Comparative Cognitive Task Analyses of Experimental Science and Instructional Laboratory Courses

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Undergraduate instructional labs in physics generate intense opinions. Their advocates are passionate as to their importance for teaching physics as an experimental activity and providing "hands-on" learning experiences, while their detractors (often but not entirely students) offer harsh criticisms that they are pointless, confusing and unsatisfying, and "cookbook." Here, both to help understand the reason for such discrepant views and to aid in the design of instructional lab courses, I compare the mental tasks or types of thinking ("cognitive task analysis"[1]) associated with a physicist doing tabletop experimental research with the cognitive tasks of students in an introductory physics instructional lab involving traditional verification/confirmation exercises.

Examining the detailed cognitive activities of experts has proven to be useful in designing effective learning activities[2-6] and in designing better measurements of how well students are learning to think and solve problems like experts in the relevant field.[7] An important finding of the research into the acquisition of expertise is that a fundamental requirement for developing expertise is that the learner must explicitly practice all the components of expertise, with guiding feedback on his or her practice.[8] This finding makes it clear why cognitive task analyses are important.

Below I give a list of cognitive activities that a scientist goes through in the process of doing experimental research, based on my career in experimental atomic physics. How well a physicist executes these tasks is a measure of his or her expertise. Scientists from a number of other disciplines confirmed that these generally apply in much the same way in their fields, although the specifics vary. Each item listed contains a rich set of mental models, procedural and factual knowledge, and self-testing procedures and criteria that are quite specific to the context. For example, while there are general strategies to use in troubleshooting a misbehaving apparatus, such as subdividing and analyzing the behavior of the component parts, the optimal division and the performance to measure depends on the nature of the apparatus. Although I list them below as a clear chronology, that is misleading. There is frequent looping back to an earlier stage to make modifications.

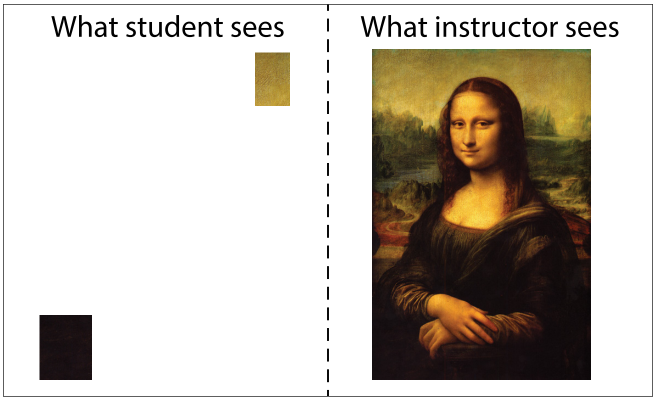

Fig. 1. Illustration of contrast between student and instructor views of a typical introductory laboratory with traditional verification exercises.

Cognitive tasks involved in carrying out experimental physics research

1. **Establishing research goal:** *What are the goal(s) and question(s) of the research?**
    - a. Deciding if the goal is interesting, timely, worthwhile, etc.
    - b. Predicting if the goal is sufficiently ahead of current knowledge to be interesting but not so far ahead that it might have too high a risk of failing or be ignored.
    - c. Evaluating whether the research question is consistent with the constraints on funding, time, equipment, and laboratory capacity, including personnel.
2. **Defining criteria for suitable evidence:** *Deciding what will constitute suitable evidence to achieve the goal by developing and/or utilizing existent criteria:*
    - a. What data would be convincing given the state of the field?
    - b. What variables are important and how might they be measured and controlled?
    - c. What types of experimental controls and checks would need to be in place?
3. **Determining feasibility of experiment**
    - a. Predicting whether or not it is realistically possible to carry out the experiment, and, if it is, analyzing the scale of time and money required and deciding if these are reasonable. (This involves a more detailed reiteration of 1.c.)
    - b. The researcher must also analyze contingency options, if the results of the experiment are not what is hoped for. Will the data produced still provide novel publishable information? Will the results show how to improve the apparatus to achieve conditions needed to obtain hoped-for results?

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4. Experimental design

- **a.** Exploration of many possible preliminary designs (requires clear definition of the optimum depth of analysis of the alternative designs).
- **b.** Analyzing relevant variables that may lead to systematic errors in results and interpretation. This requires having complex cause and effect models for the experiment. (Will be repeated after measuring performance of the apparatus.)
- **c.** Finalizing the design, taking into account construction details and performance requirements of each component. Often requires bringing in additional expertise.
- **d.** Developing detailed data acquisition strategy: How much data to take and over what parameter ranges, how long to accumulate data in each measurement, in what order are things measured, which measurements do you repeat and how often? Deciding on required precision and accuracy: This includes deciding which quantities need not be measured. This must take into account constraints on time, clarity of results, all potential statistical and systematic uncertainties, and the importance and requirements for distinguishing between different potential interpretations of results. (This step is repeated/revised after performance of apparatus has been measured.)

