Exploring ideation strategies as an opportunity to support and evaluate making

Marcelo Worsley
Learning Sciences and Computer Science, Northwestern University, Evanston, Illinois, USA

Received 16 August 2020
Revised 5 February 2021
Accepted 4 March 2021

Abstract

Purpose – This paper aims to compare two types of prompts, encouraging participants to think about real-world examples or engineering principles to show how these two approaches can result in vastly different design practices.

Design/methodology/approach – Two studies (N = 20, N = 40) examine the impact of two different prompts. Non-expert students, from high school and university, completed a hands-on, engineering design task in pairs. Half were prompted to ideate using real-world examples, while the other half were prompted to ideate using engineering principles. The findings are based on human coding and artifact analyses.

Findings – In both studies, and across multiple measures, students in the principle-based condition performed better than students in the example-based condition.

Research limitations/implications – A seemingly small difference in how students are prompted or encouraged to approach a problem can have a significant impact on their experience. The findings also suggest that leveraging engineering principles, even when those principles are only loosely formed, can be effective even for non-experts. Finally, the findings motivate identifying student reasoning strategies over time as a potential means for assessment in Makerspaces.

Practical implications – Encouraging makers to think about different ways for approaching problems can be an important way to help them succeed. It may also be a useful way to chronicle their learning pathway.

Originality/value – To the author's knowledge, explicitly looking at ideation strategies has not been widely discussed within the Maker community as a way to support learners, or as a way to evaluate learning.

Keywords Problem solving, Collaborative learning, Assessment, Constructionism, Engineering design, Design process

Paper type Research paper

Introduction

One of the exciting elements of the Maker Movement is the ways that it takes on many different forms, exists within a variety of contexts and has applicability across age groups. In the last fifteen years we have seen making leave the confines of university laboratories and Silicon Valley garages, and become a mainstay within libraries, schools, museums and youth after-school centers. Across these different spaces, makers can embark on a variety of activities that involve different pedagogical structures. In some spaces participants are encouraged to follow step-by-step instructions as they get to know a given piece of technology or learn a certain technique. In other spaces, participants might drop-in for a short open-ended design challenge. Still other spaces will involve participants collaborating on a shared project for weeks, months or even years. This diversity in how making takes place and who participates in making has been important for inclusion and epistemological pluralism. However, the breadth of experiences also means that it can be challenging to

Information and Learning Sciences

2398-5348
DOI 10.1108/ILS-08-2020-0194

effectively support and evaluate learners without developing very content- and context-specific solutions. A primary contribution of this paper is to compare two general purpose ways to support making (i.e. examples-based prompts and principle-based prompts (Worsley and Blikstein, 2017) that are applicable for both undergraduate and high school students. The analyses presented in this paper are drawn from a pair of studies where high school and undergraduate students worked in pairs to complete an engineering design task. The featured analyses compare the efficacy of the two approaches, but generally situate both as useful for Makers to use. Additionally, this paper draws connections between these two types of supports and learning theory and suggest that they represent an important dimension for chronicling participant learning over time. The emphasis on using student reasoning strategies as a means to chronicle learning is a primary contribution to assessing learning among Makers.

Assessment in makerspaces

As Makerspaces and Fablabs have grown in popularity among education researchers and practitioners, there has been a complementary growth in discussions of assessment and evaluation. Much of the early discussions within the Making community seemed to spurn the need for assessment, at times projecting a viewpoint that any form of assessment was a disruption to the learning process (Martinez and Stager, 2013) or otherwise unnecessary (Gabrielson, 2013). Some of this likely reflects a counter-cultural narrative that refuses to allow standardized tests, or narrow conceptions of "learning" to shift the common ethos of making as an opportunity for self-directed, yet collaborative, personal expression and tinkering. More recently, various scholars have found ways to reconcile the opportunities for assessments to support the Making process, while still maintaining a comfortable distance from many of the traditional evaluation approaches used in school. Ostensibly, many of these more recent approaches make use of surveys, rubrics and portfolios that can be operationalized to look at a variety of constructs (Bergner *et al.*, 2019; Blikstein *et al.*, 2017; Chang *et al.*, 2015; Wardrip and Brahms, 2015) . Blikstein *et al.* (2017), for example, uses pre- and post-surveys within Fablearn Labs partner school to examine changes in learner technological literacy. The survey instrument looks at confidence and expertise within computing, information communication technology, and exploration and fabrication technologies. This is a model that is quite scalable but overlooks process. Chang *et al.* (2015) and Wardrip and Brahms (2015) take more process centric approaches by closely considering the artifacts that students create and the behaviors that they exhibit. The Maker Ed Open Portfolio initiative (Chang *et al.*, 2015) popularized the use of portfolios to surface the breadth and depth of student learning and provide materials for both learners and educators to evaluate. Wardrip and Brahms (2015) provide a complementary set of practices that are closely tied to many of their underlying goals for making. Some of these constructs include: inquire, tinker, seek and share resources, hack and repurpose, express intention, develop fluency, simplify to complexify. Looking across the pre/post models and the rubric and artifact models there are a number of apparent competing interests. First, there is a goal of scalability, which comparing pre-tests and post-tests can provide, but that can be quite challenging for assessing process. At the same time, there is a goal of appropriately and authentically representing the breadth of what students undertake and accomplish and to use that information to support learners. Moreover, these observations of practice afford a window into student thinking and dispositions. Quite simply, the goal of many assessment strategies is to connect scalability, with substantive theories of learning and cognition. This, then, is an overarching objective of this paper. We propose that looking at student ideation strategies can reveal meaningful information about how they are developing important skills. Additionally, motivated by Bergner *et al.* (2019), this paper is further situated as addressing questions of what to assess and how to assess. The paper also resonates with their articulation of assessment and supporting learning and being analogous, and the need to connect with theory. In the section to follow, the paper will discuss the underlying theory in more detail.

Student reasoning strategies

The two studies in this paper are informed by Worsley and Blikstein (2017), who described four non-mutually exclusive reasoning strategies that students use when generating solutions to engineering design challenges. These reasoning strategies include unexplained reasoning, materials-based reasoning, example-based reasoning and principle-based reasoning. This paper will focus on example-based reasoning and principle-based reasoning.

