

## **Integrated Science and Engineering Design Assessment to Support Teaching and Learning (Fundamental)**

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## **Abstract**

Engineering design has become an integral part of K-12 science education with the release of the Next Generation Science Standards (NGSS) and their adoption by almost 20 states. Both the core ideas and practices in the new standards include engineering design. Significant anticipated challenges have been described related to the prospect of teaching and assessing this new aspect of the science curriculum. Two of the primary challenges are that (a) few science and general education teachers have the knowledge and skill to guide students in engaging in design activities that integrate engineering and science and (b) assessments currently being used in the K-12 arena do not measure engineering design and cannot easily be adapted to do so. In this paper, I describe research efforts to inform the development of assessments that engage students in a design process. The focus here is on the use of student engagement in a paper-based design activity with the students' design goal being to suggest improvements to a solar still such that it could be used to provide drinking water for households that have access to ocean water but limited access to fresh water. The data collected as pairs of students engaged in the activity are being used to inform development of an interactive online simulation for a design activity that is currently being developed as a performance assessment that might be used formatively to guide instructional decisions around engineering design.

## **Background**

The vision for science education presented in the framework for the Next Generation Science Standards (NGSS) (National Research Council [NRC], 2012) includes both science and engineering. The standards place equal emphasis on the need for preparing students for STEM-related careers and citizenship in a society where science, engineering, and technology permeate all aspects of our lives. While aspects of technology and engineering have appeared in some K-12 science classrooms and, to a limited extent, in prior national science standards, the NGSS present a true integration of science, engineering and technology (Sneider and Purzer, 2014). This is a new approach to teaching science that will require new curriculum materials, professional development and other supports for teachers, and new assessments (Penuel, Harris, & DeBarger, 2015).

Teachers who are generalists as well as those certified in science typically have very little knowledge of and experience with engineering content or practices (Cunningham, 2009; Custer & Daugherty, 2009). They will need professional development to effectively use engineering design pedagogies (National Academy of Engineering [NAE], 2009). A system of assessments including formative and summative assessments designed specifically to integrate science core ideas, cross-cutting concepts, and science and engineering practices may contribute to science teachers' ability to successfully incorporate engineering design in their classrooms, provided these are coupled with professional development.

Formative assessment as described by Black and Wiliam (1998) is what occurs when information about learning is elicited and the teacher then adjusts instruction based on that

information. There is great potential for formative assessment to improve student outcomes, but effective implementation of formative assessment is difficult for teachers to achieve (Herman, Osmundson, Dai, Ringstaff, & Timms, 2015; Wylie, & Lyon, 2015). That potential is most often not realized because of the complexity of interpreting the evidence that teachers collect in the form of student work. Therefore, the feedback teachers provide is less than optimal, as are their decisions regarding next instructional steps (Heritage, Kim, Vendlinski, & Herman, 2009). Given the challenges faced by teachers to implement formative assessment successfully, it may seem an unusual recommendation to suggest linking formative assessment to the incorporation of engineering in science, which has already been identified as an area in great need of providing professional development for teachers (Cunningham, 2009; Custer & Daugherty, 2009; NAE, 2009). However, if we can provide teachers with a system of assessments for a selected sample of the grade-level-appropriate science core ideas and cross cutting concepts that incorporates engineering and provides some automated evaluation of student work, it may contribute to teachers' understanding of engineering and facilitate their successful implementation of integrated design-based activities in the classroom.

