Learning Design Through Science vs. Science Through Design

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Abstract: This research investigates two ways of framing design projects and their impacts on learning. The study explores the benefits of learning science concepts before or during a design project. Based on the NGSS science and engineering practices, in an *engineering* condition, students learn the necessary science concepts during a design project. In a *science* condition, students learn the science concepts first, then apply them during a design project. The study explores the benefits of each approach to inform instructional design. We use the knowledge integration framework to develop curriculum and assessment items, including an interactive computer model of a solar oven. Using three types of pre/posttest assessment items, we found students in both conditions gained insights on science and engineering design items; students in the *engineering* condition outperformed the *science* condition on a science-design integration item and conducted more trials during the design process while using an interactive computer model.

Introduction

Engineering projects are becoming more common in K-12 schools, but while it is often claimed that engineering projects improve student achievement in mathematics and science, research on this topic has shown that many projects do not live up to the claim (Teacher Advisory Council, 2009). While engineering projects may generate more student interest and engagement (Hmelo et al., 2000; Cantrell et al., 2006) than typical science curricula, they often fall short on developing science concepts. Ideally, undertaking a science project should be motivating, while also helping students to understand the interplay between science concepts (like energy transformation) and engineering design decisions. However, the framing of goals can impact what aspects of the project are emphasized. In projects framed around science goals, students learn the science concepts and then do a design project to apply those concepts (*science* condition). In projects framed around engineering goals, students learn the science concepts during the process of completing a design project (*engineering* condition). We investigate ways these two goal frameworks impacts student learning.

Often, in science the goal is to develop knowledge, while in engineering the goal is to develop a solution (Lewis, 2006; Purzer, et al., 2015). In addition, we use the Next Generation Science Standards (NGSS) focus on science and engineering practices, specifically the practice of "constructing explanations (for science) and designing solutions (for engineering)" (NGSS Lead States, 2013) to inform our conditions. This study compares versions of a solar ovens unit that loosely use one or the other goal frames and present a focus on either constructing explanations or designing solutions, while keeping the overall content of the curriculum the same.

We use the knowledge integration framework (Linn & Eylon, 2011) to guide the development of the curriculum and this study. This framework focuses on building a coherent understanding of concepts, and has proven useful for design of instruction featuring dynamic visualizations (Ryoo & Linn, 2012) and engineering design (Chiu et al., 2013; McElhaney & Linn, 2011). The framework emphasizes linking of ideas by eliciting all the ideas students think are important and engaging them in testing and refining their ideas. When students build a physical artifact, as in many engineering projects, they can only test a few of their ideas due to time and material constraints. Features in this curriculum, like using interactive computer models, allow students to explore many more ideas, thereby facilitating knowledge integration.

Though engineering projects are potentially motivating, when students build a physical model they often neglect the scientific basis for their decisions (Crismond, 2001), instead focusing on aesthetic and otherwise superficial details of construction. Tools like interactive computer models can help students connect science principles and design decisions by making mechanisms such as energy transformation visible (Snir, Smith, & Grosslight, 1993; Wilensky & Reisman, 2006). The combination of computer models and hands-on activities in design activities allows students to test many designs while also visualizing how energy transformation takes place in their designs.

In addition to providing science content knowledge, design projects utilizing computer models provide students with an opportunity to explore authentic practices of scientists and engineers. The NGSS envision that instruction would combine practices including modeling, data, analysis, computational thinking, and design to enable students to integrate their scientific and engineering ideas (NGSS Lead States, 2013). The solar ovens curriculum used in this research familiarizes students with the way energy transforms from solar radiation to heat (MS-PS3-3) by using a hands-on project and interactive models, emphasizing the modeling aspect of the science and engineering practices of the NGSS as well as the standards associated with energy (NGSS Lead States, 2013). This curriculum draws on all eight of the science and engineering practices in the NGSS, focusing on using models, developing solutions, and engaging in argument from evidence.