Previous literature has talked about example-based reasoning and principle-based reasoning as representing top-down and bottom-up reasoning strategies (Ahmed *et al.*, 2003; Chi *et al.*, 1981; Cross and Cross, 1998; Mosborg *et al.*, 2005). When using example-based reasoning, students begin with an example structure and work their way down to their eventual design. For instance, students might base their design on a table, chair or tower and attempt to replicate that real-world structure for their design. When using principle-based reasoning, students start with engineering principles and work their way up to their solution. For example, in Worsley and Blikstein (2017) students that employed principle-based reasoning relied on the insights of using triangles, reinforcement, and a wide base in order to promote structural stability in their designs. However, the two strategies need not be mutually exclusive. In fact, prior literature documents how experts will use both top-down and bottom-up strategies when faced with a new challenge. In this way, well-developed engineering design cognition includes both example-based reasoning and principle-based reasoning. That said, prior literature also suggests that principle-based reasoning is more closely associated with a higher level of expertise than example-based reasoning. Moss *et al.* (2006) is an example of such findings. Moss *et al.* (2006) compared freshman and senior undergraduate students and noted that when faced with an engineering design task, the seniors used a more principle-based approach for recalling the design of various mechatronic devices. The authors inferred that the seniors were able to draw from principles that were not yet salient to the younger students. Within this research community there is also discussions of novices being incapable of principle-based strategies (Anderson *et al.*, 1981; Chi *et al.*, 1981; VanLehn, 1996). They note that novices do not yet have sufficient knowledge to effectively use principle-based reasoning. One goal of this paper is to demonstrate that non-experts can make use of principle-based reasoning. Consistent with Worsley and Blikstein (2017), this paper takes the position that the use of principles is a practice that experts use to improve their design process, and not what distinguishes experts from non-experts. Hence, non-experts should be able to use principle-aligned ideas to inform their engineering design process.

Principle- and example-based reasoning are significantly motivated by prior work on analogical problem solving (Anderson *et al.*, 1981; Carbonell, 1982; Gentner and Holyoak, 1997; Gick and Holyoak, 1980, 1983; Polya, 1945). This paper will not endeavor to highlight all of these similarities, but will instead briefly discuss some important distinctions. Whereas analogical problem solving is typically differentiated into categories that correspond to surface features and deep features, both example-based reasoning and principle-based reasoning can be based on surface features or deep features. Typically, surface features are those components of a problem that might seem obvious, or that are explicitly stated. Deep features, on the other hand, require some amount of user inference, nuance, or interpretation. As an example of how the language of surface features and deep features is not a direct parallel to examples and principles, consider the following. The inspiration for constructing a mapping between a problem and a real-world object could be based on similarities between the domain of a target problem and a target solution (e.g. two word problems that are both about dogs, but for which dogs provide no real insights into the problems). Alternatively, a student could leverage a real-world object based on identification of shared engineering principles between the problem and the object. At the same time, principle-based reasoning could be based on surface features or deep features (Chi *et al.*, 1981). Notably, Chi *et al.* (1981) describes how students may map between a problem and a solution based on the perceived similarity in the problem type (i.e. related to velocity, for example). In this way, example-based reasoning and principle-based reasoning operate on a dimension that is orthogonal to analogical problem solving. However, the goal of this manuscript is not to argue between the theoretical distinctions between example- and principle-based reasoning. Instead, the paper looks at a very practical question of how subtle changes in the brainstorming phase can result in drastic differences in student success. Specifically, this paper will show that product and process of designing can be significantly impacted by whether students are prompted to use example-based reasoning or principle-based reasoning. This has implications for how we assess and support making.

Methods

This paper was initially conceptualized based on the specific challenge of supporting learners as they complete the types of short design challenges that might frequently be used in museums, libraries, classrooms, and after-school spaces. Participants are given access to a set of materials, a loosely constraining challenge, and then asked to collaboratively build. While completing these design challenges, it can sometimes be helpful to proactively support student brainstorming, or be prepared with additional prompts that might help students more tractably approach the challenge. The two prompts that this paper uses (one example-based, one principle-based) align with this paradigm, by offering short introductory activities that participants can use to think through their design process. However, as suggested in the prior literature, these two prompts also have important connections to learning theory. A pair of studies (N = 40, N = 20) was designed to compare these two approaches and answer the following research question.

RQ1. What differences in design quality and design process emerge between students who are prompted to use examples versus principles when ideating potential solutions to an engineering design challenge?

Participants and settings

Study 1. Forty high school students from around the USA participated in this study. The study took place at a private university where the students were participating in a summer science, technology, engineering and mathematics program. This implementation was similar to that of a high school maker class or museum activity in that the entire population of students worked on the task at the same time in a largely self-directed fashion. Each student received a worksheet with instructions for their specific intervention. Student pairs worked at tables throughout the study space. No recording was made of student build actions, but pictures were taken of the final structures, and the student worksheets were returned. Study 1 affords a general comparison of example-based reasoning and principle-based reasoning in an ecological setting that mirrors its likely implementation in classrooms, museums, or after-school spaces. This is in contrast to the more laboratory based setting of Study 2.

Study 2. The population of students included 20 high school and undergraduate students. Half of the high school students were in each of the two experimental conditions. Similarly, half of the undergraduate students were in each of the two experimental conditions. The number of high school students and undergraduate students was the same across the two conditions. In all, 12 participants were from a charter high school and had little to no formal training in engineering design. The eight undergraduate students had received basic college level instruction in mathematics and science. Four of the undergraduate students identified as having taken some courses in engineering, but had never before completed a task of this nature. The four undergraduate students with some engineering background were equally split across the two conditions. Additionally, even though some students had received instruction in engineering, they were not experts. Nine of the participants were female, while the remaining 11 were male. Participants were equally split across conditions by gender (five females in the one condition, and four in the other). Undergraduate students were paired with other undergraduate students, and high school students were paired other high school students. Each pair of students completed the activity at a different time, and a research assistant closely watched the process while also taking field notes. Students sat at a large desk and were videotaped during the entire process.