A review of the literature associated with this project has identified several efforts to assess engineering at the K-12 level (e.g. Daugherty, Custer, Brockway, & Spake, 2012; Hsu, Cardella, & Purzer, 2014; Lachapelle & Cunningham, 2010; Moore, Tank, Glancy, & Kersten, 2015; National Center for Educational Statistics [NCES], n.d.), although none were found that take a formative assessment approach that integrates concepts and practices as delineated in NGSS. Also, most have focused on engineering as content or engineering literacy and have not addressed engineering process or practices, a finding also reported by Hsu, et al. (2014). Definitions of engineering as content, literacy, and process vary to some extent in the field and have limited research support as they apply at the K-12 level. For the purposes of distinguishing among these for this paper, engineering content might be considered knowledge about engineering. This would include an understanding of criteria and constraints and how they impact a design solution, for example. Engineering literacy extends this to include the application of this knowledge to understanding the use and effects of technology that result from engineering, and the ability to engage in a systematic iterative process to solve a problem. The problem solving process as represented in engineering literacy might be thought of as pure problem solving. Engineering as a process includes engaging in a systematic iterative process that *draws upon science and mathematical knowledge* to solve an ill-structured problem. This also includes attention to criteria and constraints in optimizing a solution to the problem. Certainly each of these is a bit broader than characterized here. The intent here is to provide a comparison without fully explicating the constructs.

As the first state to include engineering in state standards, Massachusetts has been assessing students on engineering for more than a decade. If the released items from those assessments are representative of the full pool of items, the focus of the items is on engineering as content. Also addressing engineering as content are the assessments created for Engineering is Elementary (EiE), a program that engages students in engineering through literacy. Iterative development of these assessments is anticipated so as eventually to include the assessment of engineering as a process (Lachapelle, et al., 2010). At the secondary level, an assessment of engineering concepts was developed for teachers that could be adapted for high school students (Daugherty, et al., 2012). And the NAEP Technology and Engineering Literacy (TEL)

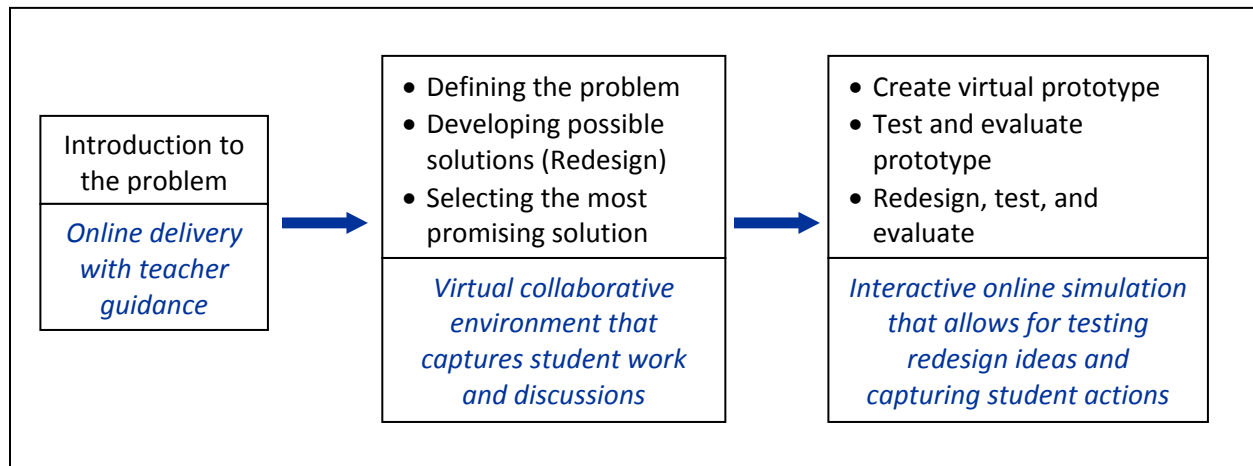
assessment is a significant advance in assessing engineering as pure problem solving (NCES, n.d.). These assessments have made great strides in assessing aspects of engineering, focusing primarily on engineering as content, engineering literacy, or aspects of specific engineering practices taken out of context, such as analyzing alternative design solutions. Hsu and colleagues (2014) have further advanced engineering assessment in their recent adaptation of a post-secondary approach to measuring students' understanding of engineering as a process. In that assessment, students are provided with documentation of a design process from a hypothetical peer group of students, and test takers are asked to critique the process that the peer group followed.