A project framed as an engineering design project from the beginning may offer students meaningful opportunities for science learning, especially when they must consider trade-offs in their designs (Purzer et al., 2015). This type of consideration of design trade-offs may be especially useful in helping students to integrate their science ideas with their design decisions. Design projects have been found, in some cases, to positively impact students' scientific reasoning (Silk et al., 2009). However, these students may not learn complex science concepts if their focus is on incidental aspects of design. Hands-on projects that directly follow a related science unit may allow students more time to focus on understanding the complex scientific phenomena they are being asked to apply, while still motivating them to learn the concepts in order to apply them to their design. However, the separation of the science content from the design project may seem disjointed to students and lead to lower motivation in learning the concepts.

We use knowledge integration assessment items (Linn & Eylon, 2011; Liu et al., 2008) at pretest and posttest targeted at three specific areas to better understand how each of our conditions impacts learning. These items measure science concept integration, engineering design practices, and the integration of science and engineering design practices. While there has been much work done to advance engineering education at the K-12 level (e.g., National Research Council, 2009; Bybee, 2011), there has not been as much work done to develop valid items for assessing engineering practices.

The two conditions in this research are meant to understand two common ways hands-on activities are framed in the classroom. By understanding the benefits of each method of framing, we hope to develop a curriculum that helps students to integrate their ideas about science concepts and engineering design better. While teachers may have their own preferred way to conduct hands-on projects in their classrooms, this work is meant to help strengthen student learning in both the science and engineering domains no matter the framing of the classroom project.

Methods

Participants and procedures

One teacher and her 153 students participated in this study. Out of these students, 139 students completed a pretest, (some part of) the curriculum, and a posttest. The pretest was conducted one day before beginning the unit, and the posttest was conducted one day after finishing the unit. Both the pretest and posttest were administered to students individually. Pairs, or in some cases triads, of students were assigned to collaborative workgroups by their teacher to work on curriculum. Workgroups were randomly assigned to a condition (*science* or *engineering*) by the software. All students received the same curricular content, but activity focus and order varied by condition.

Curricular materials

This study was implemented in a curriculum module entitled *Solar Ovens* in the Web-based Inquiry Science Environment (WISE), which utilizes a variety of instructional and assessment tools (Linn & Eylon, 2011). The goal of the unit was to familiarize students with the way energy transforms from solar radiation to heat through a hands-on project and interactive models, covering the modeling aspect of the Science and Engineering Practices of the NGSS, as well as the standards associated with energy, specifically standards related to the transfer of thermal energy (NGSS Lead States, 2013).

The solar ovens curriculum within WISE has been designed and refined with the collaboration of multiple expert teachers and researchers to help students test and refine their ideas about energy transformation. The curriculum seeks to help students utilize their ideas about how radiation works in various contexts, like in the atmosphere and inside solar ovens.

Students in both conditions followed a modified "design, build, test" approach. An important feature of this unit is a budget activity in which students make decisions about and justify the materials they choose to use for building (Figure 1). During the design phases, students also draw pictures of their ovens and explain how energy transfer will occur. Students also use an interactive model of a solar oven, designed using NetLogo (Wilensky, 1999), to test features in the solar oven and understand how solar radiation transforms into infrared energy (Figure 2). Students generate trials using the model by allowing the model to run for 5 simulated minutes without changing the input variables. When students test their physical prototypes they also test them under a lamp for 5 minutes. After each trial is generated, it is automatically added to a table, allowing students to track the trials they ran and the results of those trials. The computer model has been previously tested to understand how students use it at different points during the curriculum and how it impacts learning. Our earlier findings indicate that the computer model aids students in integrating their science and design ideas, and that students interacting with the model earlier during the curriculum (during the planning phase) benefit more than students who interact with the model later in the curriculum (the reflecting phase) (McBride, Vitale, Applebaum & Linn, 2016). After designing, students build physical solar ovens, which are tested under lamps with a common set of requirements, so results are comparable between trials and groups.

