Exploring Expert Reasoning through an Optics Assessment

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Abstract

This paper discusses an optics assessment designed to measure problem-solving decisions in the context of optical engineering. It is part of a larger, cross-disciplinary collaboration to identify important problem-solving decisions across science, engineering, and medicine and create assessments that measure these decisions within the context of a given field. We describe the structure of the assessment, the problem-solving decisions it assesses, and our qualitative analysis for the refinement and preliminary evaluation of the assessment. We used think-aloud interviews to observe students' problem-solving processes as they worked on this assessment. Students struggled with creating predictive frameworks, constraining the solution space, and reflecting on solutions. From the results of this analysis, we are creating a shorter, computer-based version of the assessment that still captures the most difficult problem-solving decisions, but allows for easier analysis and testing on a larger sample size.

Introduction

From ABET criteria to the DBER report from the National Academy of Sciences, our community acknowledges the importance of skills beyond content knowledge, yet very little research has been done to define and assess these skills [1] [2]. The goal of our cross-disciplinary collaboration is to identify important problem-solving skills across science, engineering, and medicine and to create assessments that measure these skills within the context of a given field. This paper discusses a particular assessment developed for optical engineering, called optics black box, which is designed to test a number of problem-solving decisions. Students worked on this assessment during think-aloud interviews, which allowed us to hear their problem-solving processes in depth. From this, we were able to refine the optics black box problem for increased clarity, gauge students' strengths and weaknesses on the problem-solving decisions, and determine which decisions differentiate students. The struggle students had with this optics problem highlights current deficiencies in the standard learning environment and highlights areas of problem-solving where teaching might be improved.

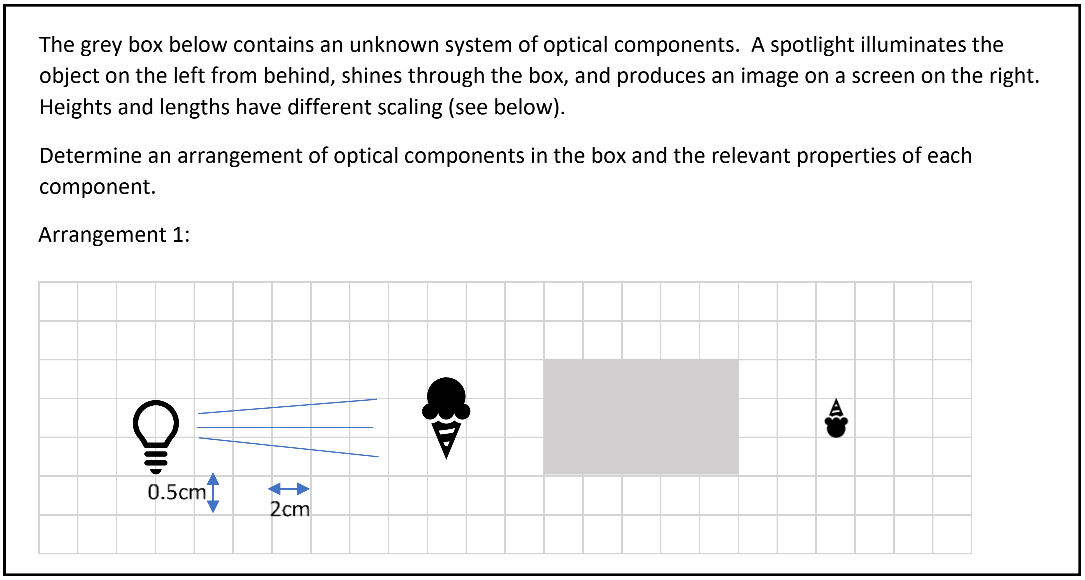
We are not the only ones to attempt to measure problem-solving skills in the context of physics and engineering. Jonassen spent many years investigating the role of problem-solving in engineering design [3]. Novice-expert comparisons of problem solving have been carried out by Chi et al. in the context of physics and Atman et al. in the context of mechanical engineering design [4] [5]. Atman et al. found discrepancies between students and experts in identifying criteria, constraints, goals, and requirements along with approaches to gathering information, which is consistent with our own findings. Researchers have also attempted to teach problem-solving skills, specifically identifying key features, in the context of mechanical engineering [6]. Our work focuses on the role of decisions in problem-solving. We seek to create an instrument that measures the problem-solving decisions students are successfully making in the context of optical engineering. We expect it to support improved teaching and learning in the future. We describe the structure of the assessment, the problem-solving decisions it assesses, and our qualitative analysis for the refinement and preliminary evaluation of the assessment.