Even with this broader range of engineering-related assessment targets, the focus of these assessments remains on knowledge about engineering, whether it is engineering-related content or the process of engineering. My colleagues and I are working to further extend the assessment of engineering to include a performance component that engages pairs of students in solving a design challenge. Our primary goal in developing this assessment is to provide an example that broadens the perception of the possibilities in assessing engineering design to include an actual performance component and to explore potential applications. We are beginning with a formative assessment for several reasons, including the acknowledged need for classroom and teacher support materials related to engineering and the expectation that the data we collect in a formative assessment will help to inform the development of a summative assessment. The online assessment system will allow teachers to see each individual student's contribution to the design solution and the process the team uses to reach that solution. The assessment is intended to be used formatively, therefore this ability to parse each student's contribution from the group's accomplishments is important for determining next instructional steps at the individual student level. Teacher support materials will be provided to facilitate a formative classroom implementation. Therefore, in addition to broadening the scope of assessing engineering, this assessment, coupled with the support materials, is also intended to help address the challenge related to the limited preparation of teachers for guiding integrated science and engineering activities.

## **Research and Development Goals**

Our goal is to create a research-based formative assessment task for engineering design that engages students in a design process or, in this case, a redesign problem. Redesign problems start by providing students a flawed or otherwise less than perfect design solution to a problem and ask students to improve upon the original design. Redesign is typically an integral part of the design process, which is an iterative and often time intensive process. Schunn (2009) has suggested that starting with a flawed design can be advantageous as students are learning to design because it allows for multiple iterations, greater opportunities for learning, and a more satisfying design solution than when only a single iteration might be possible if students were designing from scratch due to the time required. This reasoning also seems appropriate for assessments intended to measure design practices—that redesign tasks are likely to provide more opportunity to measure students' abilities than designing from scratch. And a practical reason for using redesign in the case of an interactive simulation, whether for learning or measuring design ability, is that it narrows the universe of design ideas that need to be represented and programmed.

Having students work together to solve a design problem better represents the collaborative nature of design, but it introduces the challenge of determining each student's contribution to the design process and solution. In a virtual environment that colleagues have used for other types of collaborative problems, individual student contributions and their group discussions have been captured and are accessible to teachers in real time. This virtual environment will be used for the collaborative component of the formative assessment to capture students' design ideas and discussions in the design process. This will allow teachers to make decisions regarding classroom instruction on a more individualized basis. The assessment will comprise multiple components in different virtual environments as shown in Figure 1.



*Figure 1.* Overview of the design of a formative assessment task for engineering design that captures individual student work in a virtual environment.

Our current work in supporting the development of this formative assessment involved investigating the questions:

- To what extent does the solar still redesign activity elicit a range of design ideas from students that might also be presented in a virtual environment to provide evidence of student design proficiency?
- To what extent (and how) can data collected during cognitive interviews with students using paper-based materials for specific design (or redesign) challenges be used as evidence to guide the development of an interactive virtual formative assessment task for engineering design in science?

These questions were generated as a result of discussions with colleagues and collaborators about the relative potential of the solar still redesign to engage students and elicit a range of performances across the targeted population. Programming a simulated design activity is resource intensive. If the selected design challenge does not have potential for eliciting a range of student performances with respect to conceptual understanding and/or engineering practices, it would be unwise to invest the resources. But, how to evaluate the relative potential of a virtual interactive design challenge without creating it? Paper-based activities have been used to measure students' understanding of an engineering design process by critiquing a process

documented by a hypothetical peer group (Hsu, et al., 2014). We would be attempting something similar, but having students actually engage in the first steps of a design process, going as far as possible with a design task without actually creating a prototype. Our hypothesis was that the students' discussions as they engage in the early steps of a design process would provide us with insight into the range of design ideas that students were considering and the rationale for their design decisions. The number and range of these design ideas and rationales would suggest the relative value of the activity for measuring at least some aspects of engineering practices. While a programmed simulation might be able to capture and measure several aspects of engineering design practices, including idea generation (brainstorming); selecting a promising solution; testing and evaluating a prototype; and engaging in additional redesign cycles, the paper-based version would not be able to address the full range of design practices. Our hypothesis was that the paper-based cognitive interviews would likely capture students' brainstorming and selection of a promising solution with perhaps some elicitation of the scientific rationale for their decisions.