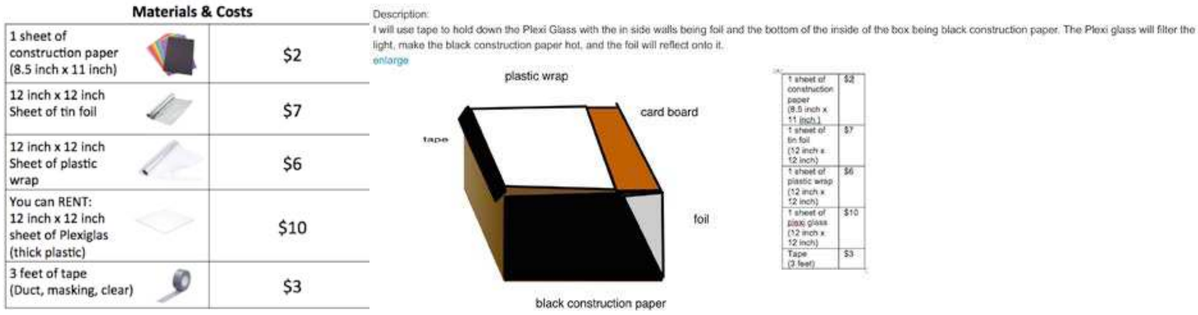

Figure 1. Student budget (left) and example of student design (right); students were given $20 for their first design iteration and $13 to add to their oven for the second iteration.

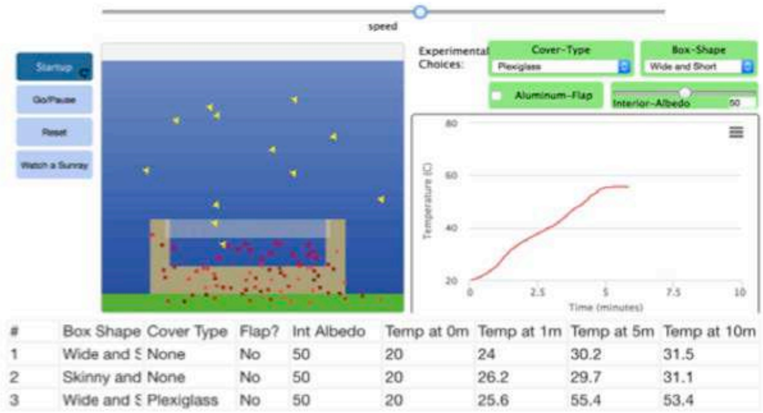

Figure 2. The interactive model used by students for design solar ovens and understanding energy transformation, with an automatically generated table below.

Condition differences

Conditions did not differ in content, only in the order the content was presented and in the framing of questions or activities. In the *engineering* condition students were introduced to the design project in the first step, then were prompted to learn or consider science concepts during the design process. In the *science* condition, students learned all the science concepts at the beginning of the project in a module about the atmosphere and were then introduced to the design project as a way to apply what they had just learned. Students in each condition used a concept-mapping tool to map energy flow. In the *engineering* condition, students mapped energy flow in their solar ovens, while in the *science* condition students mapped energy flow in the atmosphere. These differences are outlined in tables 1 & 2.

Tables 1 & 2: Table 1 (left) shows the main steps in the curriculum for the *engineering* condition, including the number of steps. Table 2 (right) shows main steps in the curriculum for the *science* condition

Engineering Condition (26 steps)	
Activity (# Steps)	**Details**
Design & Science Concepts (18)	- Introduction to project - Solar radiation - Solar oven model - Concept map of energy transformation (in solar oven) - Reflectivity - Preliminary design - Why do you need a cover? - Greenhouse gas model - Budget and final design
Build (1)	- Build physical solar oven
Test (3)	- Test physical solar oven
Redesign (2)	- Collaborative critique activity - Use solar ovens model to redesign oven, write updated description
Connect (2)	- Make connections between solar oven and greenhouse gases

Science Condition (25 steps)	
Activity (# Steps)	**Details**
Solar Radiation and the Atmosphere (7)	- Solar radiation - Reflectivity (of earth) - Concept map of energy transformation
Solar Radiation and Greenhouse Gases (3)	- Greenhouse gas model - Update concept map of energy transformation to include greenhouse gases
Design & Build & Connect (10)	- Introduction to project - Model a solar oven - Make connections between solar oven and greenhouse gases - Budget and design - Build physical solar oven
Test (3)	- Test physical solar oven
Redesign (2)	- Collaborative critique activity - Use solar ovens model to redesign oven, write updated description

Test materials

The pre- and posttest assessments we used consisted of 9 assessment items. These items fell into three areas: science concepts, engineering practices, and the integration of science and engineering. All items use short response format and are scored using knowledge integration rubrics. Of these 9 items, 5 items measure integration of science concepts, 3 items measure integration of engineering design ideas and practices, and 1 item measures the integration of design practices with science concepts.