Procedure

Both studies involved dyads of students working to complete an engineering design challenge. The challenge asked students to build a structure that could support a cylindrical, 0.5 lb. weight as high above a table as possible. The students were given basic household materials: one paper plate, four straws, five wooden sticks, and garden wire. The sequence of events completed for both studies is included below. Note: The pre-test and post-test were not reliably captured for Study 1 as many students immediately started with the intervention:

- Pre-test (5 min) (Figure 1) – students were asked to generate as many ways as possible to make an unstable structure more stable. The goal of the pre-test was to account for any differences in prior knowledge, as well as serve as a reference point for assessing how each student's conceptual intuitions changed through the experiment.
- Intervention (3 min) – students participated in either an example-based reasoning intervention or a principle-based reasoning intervention. During both interventions, students were first shown a picture of a ladder (Figure 2), a bridge (Plate 1) and an igloo (Plate 2). In the example-based condition students were asked to generate three ideas of relevant structures from their home, community or school that would be useful in thinking about completing the design challenge. In the principle-based condition students were asked to generate three mechanisms, or engineering

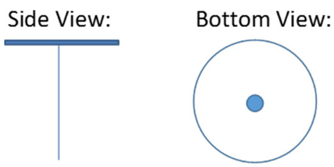


Figure 1.
Diagram presented for pre- and post-test

principles, that cause one or more of the three items pictured (Figures 2, Plate 1 and 2) to be structurally sound. These mechanisms, or principles, were generally not at the level of complex scientific or mathematical equations, but instead, at the level of intuitions. The intervention design as well as some of the artifacts created will be described in more detail in the Experimental Conditions section.

- Initial Design Drawing (1 min.) – students worked individually to create a quick sketch of what they thought their final structure would look like. This task was done as an intermediate step that would highlight if the intervention alone conferred noticeable advantages to one experimental condition or the other.
- Building Activity (15 min.) – students were given the materials and had fifteen minutes to complete their structure.
- Post-Test (5 min.) – students repeated the pre-test task, and were given access to their pre-test data. Each student had access to their pre-test to allow them to reflect on their prior designs (i.e. reuse them if they so pleased) and eliminate any concerns

Figure 2.
Ladder picture

Plate 1.
Bridge picture

Plate 2.
Igloo picture

that some students may have forgotten their pre-test answers, while others memorized theirs.

- Reflection (untimed) – student were verbally asked about the origins of their designs as well as some additional questions about their overall building experience.

Experimental conditions

Two experimental conditions are included in these studies. These two conditions are linked to two different engineering design strategies. The specific manipulations used for each reasoning strategy are based on prior research. For example, both interventions involved interactive learning, as opposed to passive learning (Menekse *et al.*, 2013). Careful consideration was also taken to:

- effectively prompt students to generate principles;
- identify the number of structures to show; and
- determine the nature of the structures.

Colhoun *et al.* (2008) demonstrated that extracting principles is significantly less likely to occur when the principle is not placed in the context of an example. Accordingly, pictures were used to ground the discussion of principles. Three structures were included because several studies have demonstrated that students are much less likely to properly encode principles from a single example, than from multiple examples (Colhoun *et al.*, 2008; Gentner *et al.*, 2003; Kurtz and Loewenstein, 2007). Finally, the three sample structures were chosen to provide a variety of principles for students to identify. Specifically, students are likely to have different levels of familiarity with each of the objects. It was assumed that many students will have interacted with and used a ladder; that all will have driven or walked over a bridge; and that none of them have extensively considered how to construct an igloo, but may still be able to draw useful insights from its design. Providing a variety of example structures, was done to create a multitude of entry points for students to be able to tractably approach the task.

The reader will note that the same images were used for both conditions. Accordingly, one initial concern is that by using the same images, students in the example-based reasoning condition would start to look for principles. However various studies have shown that students have a tendency to focus on surface features even when presented with multiple items to compare (Hammer and Russ, 2008; Kurtz and Loewenstein, 2007; Roll, 2009). Additionally, case study analyses were conducted of one pair of university students in the example-based condition, and a pair of high school students in the principle-based condition. These two pairs were chosen because they seemingly include more novice individuals (high school students) using a principle-based prompt, and more educated individuals (university students) using an example-based prompt. The example-based reasoning pair that was chosen because these two students initially started by identifying something that could be interpreted as a principle. As such, if these students, who were initially bent on using principles, still followed an example-based approach, this would suggest that the intervention likely took hold. The principle-based reasoning pair was selected because the principles that the students provide are not formal, or scientific, in terms of language or specificity. Nonetheless, these students were able to create a stable structure. In this respect, effective principle extraction may not need to be in the form of specific mathematical formulas. Instead having students identify principles and mechanisms in everyday language may be sufficient (Brown and Ryoo, 2008; Brown and Spang, 2008; Brown and Kloser, 2009). Appendix 1 includes example artifacts from these two pairs of students and presents their design drawings, the product of their intervention phase and pictures of their structures.

Measures

The data collected through these studies lends itself to several different possible points of comparison. This paper will not endeavor to cover all possible dimensions available, and will instead focus on one product measure and one process measure. The product measure that this paper considers is design quality, or how high of a structure the dyad made. The process measure is the inclusion of principle-based modifications each dyad used between successive tests. Both of these measures will be described in more detail in the following sections. Note: while pre-, mid- and post-test data was collected, it is omitted from this analysis because it was collected on an individual basis, which adds significant nuance to its interpretation and analysis that is beyond the scope of this paper.

Design quality

At the conclusion of the building process, each pair's design was tested for height and stability. The height was measured using a tape measure, while stability was determined by visually observing if the designed structure fell under the weight of the 0.5 lb. cylindrical object. Comparison of the two experimental conditions along this dimension used a binomial test to compare the rate of success, and a Wilcoxon Ranked Sum test to compare the heights of successful structures. The binomial test computes the likelihood of a given distribution of events, based on a known probably of success for a single event. This type of calculation is often what is used for looking at the likelihood of flipping a 2-sided coin to "tails" 100 times in row, for instance. The Wilcoxon Rank Sum test looks at the likelihood that the ordering of a given set of values is random. For example, if one were to compare the weight of 20 elephants and 20 mice, you would likely find that all of the mice weigh less than all of the elephants. A Wilcoxon Rank Sum test would surface this that this ranking of weights is not random. These two statistical analyses were used because of the relatively small number of groups that were successful in each study.

Process

In addition to looking at the final product, this analysis is also concerned with the changes that each design went through to arrive at that final state. This paper will refer to these as intermediate designs. Specifically, an intermediate structure was defined as those structures that the students tested. Intermediate designs could emerge in different ways. In some cases, students would make considerable changes to their designs before testing again, while in other instances they would only make a small adjustment before re-testing. Each intermediate design was compared to the previous design to identify principle-based modifications. Principle-based modifications included:

- adding a base;
- adding reinforcement;
- adding triangles;
- making strong connections; and
- adding symmetry.