To answer these questions, we conducted cognitive interviews (cog labs) with pairs of students using paper-based materials comprising an introduction to a design problem and a diagram of an inefficient device for which they were to suggest possible redesigns. The design problem being addressed is providing individual households with purified ocean water for drinking and cooking. Details for the data collection and findings follow in subsequent sections of the paper.

## Data Collection

### *Participants*

Twenty-eight students participated across two rounds of data collection sessions. The participants ranged in age from 12 to 14 years old, and the sample was almost two-thirds female. The race/ethnicity backgrounds of the participants included Asian, African American, and White, some of whom were of Hispanic origin. The specific demographic information for the participants is shown in Table 1 below.

Table 1  
*Participants' Demographic Information*

Grade Level	N	Gender		Race/Ethnicity			
		M	F	Asian	African-American	White	
						Non-Hispanic	Hispanic
7	10	6	4	2	3	4	1
8	15	4	11	4	1	8	2
9	3	0	3	3	0	0	0
<b>Total</b>	<b>28</b>	<b>10</b>	<b>18</b>	<b>9</b>	<b>4</b>	<b>12</b>	<b>3</b>

Pairs of students who are friends or siblings and who are comfortable working together were recruited to optimize the verbal exchanges and collaborative effort in the short activity period

during which they would be engaged. Eight participants were recruited from a local middle school where one session of cog labs was held. The remainder were recruited through an intranet site accessible to Educational Testing Service (ETS) staff. Those data collection sessions were conducted at ETS. Participation by the students was voluntary, and each student received a \$25 gift card for completing a one-hour session.

### *Cognitive interviews*

Two rounds of data collection were conducted following the same approach but with slightly different materials. The materials were revised based on the results of the first round of data collection. Each one-hour data collection session was conducted by two ETS staff – one interviewer and one observer. The first round of cog labs with 20 students was audio recorded, and the second round, with 8 students, was video recorded. The decision to make this change in recording formats came as a result of analyzing transcripts of the first round of cog labs. There were many instances when students were referring to their drawings, and it would have been beneficial to see what they were referencing. The audio files were transcribed for coding and analysis purposes.

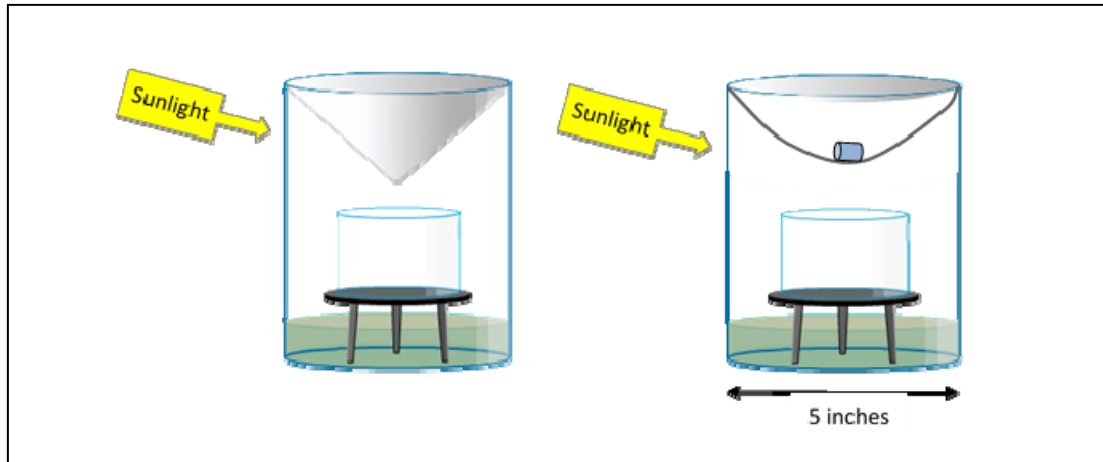
In each cog lab session, participants first completed background questionnaires to provide demographic information and information about their experiences with science topics and activities at school. Then, they engaged in two design activities sequentially, an introductory activity that involved redesigning a ball sorter and the primary activity which required students to redesign a solar still. The redesign of the solar still was completed in two parts: with individual students brainstorming for a period of time and then working together to exchange ideas and brainstorm as a pair. After completing the redesign activities, students were asked a series of reflection questions related to the difficulty and engagement of the activities as well as questions about their experiences, if any, with similar kinds of activities. We have preliminary findings from the cog labs conducted with all students working in pairs and a few comparisons between the two sets of cog labs.

