Undergraduate instructional labs in science generate intense opinions. Their advocates are passionate as to their importance for teaching science 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, to both help understand the reason for such discrepant views and to aid in the design of instructional lab courses we compare the cognitive activities associated with a scientist doing experimental research with the cognitive activities of students in a typical instructional lab. Examining the detailed cognitive activities of experts (“cognitive task analysis”) has proven to be useful in designing effective learning activities and in designing better measurements of how well students are learning to think and solve problems like experts in the relevant field.

Below I give a generic list of cognitive activities that a scientist goes through in the process of doing experimental research. The details of how each of these generic tasks are carried out are deeply embedded in the knowledge and practices of the specific discipline. Each item listed contains a rich set of mental models, procedural and factual knowledge, and self-testing procedures and criteria that are quite discipline specific. Also, there may be additional discipline-specific cognitive activities that are not included in this list. Although I list them below as a clear chronology, in reality, the scientist frequently must loop back to repeat an earlier stage(s).

**Cognitive Tasks involved in carrying out experimental research**

1. Establishing research goal: What are the goal(s) and question(s) of the research?¹
   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 or 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 they might 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. (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

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¹ Ido Roll and Lisa McDonnell assisted with the presentation.
information? Will the results show how to improve the apparatus to achieve conditions needed to obtained hoped-for results?

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: \(^1\), \(^2\)
   a. Deciding who should build the various parts and on what schedule. (in-house, purchase standard parts, special construction by outside companies, ...?) Requires evaluation and application of tradeoffs 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. Develop 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 trouble-shooting regimes that are highly specific to the field, the apparatus, and the approach being used. \(^2\)
   e. Figure how to modify particular parts, or overall apparatus, as needed according to test results.
   g. After completion, collect 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 is already done as part of the data acquisition strategy).

7. Evaluating results: \(^1\), \(^2\)
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 separately 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 comes 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? ¹

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. Explaining 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.

¹ Requires extensive expertise in the research field.
² Requires extensive experience with the relevant equipment.

**Cognitive Tasks involved in a typical instructional laboratory.** In a typical instructional lab class, the student uses a given apparatus to confirm an established scientific result. Thus, the questions or goals are pre-established, the data to be collected largely predetermined, the experiment has been designed, and the apparatus has been constructed. Of the cognitive tasks required for experimental science listed above, only some part of 4.d., along with 6.c., 7a., and 9.a. are components of a normal instructional lab. 7.a. is the most complex cognitive activity of the three, and realistically requires far greater expertise than is reasonable to expect of a typical student in an instructional lab course if they are analyzing anything beyond the very simplest of experiments—far simpler than what they are usually given. In instructional labs, students typically also go through the procedure of writing up a lab report, but this is typically a far different cognitive task from presenting the results of a real experiment, as the lab report typically only requires filling in text and numbers to a given template.

When compared in this way, one can see the profound difference in the cognitive tasks involved in true experimental science compared to the cognitive tasks involved in a student performing the requirements of an instructional laboratory. Too often instructors assume the act of carrying out experimental measurements implies that the student is carrying out the full cognitive processes of experimental science. This erroneous assumption is responsible for much of the frustration of instructors at the lack of learning achieved by students in their instructional lab courses and for much of the frustration of students at the lack of value and meaning to the course. 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 trouble-shooting is completed is a very different experience.
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 would also enhance learning.