A single value for process was determined by dividing the total number of principle-based items by the total number of intermediate structures. A *t*-test is used to compare the rate of principle-based additions between the two experimental groups. The analysis will also draw on a sequences of intermediate structures from two groups (one from each experimental condition) to further concretize this measure and its relevance to the design task.

Results

Comparing design quality

In Study 1, four of the ten pairs in the principle-based condition were successful along this measure, while only one pair from the example-based condition was successful. There is a clear indication that the principle-based reasoning condition correlates with better performance than the example-based reasoning condition. Specifically, if the probability of success on the task is the rate observed among the example-based reasoning condition (0.1), then the probability of four of the ten pairs randomly being successful on the task is approximately 1%. For this calculation, 10% was used as the probability of success because there is no a priori value for the likelihood of student success for this task. Accordingly, the probability from the example-based reasoning condition was used as the baseline probability. Additionally this probability is consistent with prior research related to spontaneous idea generation in analogical problem solving literature (Colhoun *et al.*, 2008; Gentner *et al.*, 2003; Gick and Holyoak, 1980).

The second measure is the height of the successful structures (Table 1). A one-tailed Wilcoxon Rank Sum test suggests that the rank of the principle-based reasoning pairs is different from that of the example-based reasoning condition pairs ($p = 0.0013$).

Study 2 provides analogous results. In this case, three of the five pairs in the principle-based reasoning condition were successful, whereas only one of the five dyads in the example-based reasoning condition was successful. A binomial test is again used to compute the probability that these events happened randomly, given that the probability of success was 0.1. Relative to Study 1, the effect in Study 2 is even more pronounced. The probability that the principle-based condition randomly resulted in three pairs being successful is less than 1%.

Confirmation that principle-based reasoning was associated with more stable designs was also seen in the Study 2 height ranks (Table 2). All of the stable principle-based reasoning designs were taller than the one stable example-based reasoning design.

Rank	Condition
1	Principle-based
2	Principle-based
3	Principle-based
4	Example-based
5	Principle-based

Table 1. Relative rank of structures which held up the weight by condition

Rank	Condition
1	Principle-based
2	Principle-based
3	Principle-based
4	Example-based

Table 2. Relative rank of structures which held up the weight by condition

Specifically, using a Wilcoxon Rank Sum test indicates that the probability that the two conditions' ranks are equal is less 1%.

On average, then, pairs that were prompted to use principles instead of examples, tended to perform better on this design challenge. This analysis, however, does mask one important observation that is difficult to express in quantifiable terms. While, there were clear metrics for determining which designs most clearly met the design goals, recognizing the designs that were least effective is considerably more difficult. That said, to the author's observation, the pair of students that experienced the most trouble, and whose structure was visibly the least viable was developed by a pair that received the principle-based reasoning prompt. For the sake of brevity, a full description of their design will not be included in this paper, but it is important for the reader to consider this observation alongside the trends that were quantitatively presented.

Comparing process

When looking at the rate of principle-item inclusion in intermediate structures (Figure 3), the principle-based reasoning group ($M = 0.45$, $SD = 0.078$) has a significantly higher rate ($t(6) = 2.02$, $p = 0.044$) than their peers in the example-based reasoning condition ($M = 0.26$, $SD = 0.16$). Pairs in the principle-based reasoning condition were almost twice as likely to make a principle-based modification between intermediate structures. This result could stem from differences in the total number of principle-based items added, the total number of intermediate structures, or a combination of these variables. Based on the data, the most plausible explanation is that students in the principle-based reasoning condition were less likely to have consecutive structures in which no principle-based items were added. Hence, it is not that the principle-based reasoning condition used a larger number of principle-based items, nor is it the case that they had a smaller number of intermediate structures. Instead, students in the example-based reasoning condition simply had more intermediate structures that represented making minor changes. This finding provides additional support for the claim that students who participated in the principle-based reasoning condition were more likely to take a principled approach to solving the design challenge.

To better ground this idea for this reader, the following section walks through the design process and intermediate structures for a pair from the example-based reasoning condition and a pair from the principle-based reasoning condition.

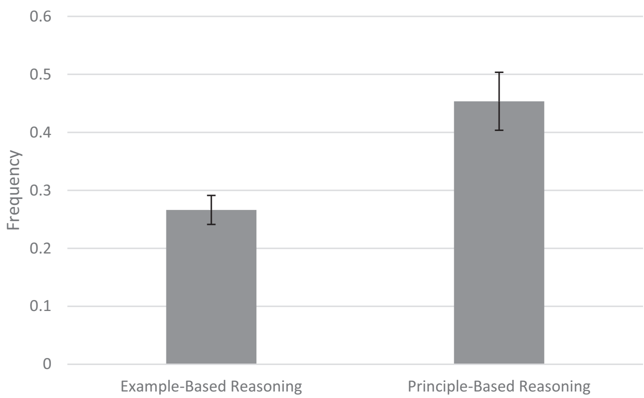


Figure 3.
Frequency of principle-relevant additions by condition

Process quality and example-based reasoning sample artifacts

The students, both male undergraduates, wrote down four items during the initial ideation phase: triangle, swing, easel and dinner table. In interpreting the remainder of the artifacts and the designs that they created, it is important to understand that the students were specifically referring to a baby swing that has a "t" shaped cradle.

Figure 4 contains one of the students' initial design sketch from a pair in the example-based reasoning condition. Of central importance to the image is the item circled with a dashed line at the bottom of their diagram. This student took the idea of a baby swing and tried to model their design after it. Specifically, the cross structure was intended to mirror the design of the baby cradle. This is explicitly noted by the text "create a cradle for the weight" (in the rectangle with a dashed line in Figure 4).

When transitioning to the examination of the physical structure that the students created, the swing cradle remains the focal point of their design. Unfortunately, as they designed it, the cradle did not serve its purpose. In fact, had they abandoned the cradle, and simply placed the weight directly on top of the straws they would have succeeded. However, they were so centrally focused on using a baby swing as the model for their design, that they overlooked the actual utility of the cradle (Plate 3).

Nonetheless, this first pair provides a clear instance where the manipulation worked as expected. The pair of students identified an example object, from which they modeled their structure.