### *Redesign Challenge*

Students were provided information about the relative access people worldwide have to drinking water. And they were given a labeled diagram and description of a solar still that can produce pure water from ocean water, although not efficiently and with limited usability. The two different versions of the unlabeled diagram that were used are shown in Figure 2. The diagram was revised after the first set of cog labs with 20 students, primarily due to the frequency with which students recommended filtering the water in that set of cog labs, perhaps due to the cone-shaped lid in the diagram. Their challenge was to suggest as many different ideas as possible for improving the solar still for use by a family. After an initial individual brainstorming session, they were directed to discuss their ideas with each other and decide on a final design solution.

## **Findings**

A primary goal of this investigation was to collect data regarding students' design ideas related to the solar still redesign to determine whether there would be a significant range of ideas, yet enough commonality that it would be reasonable to program an interactive simulation for students to test their design ideas. A secondary goal was to determine the extent to which cog labs conducted with pairs of students using paper-based materials would provide useful



*Figure 2.* Two versions of the model solar still provided to students during cog labs. The diagram was revised based on the concern that the cone-shaped lid was leading students to suggest filtering as a redesign element.

information to inform our decisions related to the simulation and the larger formative assessment in which it would be embedded. While the use of paper-based materials limits the amount and type of information that can be collected, this appears to be a reasonable first step, especially given the time and cost associated with programming a simulation. The cog labs provided a significant amount of information about students' design ideas as well as providing insight with respect to their approaches to defining the problem and their understanding of related science concepts. However, this paper-based approach does not allow for students to develop and test their prototypes and refine them based on the results of those tests. The interactive simulations are intended to allow an opportunity for students to engage in a fuller range of engineering practices that include these aspects.

Students' final designs span a wide range as can be seen in the two design sketches shown in Figure 3. One of the teams did not understand the function of the solar still and insisted that filtering alone would purify the water, so their final design was limited to replacing the plastic lid with a filter. At the other extreme, another team made changes intended to increase both the efficiency and usability of the still. Their design, shown on the right includes changing the color of the still, slightly changing the dimensions, and adding an inlet tube and outflow "faucet." Their discussion and sketch also refer to the greenhouse effect, which is incorrectly applied here, however, with the changes in the color described. They recommended painting the outside black and the inside white because "[b]lack absorbs more heat, and the white can, like, reflects heat. So put white on the inside, black on the outside because the black could absorb it." While the statement is essentially accurate about relative absorption of the sun's radiation, these students incorrectly relate this to the greenhouse effect. They are transferring knowledge from an example of a system open to the atmosphere, unlike a greenhouse, that is incorrectly applied here. In that open system example, painted cans that are open on top and contain water or sand are placed in the sun. The contents of the black can in this example would experience a greater increase in temperature than the contents of the white can due to the differential absorption of radiation by the black and white paint. The contents of the still, however, are closed to the atmosphere. And in this case, painting the still black would actually decrease its efficiency because the black paint would absorb some amount of the sun's radiation, holding it on the



surface of the still. Conversely, colorless glass allows the sun's radiation to penetrate the still while trapping much of that radiation within the still, more effectively raising the temperature of the water in the still and the rate of evaporation. In an interactive simulation, students would be able to test the impact of this design decision and when used formatively, the teacher could provide appropriate instruction to increase students' understanding of energy.

