

# Using Students' Design Tasks to Develop Scientific Abilities

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**Abstract.** To help students develop the scientific abilities desired in the 21<sup>st</sup> century workplace, four different types of student design tasks—observation, verification, application, and investigation experiments—have been developed and implemented in our calculus-based introductory courses. Students working in small groups are engaged in designing and conducting their own experiments to observe some physical phenomena, test a physical principle, build a real-life device, solve a complex problem, or conduct an open-inquiry investigation. A preliminary study has shown that, probed by a performance-based task, the identified scientific abilities are more explicitly demonstrated by design-lab students than non-design lab students. In this paper, detailed examples of the design tasks and assessment results will be reported.

**Keywords:** Experimental designs, lab skills, scientific abilities, lab instruction, physics education research

**PACS:** 01.50.Pa, 01.40.gb, 01.40.Fk

## INTRODUCTION

This article describes experimental design tasks for students that have been developed, tested, and implemented in introductory physics labs. These design tasks are aimed at developing physics students' scientific abilities [1]. Detailed examples of the design tasks and preliminary assessment results will be reported below. This work is a collaborative effort with Eugenia Etkina and Alan Van Heuvelen at Rutgers University. For more information on scientific abilities and related rubrics, visit <http://paer.rutgers.edu/scientificabilities>; for more examples of different experimental design tasks, visit <http://www.csuchico.edu/~xzou>.

## DEVELOPMENT AND IMPLEMENTATION OF STUDENTS' DESIGN TASKS

Four different types of hands-on design tasks—observation, verification, application, and investigation experiments—have been developed for calculus-based introductory physics labs. Students working in small groups are engaged in designing their own experiments either to explore some physical phenomena, verify a physical principle, build a real-life device, solve a complex problem, or conduct an open-inquiry investigation. These design activities, including both qualitative and quantitative tasks, help students not only better understand concepts, but also think creatively and develop important workplace

skills in design, complex problem solving, scientific investigation, teamwork, communication, and learning-how-to-learn. Identified scientific abilities in conducting the design tasks, related sub-abilities, and scoring rubrics are reported in detail in Ref. 1.

An *observation experiment* asks students to “play around” using some given equipment so as to explore and observe certain physical phenomena. Fig. 1 describes an example of a qualitative observation experiment used in a calculus-based electricity and magnetism course. These observation experiments are carefully selected and given to students before related concepts are discussed in class. In a traditional instruction setting, these observation experiments are usually conducted by the instructor as lecture demonstrations while associated concepts are introduced. For many students, the experiments are more like magic shows; they have no ideas about how

### Can you generate currents without a battery?

Using the given materials, including a magnet, a Galvanometer, some wire coils, and wires, conduct some experiments so as to generate a current through the Galvanometer. In your lab notebook, please (1) sketch your experimental setup and describe what you have performed, (2) record in which ways the magnitude of the generated current could be changed, and (3) record in which ways the direction of the generated current could be changed.

**FIGURE 1.** Example of a qualitative observation experiment

they work. As a result, of course, it is difficult for students to construct the experiments as part of their own knowledge.

While using these experiments as design tasks, students themselves need to come up with some ideas and conduct the experiments. Students not only gain a better understanding of the phenomena, but no longer view them as magic. The experiments also arouse their curiosity to further study the phenomena, which is evident from the many questions students ask when the phenomena are discussed in subsequent classes.

Many observation experiments have been developed covering the important concepts in calculus-based introductory mechanics and electricity and magnetism courses. For some electrostatic phenomena, which are difficult for students themselves to perform successfully due to physical restrictions (e.g., room humidity) in a student lab room, digital videos have been made for students to observe and construct the concepts. Those videos are available at <http://www.csuchico.edu/~xzou>.

A *verification experiment* asks students to devise an experiment to test a conceptual or mathematical model. Fig. 2 describes a qualitative verification design task given in a calculus-based mechanics laboratory. In contrast to a traditional verification experiment, students are not provided with step-by-step instructions and ready-to-go setups. Instead, they are provided with certain materials and equipment, as well as a procedure outline (see below) [2] and detailed rubrics (see examples in Ref. 1) as scaffolding and real-time feedback.

**Basic Procedure of Verification Experiment**

**Model:** State the model to be tested

**Plan:** Describe some phenomenon that can be analyzed using the model

**Prediction:** Predict the outcome of the situation

**Experiment:** Set up, conduct the experiment, and record, analyze data

**Conclusion:** Decide if experimental evidence supports the model

Using two carts and the other given equipment on your table, design and perform some situations for which you predict that the force exerted by cart A on cart B is greater than the force exerted by cart B on cart A (or vice versa).