Methods

Expert problem solving was defined through expert interviews. Interviewees were established scientists, engineers and doctors in both academia and industry. The standardized interviews were based off a cognitive task analysis protocol [7]. The experts were asked to recall a specific research project they had completed in the recent past and describe it step-by-step, emphasizing the decisions they made. General themes common to all fields included the characterization of problems according to important features, requirements and goals, use of predictive frameworks, determination of information needed and how to gather it, and substantial reflection on both expected and unexpected results. These problem-solving decisions are similar to the overarching themes identified by Polya: understanding the problem, devising a plan, carrying out the plan and looking back [8]. The results also agree with work on design problem solving by Jonassen, which emphasizes the importance of determining design requirements and creating constraints [9]. A detailed analysis of the interviews with unified terminology across the fields for the expert problem-solving decisions is currently being developed and will be published elsewhere.

The rest of this work described here focuses on the specific optics black box assessment, which was created based on common problem-solving decisions from the above-mentioned interviews. The problem has three different scenarios, each with a spotlight shining on an ice cream cone. The light then passes through a black box and creates an image on a screen some distance away. Students must determine the location and properties of the lens(es) in each box (see Figure 1). This is similar to a problem-solving assessment previously developed by our research group, in which students had to figure out a hidden electrical circuit [10]. Unlike a standard work forward homework problem, this problem requires students to take the given output and create a set of requirements and constraints for their solution using the predictive frameworks and equations they know relating to lenses. It is an open-ended question, in which there may be multiple solutions. The scenario is also laid out on graph paper, so students must acquire all measurements themselves, including determining which ones they actually need. Table 1a lists the skills being tested, which were pulled from common decisions found in the expert interviews.

Work is in progress evaluating the optics black box as a problem-solving assessment tool. First the problem was test-solved by two optical engineers with 20+ years of experience in the field to make sure the problems were clear, understandable, and appropriate difficulty. Next, seven student volunteers, who have taken at least one optics class, were asked to solve these problems out loud with scratch paper while being videotaped and observed by a researcher. They were given roughly 45 minutes to solve the problems. Students could ask for specific formulas, and the researcher intervened in rare cases when a student made no progress after multiple minutes. Care was taken to intervene as minimally as possible and with a guiding question rather than a statement to induce reflection. To better analyze the results, a timeline of decisions was created for each student from the transcribed audio and student’s written notes. Whenever a student portrayed one of the skills in Table 1a, a note was made of the specific way the skill was used. This coding allowed us to look for what skills differentiated students.

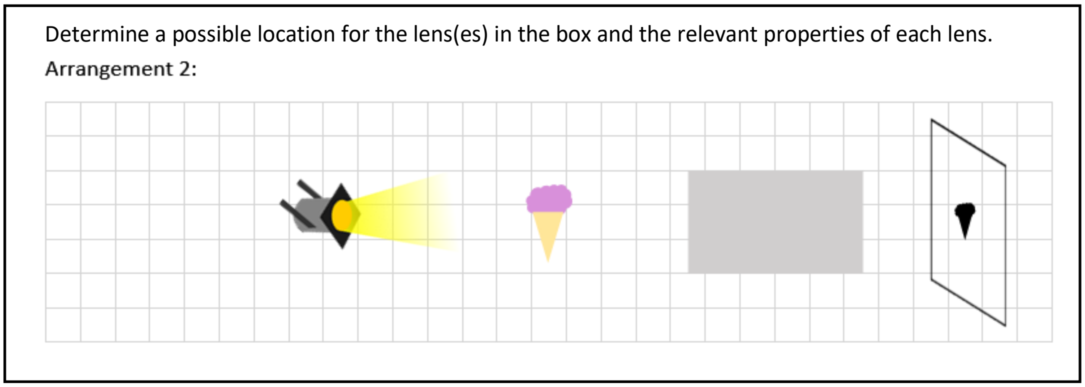


The grey box below contains an unknown system of optical components. A spotlight illuminates the object on the left from behind, shines through the box, and produces an image on a screen on the right. Heights and lengths have different scaling (see below).

Determine an arrangement of optical components in the box and the relevant properties of each component.

Arrangement 1:

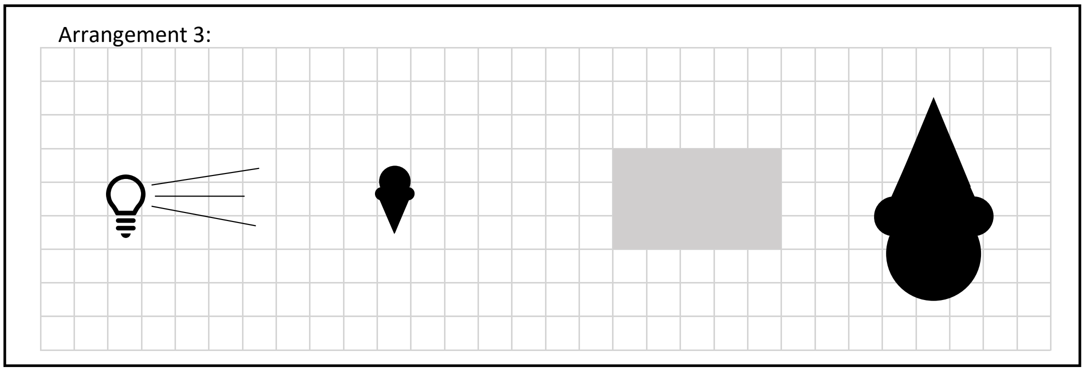
Figure 1a: Example original black box presented to students.