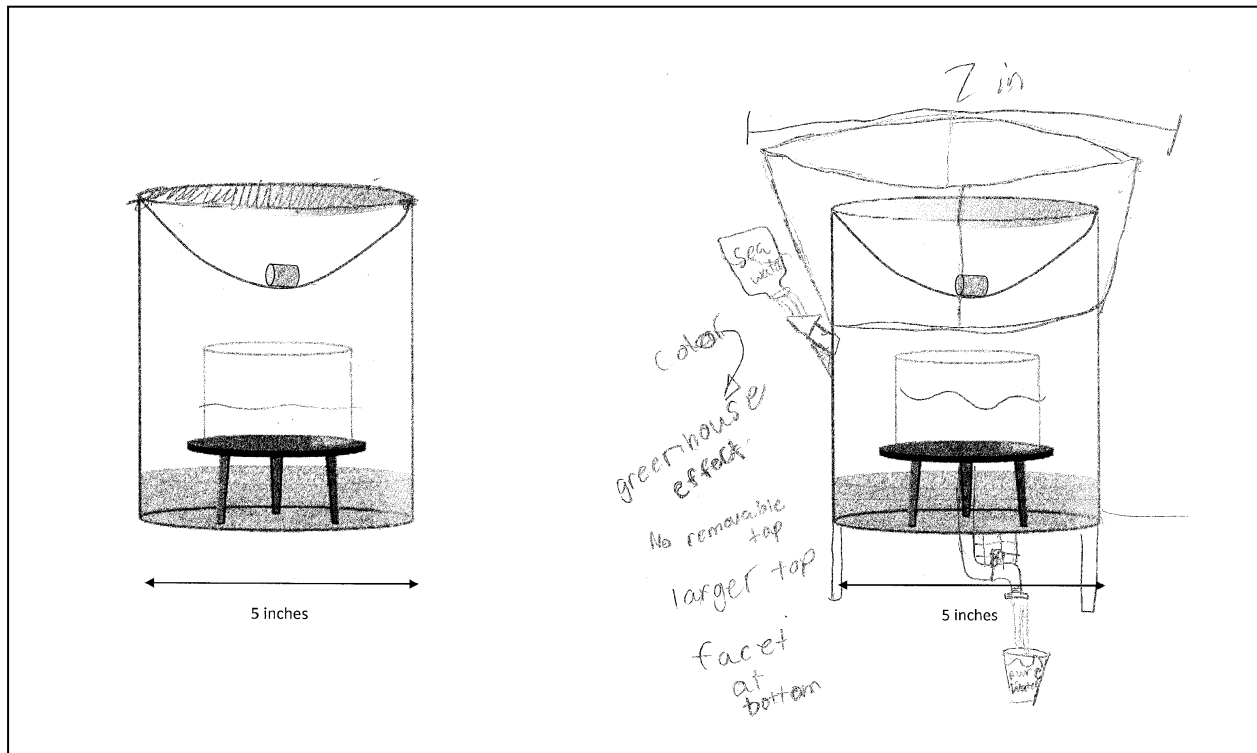


Figure 3. Final designs from two pairs of students. The design on the left indicated that filtering alone would be sufficient while the design on the right includes many changes impacting both efficiency and usability of the solar still.

Filtering, modifying the color of the still, and adding a supplemental heat or light source were among the most common recommendations or discussion topics in both sets, or waves, of cog labs (see Table 2). After modifying the shape of the lid on the original diagram so it does not suggest a funnel, filtering was still a recommendation of two of the four teams who completed the activity subsequent to that revision being made. And one of those teams made no other design recommendations aside from the suggestion to filter the water. Using supplemental heat or light sources that would need an energy source was the second most common recommendation overall. Students either ignored or were unaware of the significance of the fact that this was a *solar* still. This aspect of the students' designs will be discussed in a later section addressing the problem definition aspect of the design process.