**FIGURE 2.** Example of a qualitative verification experiment

Students work in a small group of 3 or 4 to conduct their experiments and are encouraged to follow explicitly the basic process that guides practical scientists in conducting their own experiments. It is observed that many introductory physics students have difficulties conducting such verification experiments as a scientist would since they have no similar

previous experiences. It is very important at the very beginning of lab to discuss with students what an acceptable scientific design is and what a poor naïve design is using real examples. In particular, a hypothetical-deductive reasoning [3, 4] and the power of prediction in science are addressed and emphasized explicitly with students [5, 6].

Many traditional verification experiments can be readily revised as students' design tasks. In addition, students' common-sense ideas or identified alternative conceptions can be used as "hypotheses" to be tested (see the example in Fig. 2). Ample evidence in physics education research has shown that it is very difficult to address students' "misconceptions" effectively. An experimental design task to test students' own "misconceptions" serves an innovative way to help students reconstruct their knowledge.

An *application experiment* requires students to build a real-life device or invent an experimental approach to measure some physical quantities. Fig. 3 describes a quantitative design task in measuring the maximum coefficient of static friction between a wooden block and a wooden board. To conduct such application designs, students are provided with some materials and equipment and encouraged to follow a basic process of effective problem solving (see below) [2]. A significant component of an application experiment is *evaluation*—students are required to devise an additional approach or experiment to evaluate their own design or result.

**Basic Procedure of Application Experiment**

**Plan:** Define the problem and plan an experiment

**Assumption:** State any assumptions or estimations

**Prediction:** Theoretically predict outcomes of the experiment

**Experiment:** Set up, conduct the experiment, and record, analyze data

**Evaluation:** Perform additional experiment to evaluate the result

Devise and perform an experiment to determine the maximum coefficient of static friction between a wooden block and a wooden board.  
Design and perform an additional experiment to evaluate your result.

**FIGURE 3.** Example of a qualitative verification experiment

An *investigation experiment* is a more challenging case-study which is combined with all the other three design tasks described above. For example, towards the end of a calculus-based introductory electricity and magnetism lab, students are asked to investigate the magnetic field inside a current-carrying slinky before the concepts are addressed in class. In this lab, students conduct some selected observation

experiments, come up with some conceptual ideas to account for the observations, identify possibly related physical quantities, design and conduct their own experiments to explore a quantitative model for the magnetic field inside the slinky, and finally design and conduct an additional experiment to verify or apply their own mathematical model.

## ASSESSMENT OF STUDENTS' ACHIEVEMENTS

Student experimental design tasks have been implemented and tested in calculus-based introductory physics courses with a class enrollment of about 48 students each semester at California State University, Chico since 2003. Each week the students have three one-hour lectures and are divided into two lab sections to conduct one three-hour lab. Typically, about 60% of the students are majors in engineering, 30% in computer science, and 10% in natural sciences.

To assess the impact of these innovative design tasks on students' development of conceptual understanding and scientific abilities, three types of assessment have been administered. To assess student conceptual understanding, for example, *Conceptual Survey of Electricity and Magnetism* (CSEM) [7], has been given to the second semester calculus-based physics students every seminar since fall 2003. Students' normalized gains [8] are consistently higher than 0.5 [9], which is typical for interactive engagement courses and almost double the national norm from the similar traditional classes [7].

How do students perceive the lab with design components? Do their perceptions mirror the goals of the design tasks? To answer these questions, a Q-sort instrument, *Laboratory Program Variables Inventory* [10], has been given to students since fall 2003. For example, the students from spring 2004 listed the followings as the three "MOST DESCRIPTIVE" features for the design lab: (1) "*Students are asked to design their own experiments.*" (2) "*Lab reports require the interpretation of data.*" (3) "*Laboratory experiments develop skills in the techniques or procedures of physics.*" This result [11] shows that the goals of the design tasks had been successfully conveyed to the students.

To assess students' scientific abilities, a performance-based task was given to students in both design and non-design labs at the end of spring semester 2004. Both groups of the students had learned a semester of mechanics in a traditional format, but the students from the design-lab had an additional semester of electricity and magnetism (E&M) with design tasks. Since the content of the task (see below) is in mechanics, it is reasonable to expect

that both student groups would have similar performance; the training with design tasks in E&M would have little impact on how the students conduct the experiment in mechanics.