One of the science concept items, *Car* prompted students to explain what would happen to a car left in the sun during a cold day. In an engineering item, *Budget,* students were asked to describe how two fictional students would build solar ovens using two different lists of materials and then to describe the tradeoffs made in each design. In the science-engineering integration item, *Model,* students were asked to use a basic solar oven model (like that shown in Figure 2, but with only a box shape drop-down option) to help a fictional student determine whether a tall, skinny box or a short, wide box would heat up faster. The pretest and posttest were composed of the same items.

While the science and engineering integration items measure how well students link their ideas about design or about science concepts, we were particularly interested in the performance of students in each condition on the integration item, since a goal of this curriculum is to help students use their science ideas to justify their design decisions. This integration item has been tested with over 1000 students in prior work.

We also use the automatically generated table from students' interactions with the interactive computer model (Figure 2) to analyze how many trials students ran during the design process. In addition, we use three other measures of students' interactions with the interactive computer model. We use the amount of time students spent on the project step that included the computer model, the number of clicks students made in the computer model, and the average number of clicks made per hour (time spent divided by number of clicks). All of these measures come from analysis of student log files.

Analysis approach

To measure knowledge integration, the items were scored using knowledge integration rubrics to assess links between multiple normative science ideas (Linn & Eylon, 2011; Liu et al, 2008). The knowledge integration rubric for *Model*, the science/design integration item, shows how links are scored (Table 3). Multiple researchers develop the rubrics for each item; initial scoring of data is also done by at least two researchers, with high inter-rater reliability ($\kappa > 0.8$).

Since this research investigates the differences between framing as a whole project (more similar to engineering) or as an application of concepts (more similar to science), our analysis looks at whether there are differences between conditions on the science, engineering, or integration items. However, unless otherwise specified, we examine the corpus of all 9 items.

To analyze the differences between conditions based on how students used the interactive computer model during the design phase of the project, we used a count of the number of trials run by each group. Each trial is added to an automatically generated table after students allow the model to run for 5 simulated minutes (takes about 30 seconds to 5 minutes in real time). We do not count trials that were not allowed to run for shorter than this time period because, since they were not added to the automatically generated table, students did not have a record of them and were therefore not able to look back at these trials while making their decisions. This analysis is done at the workgroup level.

Table 3: Sample knowledge integration scoring rubric for the *Model* pre/post open response item

Score	Level	Examples
1	**Off Task**	*I don't know.*
2	**Irrelevant/Incorrect**	*David is correct because I chose the skinny and tall one and the heat went up really fast.*
3	**Partial** Normative isolated ideas without a valid link	*David's claim is not correct because in the model it show solar radiation stayed trapped inside the wide and short one making heat easily trapped inside.*
4	**Basic** Elaborate a scientifically valid link	*David's claim is incorrect because the skinny box got to 33.8 in 2 minutes and the wide box got to 44.7 in 2 minutes. The wider box could keep a lot of energy because of the space and the skinny box doesn't have a lot of space. So, this means David was wrong.*
5	**Complex** Elaborate two or more scientifically valid links	*David's claim is incorrect because the more area for radation to come the more radation can get trapped and turn into heat.there is less of the when you have a skiny box.*

Results

A t-test of pooled pre- and posttest data across conditions revealed a significant effect of testing session [$t(304) = -6.44$, $p < 0.0001$], demonstrating that across both conditions students made gains from pre- to posttest (Figure 3).

There were no overall differences between the *science* and *engineering* conditions. When considering the groups of science and engineering assessment items, there were non-significant differences in condition differences. Students in the *science* condition made slightly greater gains on the science assessment items between pretest and posttest and likewise students in the *engineering* condition made slightly greater gains on the engineering assessment items between pretest and posttest; neither of these differences were significant.