5. Construction and testing of apparatus*,**

- **a.** Deciding who should build the various parts and on what schedule (in-house, purchase standard parts, special construction by outside companies, etc.). Requires evaluation and application of trade-offs of cost, construction expertise, time, degree of confidence as to specific design details.
- **b.** Developing criteria and test procedures for evaluation of the apparatus components as they are completed.
- **c.** Collecting data on performance of specific components and full apparatus.
- **d.** Developing procedures for tracking down the source of malfunction when the individual components or the assembled apparatus do not perform as designed. This necessarily involves deep familiarity with the respective hardware and a repertoire of troubleshooting regimes that are highly specific to the field, the apparatus, and the approach being used.**
- **e.** Figuring how to modify particular parts, or overall apparatus, as needed according to test results.
- **f.** Reiterate data acquisition strategy 4.d., taking into account actual performance of finished apparatus.
- **g.** After completion, collecting experimental data.

6. Analyzing data

- **a.** Modeling the data by suitable mathematical forms, including deciding which approximations are justified and which are not.
- **b.** Deciding on what statistical analysis methods and procedures are appropriate.
- **c.** Calculating the statistical uncertainty.
- **d.** Calculating the systematic uncertainties as needed (often already done as part of the data acquisition strategy).

7. Evaluating results*,**

- **a.** Checking the results, when they come out differently than expected. This involves calling on complex mental models incorporating a web of cause and effect relationships, strategies for separating relevant and irrelevant information, complex pattern recognition and search algorithms. (Also usually involves extensive additional data collection, and possible modification of apparatus and redoing data collection.)
- **b.** Testing data that come out as expected. Identify redundant tests for possible systematic errors, being particularly sensitive to experimenter biases.

8. Analyzing implications if results are novel and/or unexpected and confirmed

- **a.** What are plausible interpretations or new theoretical or experimental directions implied by these results?*

9. Presenting the work

- **a.** Follow standard data display procedures or, as needed, develop new procedures that highlight critical features of methods or results.
- **b.** Explain the work so the broader context and uniqueness of the work, the apparatus, the procedures, and the conclusions are easily understood, and the audience/readers perceive it to be of maximum interest and significance.

* Requires extensive expertise in the research field.

** Requires extensive experience with the relevant equipment.

The "Recommendations for the Undergraduate Physics Laboratory Curriculum" report[9] from the AAPT Committee on Laboratories lays out detailed recommendations for learning outcomes in six different areas, which are intended to help students learn to think like physicists. That report is much longer and more detailed than this, but the outcomes given correspond well to what I list above. (That may not be entirely coincidental, as the committee had an unpublished draft of this analysis during its deliberations.)

Cognitive tasks involved in a traditional verification/confirmation introductory instructional laboratory

In a typical instructional lab class, the student uses a given apparatus to confirm an established scientific result. So one can see most of the cognitive tasks have already been carried out and the students are simply given the result. For example:

- Given — research question: "Measure *g*"
- Given — data to collect: "period and length of pendulum"
- Given — feasibility analysis
- Given — apparatus design
- Given — construction
- Given — components already built and tested
- Not given — data, get to collect

- Given — analysis methods
- Not given — statistical uncertainty
- Given — what correct answer is, what instructor wants to see
- Given — format for write-up, data tables, and graphs
- Given — significance and context (making clarity of presentation and argument largely irrelevant)
- There is no time to go through the multiple iteration cycles

Of the cognitive tasks required for experimental science listed above, the only components found in a typical instructional lab are 6.c. Calculating the statistical uncertainty and some portions of:

4.d. Developing detailed data acquisition strategy
9.a. Follow standard data display procedures
7.a. Checking the results, when they come out differently than expected

7.a. requires far greater expertise than is reasonable to expect of typical introductory students if they are analyzing anything beyond the simplest of experiments. Similarly, it is unrealistic to expect a reasonable analysis of systematic errors if the students have not carried out items 1-5. Finally, the typical expectations for a lab report are very different from item 9.

In designing and building experiments for instructional lab courses, instructors do go through most of the cognitive tasks required for experimental science, but running such an experiment after the design, construction, and troubleshooting is completed is a very different experience for the student. An analogy that helps illustrate this difference is shown in Fig. 1.

To faculty, instructional labs are like doing real physics research, because they are projecting a background and context into them. To students, those same labs are intellectually sterile meaningless exercises. They lack that background and context, and so see little cognition and/or satisfaction in the activities.

It is important to realize that no lab class was designed to be a pointless cookbook exercise, but there are powerful structural features in the education system that drive them in that direction. Labs that were originally designed to be much more open-ended and allow more student freedom and creativity seldom stay that way for long, particularly once the original designer/instructor is gone. The reason is that for the people who are then running the lab course on a regular basis—the lab coordinators, teaching assistants, and subsequent instructors—when the experiments are not working or not giving the proper "official" results, and/or students do not know what to do, this is a problem not a feature to them. It needs to be fixed, and the fix is always to make the apparatus more operator proof and provide the students with more detailed instructions on what to do. This journal is filled with advertisements for apparatus that provide such solutions. For instructors who believe that doing an experiment (i.e., taking data and analyzing it in some form) in itself produces learning, this is also an improvement, because it means more experiments can be completed in a given time. This is an example where the intentions of all involved are good, but the nature of the situation results in bad outcomes.

I hope that this comparative task analysis will help instructors understand why scientists see mastering expertise in experimental science as the heart of the scientific expertise and the extremely demanding and diverse cognitive requirements involved, while students see instructional labs as pointless and unpleasant. Designing instructional activities based on this cognitive task analysis and using it to evaluate the value of undergraduate research experiences may also be valuable.

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