Connecting with the quantitative results noted above, Figure 5 presents the intermediate structures that this pair of students made. Most notably, the only point at which a principle-based addition is made, is with regard to the first intermediate design. All future structures involve making slight adjustments to the structure. Unfortunately, this pair's design did not meet the intended goal of supporting the 0.5 lb cylindrical container.

Process quality and principle-based reasoning sample artifacts

The sample participants from the principle-based reasoning condition were two male high school students. The principles identified by this pair includes:

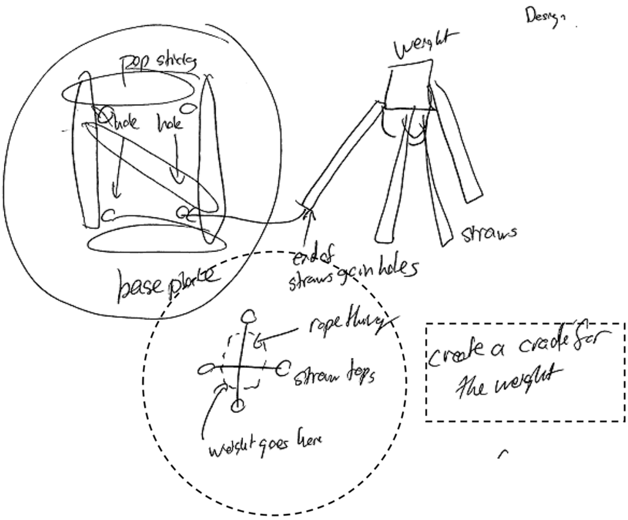


Figure 4.
Design document from example-based reasoning student

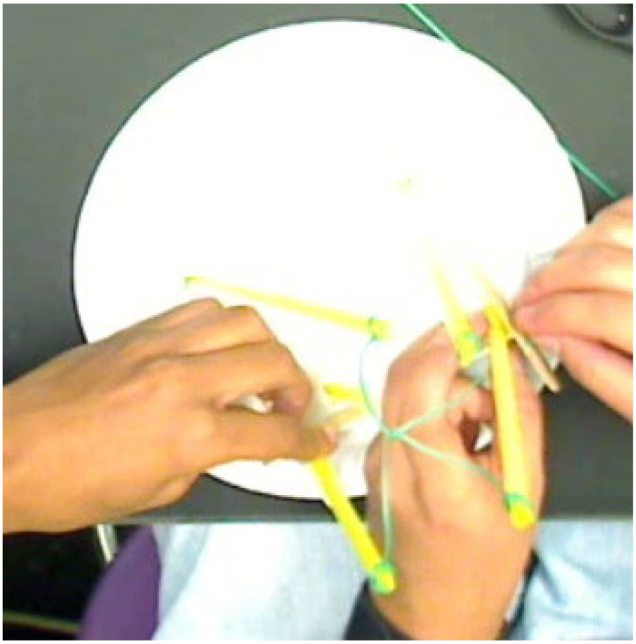


Plate 3.
Top view of the final structure from an example-based reasoning pair

- balanced force holds structure together;
- all force goes into ground; and
- no stress on joint (Figure 6).

An examination of their final structure in Plate 4, suggests that they attempted to apply these principles. Specifically, they made a balanced and symmetric design. When asked about how they came up with their design, they said the following:

Student 1: Because, it would balance more? I suppose I can try to go into detail about force, but I don't know much about that.

Student 2: I mean. My guess is that [. . .] probably what we saw from that ladder picture, right?

Student 1: Yeah. That's true.

Student 2: So just the same concept as the ladder.

The students' description is riddled with uncertainty: "I supposed I can try [. . .]", "My guess is that [. . .] probably." However, the language of symmetry and reinforcement, which were of central importance to their design, is not used at any point during their description. In their mechanisms from the intervention phase (Figure 6) they identified the basic idea of balancing forces, but here admit that they do not know much about forces. In some ways, these students have underestimated their own knowledge, since their intuitions about forces and balance appear to serve them well. They are able to attribute the idea as originating from the ladder, *but what they extracted from the ladder was not a specific component, as was*

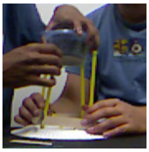
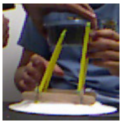
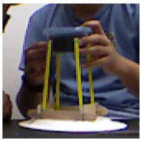
	*Students combine strong connections, with a base, reinforcement, and the principle of symmetry. Time: 1673 seconds
	Students adjust their structure. (No principle-based modifications made) Time: 1675 seconds
	Students adjust their structure. (No principle-based modifications made) Time: 2023 seconds
	Students adjust their structure. (No principle-based modifications made) Time: 2062 seconds
	Students adjust their structure. (No principle-based modifications made) Time: 2386 seconds
	Students adjust their structure. (No principle-based modifications made) Time: 2403 seconds
	Students adjust their structure. (No principle-based modifications made) Time: 2425 seconds
	Students adjust their structure. (No principle-based modifications made) Time: 2455 seconds
	Students adjust their structure. (No principle-based modifications made) Time: 2481 seconds

Figure 5. Intermediate designs and description of principle-based modifications for example-based reasoning condition

the case with the baby swing. Instead, these students worked to make their design reinforced and symmetric. Thus, the purpose and expectation of principle-based reasoning is not that students will already have a well-defined understanding of engineering and science principles. Instead, priming toward principle-based reasoning involves identifying principles that may be incomplete, inaccurate and imprecise. Consistent across comparisons between the example-based reasoning intervention and the principle-based reasoning intervention is that the latter examined the example structures with a different lens, namely one that was focused on creating explanations of structural stability that were devoid of formulas and of limited scientific precision.

We see this idea corroborated across the team's principle-based modifications (Figure 7). They began with an idea motivated by principles and included a principle-based modification in the fourth intermediate design. Specifically, in step 4 the students add reinforcement to the structure (the popsicle stick that secures the straws).

