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Reasoning Strategies in the Context of Engineering Design with Everyday Materials

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Abstract

"Making" represents an increasingly popular label for describing a form of engineering design. While making is growing in popularity, there are still open questions about the strategies that students are using in these activities. Assessing and improving learning in making/ engineering design contexts require that we have a better understanding of where students' ideas are coming from and a better way to characterize student progress in open-ended learning environments. In this article, we use a qualitative analysis of students' responses (N = 13) in order to identify the origins of their ideas. Four strategies emerged from this analysis: unexplained reasoning; materials-based reasoning; example-based reasoning; and principle-based reasoning. We examine key characteristics of each strategy and how each strategy relates to learning and expertise through in-depth case studies. Furthermore, we identify how these four strategies are a complement to prior work on analogical problem solving and creativity, and offer a number of unique contributions that are particularly relevant for engineering education. Finally, we include two coding schemes that can be used to classify students' responses. Studying reasoning strategies in this way is a fruitful means for characterizing student learning in complex learning environments. Moreover, understanding reasoning strategies impacts the nature of student–teacher discussions and informs how to help students progress most effectively.

Keywords

making, engineering design cognition

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Reasoning Strategies in the Context of Engineering Design with Everyday Materials

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Abstract

"Making" represents an increasingly popular label for describing a form of engineering design. While making is growing in popularity, there are still open questions about the strategies that students are using in these activities. Assessing and improving learning in making/engineering design contexts require that we have a better understanding of where students' ideas are coming from and a better way to characterize student progress in open-ended learning environments. In this article, we use a qualitative analysis of students' responses ($N = 13$) in order to identify the origins of their ideas. Four strategies emerged from this analysis: unexplained reasoning; materials-based reasoning; example-based reasoning; and principle-based reasoning. We examine key characteristics of each strategy and how each strategy relates to learning and expertise through in-depth case studies. Furthermore, we identify how these four strategies are a complement to prior work on analogical problem solving and creativity, and offer a number of unique contributions that are particularly relevant for engineering education. Finally, we include two coding schemes that can be used to classify students' responses. Studying reasoning strategies in this way is a fruitful means for characterizing student learning in complex learning environments. Moreover, understanding reasoning strategies impacts the nature of student–teacher discussions and informs how to help students progress most effectively.

Keywords: Making, engineering design cognition

> Making is about the active role construction plays in learning. The maker has a product in mind when working with tools and materials…. Making is about the act of creation with new and familiar materials…[it] is something powerful, a personal expression of intellect…. Making lets you take control of your life, be more active, and be responsible for your own learning. (Martinez & Stager, 2013, pp. 32–33)

Introduction

"Making" represents an increasingly popular label for describing a form of engineering, art, and computer science education. While "making" is by no means confined to those areas, nor are the terms synonymous, the current excitement surrounding the Maker Movement is providing an array of opportunities for educators in K-20 contexts to promote authentic experiences that engage students in the practices of *engineering* and *engineering design* (Blikstein, 2013; Honey & Kanter, 2013; Martin, 2015; Vossoughi & Bevan, 2014a; Worsley & Blikstein, 2013). For example, Martin (2015) writes, "there is growing interest among educators in bringing making into K-12 education to enhance opportunities to

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engage in the practices of engineering, specifically, and STEM more broadly," as to suggest that a primary driver within the Maker Movement is the potential for "making" to open up new contexts through which students participate in STEM. Within these contexts, students embark on the creation of a variety of devices, gadgets, and displays. Anyone who has watched students participate in a making experience can attest that students oftentimes surprise themselves with the level of creativity and innovation that they bring to the task. Even in the absence of innovative troubleshooting, in most projects, students must go from a problem, or challenge, to a refined final product. Given that students typically come up with one or more ideas, in this article we decided to tackle the study of the origins of those ideas. Specifically, we wish to answer the question of how students develop a solution when presented with an open-ended engineering design challenge. While some prior literature in engineering design cognition and analogical problem solving has examined elements of the student problem solving process, there is a need for additional work in this space, especially as it relates to studying engineering design cognition among high school students (Lammi & Gero, 2011; Worsley & Blikstein, 2014a). We will build on this prior literature to reconceptualize, interpret, and refine the language used for describing engineering design. Specifically, relative to prior work we will (1) provide a more contextualized description of student problem solving strategies in engineering design; (2) develop a pair of coding schemes for classifying student approaches; (3) propose the existence of "materials-based reasoning" as an important problem solving approach; and (4) describe how this work has relevance for teaching and learning.

Our contribution is based on an empirical design. Specifically, we chronicle four reasoning strategies, namely unexplained reasoning, material-based reasoning, example-based reasoning, and principle-based reasoning, that emerged as students completed an open-ended engineering design task. Understanding and documenting the reasoning strategies allowed us to develop two coding schemes (see Appendix 1) that concretize the identification of each reasoning strategy in a way that should be useful for researchers and practitioners.

In what follows, we first situate this paper in the context of prior research on engineering design, and then focus on analogical problem solving and creativity. This is followed by a detailed description of the design, methodology, and results from our study. We then move into a detailed qualitative description of each reasoning strategy, as seen through one or more case studies. Finally, we discuss the significance of studying these strategies and future research opportunities.

Prior Literature

The four reasoning strategies described in this paper build on prior work in engineering design cognition, creativity, and analogical problem solving. We will begin our discussion with a description of seminal work on the Function-Behavior-Structure model, and then transition into a synthesis of prior literature on creativity and analogical problem solving. Even though these two disciplines have historically operated independently of one another, we find many points of synergy between the communities, which we summarize and highlight in the following paragraphs.