When considering the integration assessment item, there was a significant impact of condition. Using a regression model, students in the *engineering* condition scored higher on the posttest integration item, when controlling for pretest score ($\beta = 0.18$, $p < 0.01$). This is shown in Figure 4.

We also analyze the number of trials students run in the interactive computer model during the design phase of the project. Groups in the *engineering* condition ran significantly more trials than those in the *science* condition ($\beta = 0.33$, $p < 0.02$). Figure 5 shows data on the variance between the conditions in terms of the number of trials run. In the *engineering* condition, more of the groups used the model to run trials, and a larger proportion of groups ran more than one trial. In the *science* condition, many groups did not even allow the model to run for a full trial, and of groups that did run any trials, a majority of them only ran one trial.

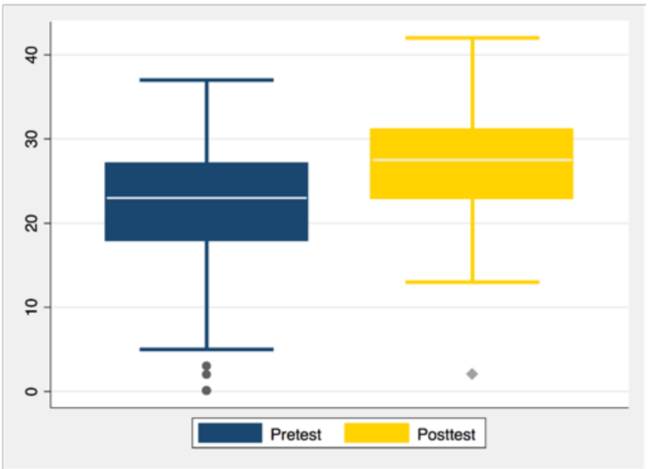

Figure 3. Differences between pretest and posttest scores for *Solar Ovens.*

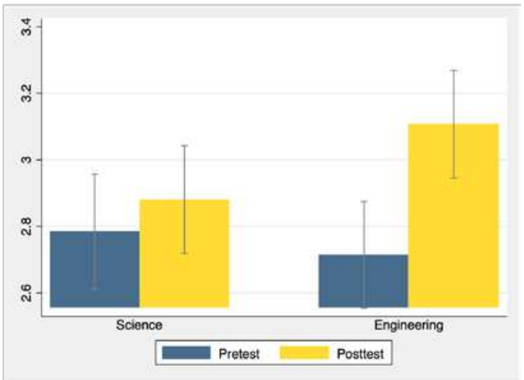

Figure 4. Differences between conditions (*Science* and *Engineering*) on the integration item at pretest and posttest.

There was not a significant difference between conditions when examining the amount of time students spent using the computer model. On average, students spent about 20 minutes using the computer model, with students in the *engineering* condition spending slightly longer on average than students in the *science* condition. However, there was a significant difference between conditions when looking at the number of clicks, or actions, students made while using the model ($\beta = 0.34$, $p < 0.01$), with students in the *engineering* condition making 25 more clicks than students in the *science* condition (mean for *engineering* condition: 56, mean for *science* condition: 31). Since students in the *engineering* condition ran more trials, we would generally expect them to also have made more clicks. When combining the measures of time and clicks to be the number of clicks per hour (calculated: clicks divided by time), we find no significant difference between conditions. This measure is important to check because in some cases, students may make rapid clicks on an interactive model without allowing the model to run and reveal the results or patterns to students. We found that there is generally a linear relationship between the amount of time spent and number of clicks in the model. We also found few outliers, meaning that most students were using the model appropriately.

Students used the model to run more trials in the *engineering* condition, even though students in both conditions generally spent the same amount of time using the model. This may mean that students in the *engineering* condition used the model more effectively to test their ideas. This is likely because students are introduced to the model very early in the project, so they are using the model to add and test new ideas about their design. Students in the *science* condition may have already been considering their design throughout the project, but before they were able to test their ideas using the model. This may have caused students to become attached to certain choices they made before they had a chance to use the model to test design options.

