonlinear fits.
  - Evaluate and decide whether it is appropriate to use linear or nonlinear plots.
  - Choose weights based on estimated uncertainties and include weights in the fitting algorithm.
  - Obtain best fit parameters and parameter errors.
  - Plot fits with data.
- Time and Frequency domain methods. (Sampling and analysis)
  - Use FFT methods to learn about the spectral information in data.
  - Describe FFT array is ordered in frequency.
  - Create a frequency array based on the sample rate and number of samples.
  - Quantitatively, state how the spectral data changes
    - when the sample rate is change?
    - when the number of samples is changed?
  - Calculate power spectrum and power spectral density using the FFT and sample parameters.
    - Explain how the normalization is chosen.

- **Mathematica Specific**
  - Use Mathematica's notebook formatting capabilities to produce easier to read and better-organized documents that include data analysis, tables, graphs, pictures, equations, and calculations.
  - Using the built-in help to learn new functions.

LabVIEW

- Students should be able to create a simple VI starting with a blank VI which does the following:
  - Record data from the NI USB-6009 DAQ
  - Plot the data
  - Add controls for the sample rate and number of samples.
  - Save the data to a spreadsheet
    - Select the delimiter and the format of the numbers (digits of precision).

- Using LabVIEW to increase their ability to record, visualize, analyze, and interpret data.
- Use LabVIEW built-in help to solve their own problems or look up new functions or example code.

Basic test and measurement equipment

Oscilloscope

- Choosing the scales depending on the features of interest in the signal.
- Controlling the trigger to capture the desired signal.
- Use cursors to measure features in the time or voltage.
- Use the measurement tools for obtaining a DC value, Peak-to-Peak range, etc.
- Save data to USB flash drive.

Optics

- Mount lenses and mirrors in mounts.
- Mounting components to the table with bases and clamps.
- Cleaning optical surfaces.
- Beam walking using two mirrors.
- Aligning a lens in a beam path.