Table 2

*Student Generated Suggestions for Redesigning A Solar Still*

Suggested Revision		Students' Rationale	No. of Interviews	
			1 <sup>st</sup> wave (N=10)	2 <sup>nd</sup> wave (N=4)
Add a component	One or more filters	Remove salt, contaminants	6	2
	Supplemental or alternate heat source	Increase the rate at which pure water is produced; purify the water	4	1
	Light source		2	2
	Mirrors		1	0
	Solar panel		2	0
	Pump	Force the pure water out of the still	1	0
	Fan	Direct condensate into cup	0	1
Change the materials	Aluminum	Various related to heat: heat up faster, hold in the heat, "attract heat"	3	0
	Dark material		1	3
	Plastic, glass, carbon fiber, wood	Strength and durability	1	1
Resize the device	Larger container	Larger volume for a family; larger diameter for faster evaporation	5	3
	Smaller container	Heat up faster	1	0

Recommendations to change the color or material used for the solar still to facilitate heating the contents of the still were common and represent several potential areas for further instruction. Several students mentioned that a still made from dark materials would be better because dark colors attract sunlight as in this example: "I said that since, like, sun's attracted to, like, darker colors and black, you could make it black so more sunlight...and you could make, like, the plastic tinted so the sun would be attracted to it in a way." We did not interrupt students' conversations to probe for their mental model of the interaction between color and solar radiation—whether students truly conceptualized this as an attraction or it was a poor choice of words to describe a conceptual model of absorption. And several groups suggested changing the materials or their colors to increase the absorption or retention of solar radiation. In all of these instances, the changes would actually decrease the efficiency of the still. In some cases, students have a correct understanding of a science concept that is being applied incorrectly in a seemingly analogous situation. A few students who have a sound understanding of the greenhouse effect, or the function of an actual greenhouse, were able to relate their understanding to the solar still redesign describing the increase in temperature within the still that would result in an increased rate of evaporation. One example of the proposed design changes that students suggested in an attempt to further contain the radiation within the still was to use a colorless container for the

still in the areas where most of the sun's rays would penetrate the still and to add reflective material or mirrors in strategic locations in an attempt to reflect the radiation back into the still or the water. While their final designs may not have a significant difference on pure water production due to other characteristics of that design, their application of science concepts to increase the energy within the still was among the best in the group we studied.

The students' ability to apply scientific ideas or principles to design, construct, and/or test the design of an object, tool, process or system is an important aspect of the engineering practice of designing solutions. Students' conversations in the paper-based cog labs as described above indicate that this redesign activity has the potential to elicit students' understanding of the principles that apply in this situation. The programmed version of the redesign activity is intended to elicit more than this narrow aspect of this construct, but we did not anticipate that we would elicit much additional information about the design process using paper-based materials. Therefore, we had not included other engineering practices in our research questions when designing the study. However, we found that the questions students' posed to the interviewer, if any, and their conversations with each other provided information about their relative abilities to define the problem, or perhaps their knowledge of the need or benefit to clarify the problem.

The practice of defining the problem involves clarifying aspects of an engineering problem, or problem scoping, to better identify and understand the criteria, constraints, and principles that govern the problem solution, for example. We characterized some of the students' questions and dialogue from the first set of cog labs that might be interpreted as functioning to better define the problem. For the second set of cog labs, we used a more systematic approach and coded questions and statements as serving a role in clarifying the problem. Those results appear in Table 3. While we encouraged students to ask questions, stating specifically that they could ask about the design drawing they were given, about how the device worked, and about what they were supposed to do or could do for the redesign, only eight questions were posed. And only two of those questions would serve to better define the problem. Most of the questions that were posed asked about the original solar still design, which we did not interpret as providing information to further define the problem. Those questions that did were related to heat sources and construction materials that might be used for the redesigned still. Although few questions were asked, students in two of the teams stated assumptions about the problem that