A short, theoretical, but *fake* "scientific paper" [12] was given to both student groups a week before the lab. The paper theoretically argues that for falling cotton balls the distance as a function of time should be  $s = (1/2)kt^2$ , where  $k$  is a constant but smaller than  $g = 9.8 \text{ m/s}^2$ . The students were asked to design, conduct, and report an experiment to test the theory in a three-hour lab.

As shown in Table 1, most students from both the design and non-design labs explicitly followed the procedures emphasized in each lab to report their results. Then students' reports were analyzed anonymously and independently by two researchers using the identified scientific abilities (see Table 2) [1] and response taxonomies (see Table 3) developed particularly for this lab based on related rubrics [1]. Discrepancies between scores given to a particular ability in a particular report were carefully discussed between the two researchers and agreements were reached at the end. Percentages of students' scores on the six identified scientific abilities are shown in Table 4 for both the design lab and the non-design lab. One major difference shown in Table 4 is that about 70% of the non-design lab students did not make any predictions in their experiments, while about 90% of the design lab students made reasonable predictions. To compare the students' overall performance from

**TABLE 1.** Format of students' lab reports

<b>Design Lab</b> (Students = 42, Lab groups = 17)	<b>Non-Design Lab</b> (Students = 25, Lab groups = 10)
<p><b>81% explicitly</b> wrote their reports following the format emphasized in the lab for a testing experiment:</p> <p><b>Model</b> <b>Plan</b> <b>Prediction</b> <b>Experiment</b> <b>Conclusion</b></p>	<p><b>96% explicitly</b> wrote their reports following the format emphasized in the lab:</p> <p><b>Introduction</b> <b>Procedure (or Experiment)</b> <b>Conclusion</b></p>

**TABLE 2.** Scientific abilities used to analyze students' reports from the design and non-design labs

1. Ability to identify the model to be tested
2. Ability to make a reasonable prediction based on the model to be tested
3. Ability to design a reliable experiment to test the prediction
4. Ability to analyze data appropriately
5. Ability to decide if or not to confirm the prediction based on the experiment results
6. Ability to make a reasonable judgment about the model

the two labs, the data was run by a Mann-Whitney U Test (two-tailed). The result is that the total score of the design lab is statistically significantly ( $p < 0.002$ ) higher than the total score of the non-design lab. This preliminary result indicates that the scientific abilities demonstrated by the design-lab students are more explicit than those by the non-design lab students.

In summary, this paper has reported on four different types of hands-on design tasks that have been developed, tested, and implemented as formative assessment activities to advance physics students' scientific abilities. Preliminary assessments have shown that students exposed to the design lab

perceived the basic goals of the design tasks, gained a good conceptual understanding, and demonstrated some desired scientific abilities in the given performance-based experiment. Carefully-designed studies will be further conducted to investigate how students' thinking processes are different in performing a design task and a traditional experiment. Moreover, based on the scientific abilities and scoring rubrics developed in this project, a simulated physics experiment is being investigated for potential use as a diagnostic tool to assess students' scientific abilities learned in the introductory physics laboratory.

**TABLE 3.** Example of response taxonomy for analyzing students' lab reports

Score	0	1	2	3
<b>Ability</b>				
<b>2. Ability to make a reasonable prediction based on the model to be tested</b>	No <i>explicit</i> prediction.	"My prediction is that the distance formula $s=1/2kt^2$ is not valid because my experience is that $s=1/2gt^2$ ."	"If our model is correct the cotton balls will take longer to fall than the heavier object. Therefore $k < g$ ."	"If the model is true, then the slope of $s$ vs. $1/2t^2$ should be constant $k < g$ ."

**TABLE 4.** Percentages of students' scores on six identified scientific abilities from the design lab and non-design lab

Score	Design Lab				Non-Design Lab			
	0	1	2	3	0	1	2	3
1. Identifying model	2	17	64	17	12	8	24	56
2. Making prediction	2	7	76	15	72	4	24	0
3. Designing experiment	0	9	17	74	0	28	24	48
4. Analyzing data	0	26	43	31	0	68	0	32
5. Confirming prediction	12	7	17	64	64	16	4	16
6. Making judgment	9	64	17	10	8	92	0	0

## ACKNOWLEDGMENTS

Special thanks go to Eugenia Etkina, Alan Van Heuvelen, Sahana Murthy, and other members of the PAER group at Rutgers for their collaboration and support. The NSF funding for this project (DUE #0242845) is also greatly appreciated.

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explicitly acquire some basic procedural knowledge in conducting scientific experiments. It is observed that the procedure outline is important to lead students conducting their experiments successfully at the beginning of the lab. While their abilities and interests in design tasks grow, the outline is not needed any more.

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