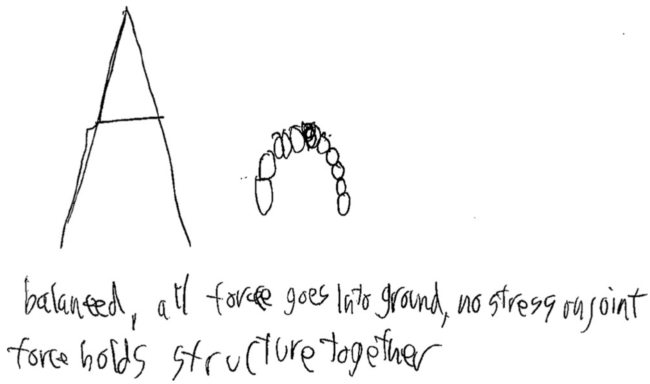


Figure 6.
Mechanisms/ principles identified by principle-based reasoning pair

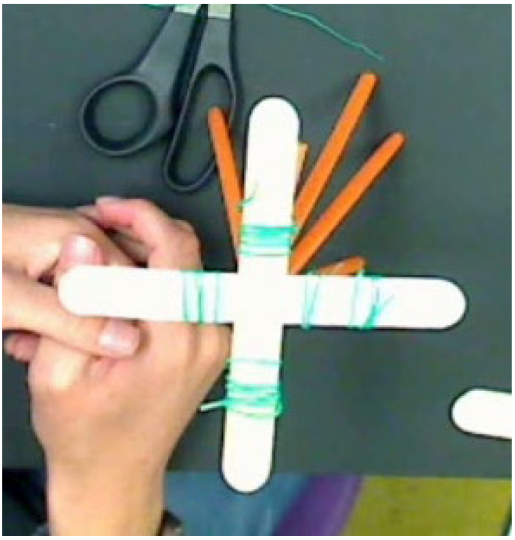


Plate 4.
Top view of final structure for principle-based reasoning pair

	*The students begin using triangles, strong connections and symmetry. Time: 256 seconds
	Students make minor adjustments. (No principle-based modifications) Time: 271 seconds
	Students remove the plate. (No principle-based modifications) Time: 379 seconds
	*Students add reinforcement with a popsicle sticks and re-add plate. Time: 703 seconds
	Students adjust the mass. (No principle-based modification) Time: 717 seconds

Figure 7.
Intermediate designs and description of principle-based modifications for principle-based reasoning condition

To reiterate, the principle-based reasoning pair had five intermediate structures whereas the example-based reasoning pair had eight. Across both pairs of dyads, four principle-based modifications are made, but in the case of the principle-based reasoning pair, fewer of the intermediate structures were the result of simply making minor adjustments. This provides some explanation for what was observed quantitatively. The total number of principled-based modifications was similar across conditions, but in many cases, the students in the example based reasoning condition simply had more intermediate structures, most of which represented minor adjustments.

Discussion

The results from two independent studies suggest that the two different ways for prompting students were associated with notable differences in design quality and design process as operationalized in this paper. Students in the principle-based reasoning condition were more likely to succeed at completing the challenge and more likely to make a taller structure than their peers in the example-based condition. Additionally, students in the principle-based reasoning condition made more frequent principle-based modifications to their intermediate structures than their peers in the example-based condition. Broadly speaking then, prompts that encourage students to think about principles, and not just examples, may be generative for promoting design success. Arguably, some of the ideas of example and principle-based reasoning may be embedded within Wardrip and Brahms (2015) practices of Tinker, Hack and Repurpose or Develop Fluency, but suggest that these must be called out more explicitly.

The results also suggest that non-experts can effectively make use of certain simple expert strategies. Despite the fact that expertise is typically defined as requiring both expert knowledge and expert organization of that knowledge (Nokes *et al.*, 2010), the students in this study demonstrated that they could use conceptual intuitions about engineering principles in order to increase their rate of success on this task. Even though it is unreasonable to expect non-experts to always behave like experts, there may be a number of micro-practices associated with expertise (Worsley and Blikstein, 2011) that can be fruitful in helping novices learn and perform more effectively.

In addition, these differences were observed from a relatively short intervention. Hence, improving the quality of making experiences may not require that students participate in long, drawn-out instruction or demonstrations that potentially detract from the generally high levels of motivation associated with making. Instead, it may be sufficient to simply:

- help students enter into a frame of mind in which they are better prepared to drawn upon their wealth of cognitive resources (Hammer 2004); and
- prompt them to consider certain engineering principles before starting to build.

The use of manifold cognitive resources, in the sense put forward by Hammer, contrasts to the typical assumption that students lack sufficient prior knowledge that they can bring to bear on a new task. Conversely, as students tap into their conceptual intuitions about engineering principles, they may be able to extend the tools and practices that they have at their disposal for a given task.

As previously mentioned, the types of activities that the students completed in this study are commonly used as design challenges in Fablabs and Makerspaces. Notwithstanding, many Makerspaces and Fablabs tend to use example-based reasoning approaches. For example, one common practice is for students to learn by following step-by-step instructions from instructables.com, a LEGO kit or Make (Blikstein, 2013; Blikstein and Worsley, 2016; Vossoughi *et al.*, 2021). These platforms teach students how to make an example structure using a set of pre-determined steps, but seldom challenge students to think about the importance of each step or the different principles at play within the structure that they replicate (Dejong and Mooney, 1986; Mitchell *et al.*, 1986). Providing room and prompts that ask students to think through underlying principles of examples, even if their principles are not well-formed, could provide benefits to their making experience.

Beyond the implications for learning and instruction, this paper also provides a methodological contribution. Identifying the impact of the reasoning strategies and their connections to prior theories, unearths a methodology that may be useful for studying student learning in Makerspaces. In particular, chronicling student reasoning strategies may be a feasible means for characterizing student growth and development in complex learning environments. The goal is not for all students to always use principle-based approaches, but to instead see how students may be using a variety of strategies, and drawing new inferences based on connecting between examples and principles, for instance. Concretely, the proposition is that researchers should document student reasoning strategies over time as a dimension for studying learner growth and development. This can be done using a simply survey or by having this be something that students include in their portfolios. Moreover, this approach has utility across a variety of projects, in that the origins of student ideas is not tied to any single domain (Worsley and Blikstein, 2017). Using this approach can be a standalone, or complement traditional assessment techniques such as pre-tests, post-tests, and artifact analyses, which may examine how well students have mastered certain STEM concepts.

Also, tracking and being aware of reasoning strategies gives the educator a basis from which to engage the student in sense making and troubleshooting. Imagine an educator or facilitator who is preparing to talk with a student about a difficulty they are having with their project. This conversation could be markedly different based on the knowledge of the approach that the student employed. For example, if a student based her design on an example structure (a bridge she had seen), facilitators may have to first draw attention to the basic elements of the structure that are not working. Alternatively, it might make sense to discuss how well the example structure fits the current design challenge. If the student used a principle-based reasoning strategy, however, educators should probably focus on first discussing the principles and their applicability to the current task. Hence, being aware of student reasoning strategies provides a better context for student interactions. In that sense, this last implication is about developing a better language to frame and talk about making. The field has developed vocabulary to discuss student work in science, and mathematics, but not much in the direction of understanding student reasoning in the process of building physical structures.