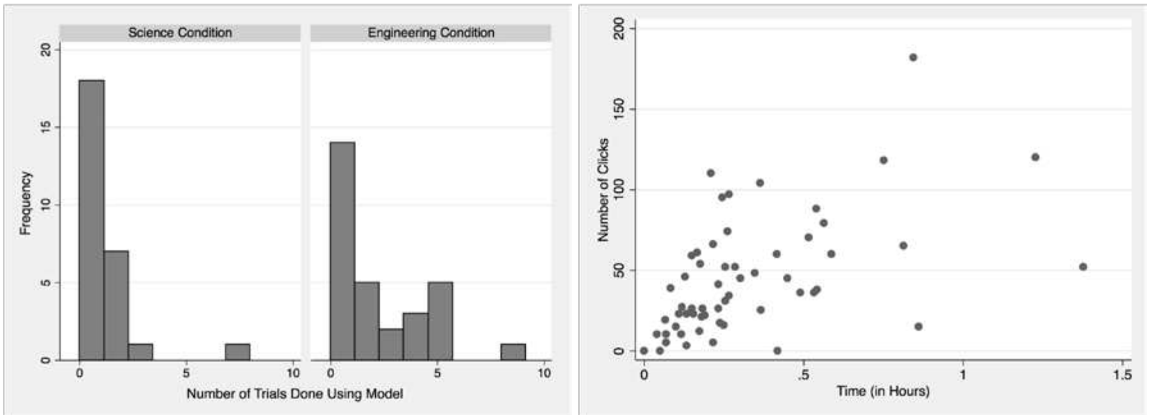

Figure 5. *left*: Histograms showing the number of trials done using the interactive computer model in each condition; *right:* scatterplot showing the number of clicks and the time spent using the model for each group of students.

Conclusions and implications

Students in the *engineering* condition were more successful in integrating their science ideas with their oven design than were students in the *science* condition. Students in the *engineering* condition may have used the design of their oven as an artifact for testing their science ideas. The students in the *engineering* condition conducted more trials than students in the science condition giving them more opportunities to test their science ideas. In the *science* condition the students may have seen designing the solar oven as separate from learning the science concepts.

Students in the *science* condition spent more of the curriculum solely focused on learning science concepts, therefore it makes sense that students in this condition would do slightly better at integrating their science ideas on the science integration items. Similarly, students in the *engineering* condition spent a longer time considering the trade-offs of their designs, and also performed better on items that measured engineering practices, like analyzing designs for trade-offs. In addition, students in the *engineering* condition may have seen the ideas they tested in the interactive computer model as more open to questioning, which may have encouraged students to test more ideas (Sandoval & Morrison, 2003). Students in the *science* condition seemed to be more attached to their original ideas, testing fewer ideas in the computer model. The *engineering* condition seemed to open students up to more possibilities in their design, while the *science* condition in some ways gave students a more limited idea of the possibilities for their designs. Since adding and testing new ideas is a proven feature or curricula that improves student learning (Linn & Eylon, 2011), it is important to emphasize this in all design projects, including those following a format more similar to the *science* condition.

These results indicate that there are benefits for each type of framing. This is important to recognize in aligning the design of the curriculum with teachers' learning goals for their students. In this work we recognize that there may be outside factors that impact teachers' choices in how to frame a hands-on project. However, the results show that there are impacts in what students take away from different framings of the same hands-on project. To improve the *science* condition, curriculum designers or teachers may have to work to integrate the addition and testing of ideas earlier during the curriculum to overcome students' fixation on certain ideas during the design process. To improve the *engineering* condition, science concepts must be emphasized.

This work included only minimal differences between conditions; ordering and question framing on only some curricular activities. While it still generated a useful and statistically significant finding, it would be more helpful for understanding how to frame design projects if the conditions were separated even further. However, separating the conditions further may be very challenging for one teacher to orchestrate (since students are randomly assigned within class periods). In addition, understanding how the framing of hands-on projects impacts learning outcomes also relies on valid and reliable measures for learning. While this has been studied and many psychometrically valid items have been developed in science contexts, this is not yet the case for engineering design in K-12 settings. This work would benefit from further research into measuring engineering and design practices in K-12 settings and the development of useful items that are not reliant on specific scientific content.

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