Table 3  
*Student Dialogue Related to Defining the Problem*

<b>Type of clarification or question</b>	<b>No. of Interviews (N = 4)</b>	<b>No. of Instances</b>
Questions for clarification (e.g., questioning actual size and materials of the original device)	3	6
Assumptions made about the problem that narrow the scope (e.g., assuming that limited resources are available to the end user)	2	6
Questions to help define the problem (e.g., questioning alternative heat sources and materials that might be used)	2	2

helped them narrow the criteria or constraints without posing a question about their assumption. Statements of this type referred to the end users and the resources that might be available to them, for example. We viewed this type of statement as an intermediate level of proficiency with respect to this construct.

It is not surprising that students in this study made little effort to define the problem. In fact, it is remarkable that students took even these tentative steps to help define the problem given the limited materials and opportunity students had during the cog lab sessions. It is also notable because students most often encounter well-defined problems throughout their K-12 education. These well-defined problems are textbook and test questions that have a single correct answer, provide all information needed to solve them, and usually do not provide any unnecessary or distracting information. So it is not surprising that students generally jump right into brainstorming design ideas or even constructing a prototype when faced with ill-defined design problems when they should be thinking and asking questions about specifications, constraints, and stakeholders. And students jump to the solution because they have little experience with this type of problem in the school setting. In fact, in other studies students at the high school and post-secondary levels have difficulty with the additional problem definition that should occur both at the beginning and throughout the design process and invest too little in this activity as compared to college seniors or experts (Bailey, 2008; Bannerot, 2003; Mentzer & Park, 2011).

The question of whether the students' design ideas would be able to be presented and modeled in a virtual environment is a separate consideration that requires input from a wider group of people, including a graphic artist, programmers, and an engineer. Some of the considerations are whether the students' ideas can be represented visually, whether mathematical models can be created to drive the simulation, and whether it can be programmed using our existing platform for research assessments and the resources required. Evidence from the cognitive interviews does not directly answer this aspect of the first question, but that evidence is required in arriving at an answer to the first question.

## **Discussion and Next Steps**

The data collected in this study, with pairs of middle school students working as a team with paper-based materials to brainstorm and propose the best possible redesign for a solar still, suggest that this may be an appropriate approach to determine the relative potential for a corresponding virtual activity. In a short period of time and with limited materials, students generated a wide range of design ideas with respect to both the efficiency of the still and its usability. Those designs included both simple, ineffective designs and designs that were deemed to be quite creative and essentially on target by a mechanical engineer. And in the process of brainstorming and discussing their design ideas, students related a variety of science concepts—both correct and incorrect—that they perceived as playing a role in the performance of the still. The activity also elicited evidence of students' relative attention to problem definition in the design process. It appears that many of the students' design ideas can be translated to a virtual environment, though with some challenges in creating a mathematical model to drive the simulation. An interactive simulation would provide additional opportunities for students to demonstrate their abilities with a broader range of engineering practices, including testing a prototype, analyzing and interpreting the data from those tests, and making recommendations

based on those results. Such a simulation could comprise the core of an assessment intended to measure engineering practices, an overarching goal of our research and development efforts.

The resulting assessment is intended to be used formatively, however, and providing teachers with another group design activity for students has limited potential for formative use because individual student abilities and conceptual understanding are difficult to ascertain when a group of students create a single product. The virtual environment provides an affordance not realized in other implementation and delivery platforms: the ability to capture—and, in a future iteration of the activity, evaluate—individual students' performance in a team design activity. Using the evidence captured in such an activity, teachers will be able to more easily determine the appropriate next instructional steps for individual students when provided with professional development and support materials. Our immediate next step toward this long term goal is the development of the interactive simulation that might serve as the core of just such a formative assessment activity for design.

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