Limitations

In considering the scope of this work, there are recognizable limitations in the generalizability of the results to other tasks and other domains. First, both studies used the same task and images to spur student ideation. While this is appropriate for conferring replicability, it is possible that the specific images were what drove the differences. For instance, the principle-based reasoning pair that was discussed in the Appendix 1, explicitly referred to the ladder as guiding their design. Thus, it may be that the specific ladder picture played a significant role in student performance, and not principles more broadly. For this reason, a goal of future research is to investigate extensions of this work to other making tasks, and using different images for the examples and principles prompts. Additionally, it is important to acknowledge that usage of different reasoning strategies is not mutually exclusive (Worsley and Blikstein, 2017). Prompting students to think about examples can lead to considering principles. However, this does not dilute the primary argument that principle-based prompts may help students marshal additional resources in the process of designing and ideating, as was suggested by the two studies within this paper. Finally, the current paper primarily focused on the theoretical foundations and instantiation of example- and principle-based prompts as used by learners. It did not include an explicit evaluation of how well studying these approaches can serve as a useful tool for assessment. Future work will explore this implication more explicitly by chronicling student reasoning strategies over time and correlating those changes with other relevant measures.

Conclusion

The call for students to participate in meaningful, hands-on, STEM learning continues to grow. Nonetheless, in order to effectively grow this type of experience, the field must improve its ability to support and evaluate making (Bergner *et al.*, 2019; Blikstein and Worsley, 2016; Vossoughi *et al.*, 2021). This paper chronicles how a very subtle change in a brainstorming prompt correlates with differences in design quality and design processes during an engineering design challenge. These results have meaningful implications for both instruction and assessment. In having students conjecture important principles or mechanisms, the objective was to encourage them to extend their engineering design cognition to an intuitive, yet ill-formed and uncertain space. Even though the students in these studies did not have expert-level knowledge or a deep understanding of the scientific theories involved, they were able to generate principles based on conceptual intuitions and by using everyday language. This seems to have provided them with a newly realized lens for approaching the task, and a different set of tools through which to troubleshoot. Accordingly, as it relates to instruction, teachers and practitioners should engage students to leverage their various cognitive resources, even in situations where students may not formally possess domain expertise. Moreover, if designers and teachers are successful in identifying objects or elements that are accessible to students for making intuitive inferences about relevant engineering and science principles, there is a strong potential for students to succeed along several different dimensions. Additionally, in these studies, images from three real-world structures helped students consider potential approaches for addressing the design challenge. Complementing those pictures with principle-based prompts qualitatively improved the building process. Supporting flexibility and development in student reasoning strategies is especially important in hands-on and project-based learning experiences where the default is to use example-based learning strategies (Hartley *et al.*, 2011; Reeves and Weisberg, 1994; Roll, 2009; VanLehn, 1996). Furthermore, awareness of student reasoning strategies may provide means for an improved student-teacher interaction and a useful resource for researchers who wish to study the complexity of hands-on STEM learning (Worsley and Blikstein, 2017). Finally, in terms of assessment, one implication of this work is the potential utility of chronicling student ideation strategies over time. The idea is not that students will uniformly gravitate toward principle-based reasoning in all situations. As previously noted, individuals who are identified as disciplinary experts draw upon a combination in approaches (Ahmed *et al.*, 2003; Anderson *et al.*, 1981; Chi *et al.*, 1981; VanLehn, 1996; Worsley and Blikstein, 2017). Hence, the proposed approach for assessment is to the see the ways that students' ideation strategies are expanding over time and across different contexts.

References

Ahmed, S., Wallace, K.M. and Blessing, L. (2003), "Understanding the differences between how novice and experienced designers approach design tasks", *Research in Engineering Design*, Vol. 14 No. 1, pp. 1-11, available at: https://doi.org/10.1007/s00163-002-0023-z

Anderson, J., Greeno, J., Kline, P., and Neves, D. (1981), "Acquisition of problem-solving skill", in Anderson, J. (Ed.), *Cognitive Skills and Their Acquisition*, Erlbaum, Hillsdale, NJ.

Bergner, Y., Abramovich, S., Worsley, M. and Chen, O. (2019), "What are the learning and assessment objectives in educational fab labs and makerspaces?", *Proceedings of FabLearn 2019*, Association for Computing Machinery, New York, NY, pp. 42-49, available at: https://doi.org/10.1145/3311890.3311896

Blikstein, P. (2013), "Digital fabrication and 'making' in education: the democratization of invention", in Walter-Herrmann, J. and Büching, C. (Eds), *FabLabs: Of Machines, Makers and Inventors*, Transcript Publishers, Bielefeld, pp. 1-21.

Blikstein, P. and Worsley, M. (2016), "Children are not hackers: building a culture of powerful ideas, deep learning, and equity in the maker movement", in Kafai, Y. and Peppler, K. (Eds), *Makeology,* Vol. 1, Routledge, pp. 64-80.

Blikstein, P., Kabayadondo, Z., Martin, A. and Fields, D. (2017), "The exploration and fabrication technology (EFT) index: assessing unexplored technology and engineering literacies in makerspaces and educational FabLabs", *Journal of Engineering Education*, Vol. 106 No. 1, pp. 149-175.

Brown, B. A. and Ryoo, K. (2008), "Teaching science as a language: a 'content-first' approach to science teaching", *Journal of Research in Science Teaching*, Vol. 45 No. 5, pp. 529-553, available at: https://doi. org/10.1002/tea.20255

Brown, B.A. and Spang, E. (2008), "Double talk: synthesizing everyday and science language in the classroom", *Science Education*, Vol. 92 No. 4, pp. 708-732, available at: https://doi. org/10.1002/sce.20251

Brown, B. and Kloser, M. (2009), "A view of the tip of the iceberg: revisiting conceptual continuities and their implications for science learning", *Cultural Studies of Science Education*, Vol. 4 No. 4, pp. 921-928.