Determine a possible location for the lens(es) in the box and the relevant properties of each lens.

Arrangement 2:

Figure 1b: Example updated black box, based on student confusions.



Arrangement 3:

Figure 1c: Example format created for online version, refined by combining student and expert feedback.

Results

The optics black box problem was surprisingly difficult for students, given that most had taken optics in the previous quarter. Students averaged about 20 minutes to solve the first problem, which has only one possible location for the lens. Multiple students commented that the problem was much more difficult than class, where "we were always told the location of the lens." No student managed to get a quantitative solution to arrangement three, which was expected, since the experts said they would normally use design software to get the final numbers for arrangement three.

Table 1a: Skills Meant to Be Tested **Table 1b:** Differentiating Skills Found

Choose predictive framework	Start with qualitative predictive framework
Identify key features	Consider whether predictive framework applicable
Determine and collect needed quantities	Plan and collect only necessary measurements
Identify constraints	Constrain solution space using predictive framework + understand free variables
Consider multiple possible solutions	
Modify approach as necessary	Check solution meets all stated criteria using predictive framework
Reflect on solution	

Italicized skills were found to be portrayed by all students.

All the problem-solving skills being tested were shown by at least some of the students during the think-aloud sessions. All seven students quickly identified that the problem involved lenses, wrote down the Lensmaker equation, and drew a basic ray diagram, but four students struggled with incorporating the magnification equation into their plan. All students also successfully identified the important features of the problem and collected measurements, though three collected extraneous measurements of the distance between the spotlight and the object. Furthermore, all students recognized that there were multiple potential solutions to problem two, but they had more difficulty coming up with suitable constraints on the solution. They also all noticed that a single lens would not fit in the box for problem three and changed method accordingly. Three students also correctly modified their predictive framework as they remembered more content knowledge or realized a discrepancy between their math and ray diagrams.

While all students showed problem-solving skills, some students had more success reaching a suitable solution. Only two students were able to come up with suitable solutions for all three problems, and they were also the only two students to portray all the differentiating problem-solving skills. We found the biggest differentiating factor was a student's ability to construct and use multiple predictive frameworks to create, constrain, and reflect on potential solutions (see Table 1b). Three successful students developed a predictive framework relating focal length and object distance to qualitative magnification, which also allowed them to reflect on their solution. In contrast, the three students who immediately used an equation-based approach later struggled with constraining solutions. Checking whether the point-source, thin-lens predictive framework was actually applicable in this specific case, also correlated with greater success for four students. In regard to constraints, four students used a predictive framework to eliminate lens combinations that would not work. Furthermore, the four students who reached a numerical solution in problem two were able to do so, unlike the others, because they realized that they could constrain the system by setting a variable to a value of their choosing. Of those four students, only two noticed that their solution fit in the box, and they were also the only two students to routinely check that their solution met all stated criteria, which they did using a post-solution ray tracing check. Thus, these differentiating skills might be a good metric to assess and compare students who were not able to fully reach a potential solution.

As a result of the expert solutions and student think-aloud interviews, the problem has been changed several times to fix misunderstandings, add grid marks, make the drawings realistic, and create easily divisible numbers (see Figures 1b and 1c). To allow us to test the assessment on a larger number of students, we have put the assessment online and modified it. This new format requires minimal math calculations and instead focuses on three of the differentiating skills identified above: creating qualitative predictive frameworks, constraining the solution space, and reflecting on the solution. Ultimately, we would like an assessment of manageable length that is quick and easy to analyze, provides meaningful insights into the problem-solving decisions of students, and allows differentiation of students based on these decisions.

Conclusion

An optics assessment was created to test problem-solving decisions, which were defined by interviews of experts in various disciplines describing how they solved particular problems. To test the optics black box problem, we gave it to a number of optics experts and students. Using a think-aloud protocol we were able to watch students' problem-solving approaches and identify whether they made the decisions targeted in the creation of the assessment. Students struggled with creating predictive frameworks that allowed them to constrain the problem and reflect on their answers. The results also show the potential of problem-solving skills as a measure of student performance. We are now creating a shorter version of the assessment that will still capture the difficult problem-solving decisions, but allow for widespread use and easier analysis. We are also developing similar assessments for circuits and signal processing. We hope that such assessments could be used to evaluate teaching in electrical engineering, by giving them to students who are graduating from the program or have completed particular relevant courses.

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