Carbonell, J.G. (1982), "Learning by analogy: formulating and generalizing plans from past experience", *Machine Learning: An Artificial Intelligence Approach*, Springer, Berlin, Heidelberg, pp. 137-161, available at: https://doi.org/10.1007/978-3-662-12405-5_5

Chang, S. Keune, A. Peppler, K. and Regalla, L. (2015), "Open portfolio project research brief series", Maker Education Initiative.

Chi, M.T.H. Glaser, R. and Rees, E. (1981), "Expertise in problem solving", available at: http://files.eric.ed.gov/fulltext/ED215899.pdf

Colhoun, J., Gentner, D., and Loewenstein, J. (2008), "Learning abstract principles through principle-case comparison", *Proceedings of Cognitive Science Society*, pp. 1659-1664, available at: http://csjarchive.cogsci.rpi.edu/proceedings/2008/pdfs/p1659.pdf

Cross, N. and Cross, A.C. (1998), "Expertise in engineering design 2. An outstanding designer", pp. 141-149.

Dejong, G. and Mooney, R. (1986), "Explanation-based learning: an alternative view", *Machine Learning*, Vol. 1 No. 2, pp. 145-176, available at: https://doi. org/10.1023/A:1022898111663

Gabrielson, C. (2013), *Tinkering: Kids Learn by Making Stuff*, Maker Media, Inc.

Gentner, D. and Holyoak, K. (1997), "Reasoning and learning by analogy", *American Psychologist*, Vol. 52 No. 1, pp. 32-34.

Gentner, D., Loewenstein, J. and Thompson, L. (2003), "Learning and transfer: a general role for analogical encoding", *Journal of Educational Psychology*, Vol. 95 No. 2, pp. 393-408, available at: https://doi. org/10.1037/0022-0663.95.2.393

Gick, M. and Holyoak, K. (1980), "Analogical problem solving", *Cognitive Psychology*, Vol. 355, pp. 306-355, available at: www.sciencedirect.com/science/article/pii/0010028580900134

Gick, M. and Holyoak, K. (1983), "Schema induction and analagocial transfer", *Cognitive Psychology*, Vol. 15 No. 1, pp. 1-38.

Hammer, D. Russ, R. (2008), "Identifying inquiry and conceptualizing students' abilities... ", *Scientific Inquiry*: ..., pp. 1-20, available at: http://dhammer.phy.tufts.edu/home/publications_files/inquirybookchap.pdf

Hartley, L.M., Wilke, B.J., Schramm, J.W., D'Avanzo, C. and Anderson, C.W. (2011), "College students' understanding of the carbon cycle: contrasting principle-based and informal reasoning", *BioScience*, Vol. 61 No. 1, pp. 65-75, available at: https://doi. org/10.1525/bio.2011.61.1.12

Kurtz, K. and Loewenstein, J. (2007), "Converging on a new role for analogy in problem solving and retrieval: when two problems are better than one", *Memory and Cognition*, Vol. 35 No. 2, available at: http://link.springer.com/article/10.3758/BF03193454

Martinez, S.L. and Stager, G. (2013), *Invent to Learn: Making, Tinkering, and Engineering in the Classroom*, Constructing Modern Knowledge Press.

Menekse, M., Stump, G.G.S., Krause, S. and Chi, M.T.H. (2013), "Differentiated overt learning activities for effective instruction in engineering classrooms", *Journal of Engineering Education*, Vol. 102 No. 3, pp. 346-374, available at: https://doi. org/10.1002/jee.20021

Mitchell, T.M., Keller, R.M. and Kedar-Cabelli, S.T. (1986), "Explanation-based generalization: a unifying view", *Machine Learning*, Vol. 1 No. 1, pp. 47-80, available at: https://doi. org/10.1023/A:1022691120807

Mosborg, S. Adams, R. and Kim, R. (2005), "Conceptions of the engineering design process: an expert study of advanced practicing professionals", American Society for Engineering Education (ASEE), available at: http://monicacardella.com/mc/wp-content/uploads/2012/06/cardella_2005_ASEE_conceptions.pdf

Moss, J., Kotovsky, K. and Cagan, J. (2006), "The role of functionality in the mental representations of engineering students: some differences in the early stages of expertise", *Cognitive Science*, Vol. 30 No. 1, pp. 65-93, available at: http://onlinelibrary.wiley.com/doi/10.1207/s15516709cog0000_45/abstract

Nokes, T., Schunn, C.D. and Chi, M.T.H. (2010), "Problem solving and human expertise", *International Encyclopedia of Education*, Vol. 5, pp. 265-272, available at: http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.296.4224

Polya, G. (1945), "How to solve it".

Reeves, L.M. and Weisberg, R.W. (1994), "The role of content and abstract information in ", *Analogical Transfer*, Vol. 1 No. 3.

Roll, I. (2009), "Structured invention tasks to prepare students for future learning: means, mechanisms, and cognitive processes", available at: http://ra.adm.cs.cmu.edu/anon/usr0/anon/home/ftp/hcii/CMU-HCII-09-105.pdf

VanLehn, K. (1996), "Cognitive skill acquisition", *Annual Review of Psychology*, Vol. 47 No. 1, pp. 513-539, available at: https://doi. org/10.1146/annurev.psych.47.1.513

Vossoughi, S., Davis, N.R., Jackson, A., Echevarria, R., Muñoz, A. and Escudé, M. (2021), "Beyond the binary of adult versus child centered learning: pedagogies of joint activity in the context of making", *Cognition and Instruction*, pp. 1-29, available at: https://doi. org/10.1080/07370008.2020.1860052

Wardrip, P.S. and Brahms, L. (2015), "Learning practices of making: developing a framework for design", *Proceedings of the 14th International Conference on Interaction Design and Children*, Association for Computing Machinery, New York, NY, pp. 375-378, available at: https://doi.org/10.1145/2771839.2771920

Worsley, M. and Blikstein, P. (2011), "What's an expert? Using learning analytics to identify emergent markers of expertise through automated speech, sentiment and sketch analysis", *Proceedings of the Fourth Annual Conference on Educational Data Mining (EDM 2011)*, Eindhoven, pp. 235-240.

Worsley, M. and Blikstein, P. (2017), "Reasoning strategies in the context of engineering design with everyday materials", *Journal of Pre-College Engineering Education Research (J-PEER)*, Vol. 6 No. 2, pp. 58-74, available at: https://doi. org/10.7771/2157-9288.1126

Corresponding author
Marcelo Worsley can be contacted at: marcelo.worsley@northwestern.edu