Engineering Design Cognition: Function-Behavior-Structure Mapping

Across a series of articles Gero and colleagues (e.g., Gero, 1990; Gero & Kannengiesser, 2002) have developed and refined the Function-Behavior-Structure (FBS) model for describing the process of engineering design. While this model has received some criticism, it remains a central driver within the engineering design community, and provides language and a framework that will be useful for the analysis presented in this article.

Initially inspired by work in artificial intelligence, the FBS model provides a representation for considering the process of going from the design problem (Function) to the eventual artifact (Structure) (Gero, 1990). According to the model, this process is mediated through eight key processes that can be decomposed into additional steps when taking a more situated perspective (Gero & Kannengiesser, 2002). For the purpose of this paper we will not discuss the situated framework, but, instead, focus on the language and ontology developed in the original FBS model. FBS consists of the following eight processes: formulation, synthesis, analysis, evaluation, documentation, and three types of reformulation. Formulation involves transforming the design problem (function) into expected behaviors that satisfy the design problem. Synthesis takes the behaviors and transforms them into a solution structure that achieves the expected behaviors. Analysis then considers the behaviors actually achieved by the structure. Finally, evaluation compares expected behaviors with the actual behavior, as this will inform the designer as to whether the structure meets the specified requirements. The three reformulation steps involve changing elements of the function, behavior, or structure state spaces as needed to effectively complete the task.

In this paper we are primarily concerned with the interplay among these different processes, and what motivates their enactment. Specifically, in characterizing Gero (1990), Dorst and Vermaas (2005) write that "the knowledge that designers use to make these steps is characterized as knowledge by experience collected by designers during earlier (alike) design tasks." The idea of leveraging previous design tasks, and previous experiences, more broadly, is a central component of this paper, and is squarely situated within the analogical problem solving literature. The FBS ontology proposes that portions of the process are completed through teleological reasoning (mapping from Function to Behavior) and causal reasoning (mapping between

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Structure and Behavior). Throughout this article, we will keep with the language of "reasoning" to describe the ways that designers undergo the design process.

In summary then, FBS provides a common set of language for modeling the design process, and points to the importance of reasoning based on prior design and life experiences. However, as some have alluded to in prior literature, there are apparent gaps and inconsistencies within FBS (Dorst & Vermaas, 2005). This paper can serve to address some of these gaps by describing in more detail different strategies that students use to reason through engineering design challenges. In the sections that follow, we transition into a brief discussion of two closely related areas, creativity and analogical problem solving.

Creativity

Important contributions to the study of complex problem solving can be traced back to early research by Maier (1931), Köhler (1940) and the various authors that build on their findings (e.g., Epstein, 1999). Maier (1931) describes the emergence of human insight in complex, novel situations through a host of tasks. In one of the tasks, dubbed the "rope experiment" or the "two string problem," students were placed in a room where two ropes hung from the ceiling. In addition to the two ropes, the room had other materials (e.g., poles, clamps, chair, and an extension cord). The students were instructed to find a way to tie the two ropes together, which could not easily be completed since the student could not hold one string and reach the second string. In analyzing the students' actions, Maier studied how conscious students were of their reasoning process. Based on post-task interviews he found that solutions typically occurred spontaneously, and that students were seldom able to articulate or express consciousness of the steps that enabled them to solve the task. Elucidating these steps has been a primary line of research for several scholars, and is of central importance to this article.

Kohler (1940) completed similar work by examining the emergence of insight among chimpanzees. Kohler used a box-and-banana problem in which the subject must learn to properly position a box in order to reach a banana that is otherwise out of reach. In Kohler's work, nearly all of the chimpanzees resorted to the same approach of fruitlessly jumping up to grab the banana, without making use of the box. This activity continued for several minutes without much indication of learning. However, after some time one chimpanzee experienced the momentary insight to move the box underneath the banana. To Kohler's observations this was a moment of unexplained insight (Köhler, 1960), a form of reasoning that we will also see among the students in our studies.

Epstein (1999) pushes the idea of unexplained insights further by proposing that individuals can be trained to behave in predictable ways even when placed in new situations. In his box-and-banana study, he conditioned pigeons through various combinations of training regimens: (1) climbing a box; (2) freely pushing a box around a room; (3) directionally pushing a box around a room; (4) learning to avoid flying to grab a banana. After the training process, the configuration of the room was altered. The pigeons that had been trained in climbing and directional box pushing succeeded, while those pigeons who had not learned those skills failed. Similarly, even pigeons that learned to push the box, but never learned to push in a directional fashion, took significantly longer than the other pigeons.

In later work, Epstein more closely analyzed the predictability of human behavior through an extension of Maier's two-rope experiment. Instead of providing various props, as was the case in the original study, Epstein provided a single object, and indicated to the participants that they could use the object if they pleased. In these experiments Epstein found that student performance and behavior was largely dependent on the properties of the object that was provided. More specifically, Epstein compared performance and behavior when the additional item provided varied in length. When the additional item was relatively long he found that participants experienced great difficulty in completing the task. He attributes this to the subjects being convinced that the length of the long object was the key to solving the challenge. However, when the additional object was very short in length, participants had a much easier time solving the challenge. Namely, when a short object was provided, participants realized that the object would need to be attached to one rope, and then placed in motion in order to complete the task. Taken together, this work suggests that the types of novelty and creativity that people display in new situations can be the result of prior conditioning and the materials provided.

In a related line of research, Bruner, Goodnow, and Austin (1956) also emphasize that human insights and inferences are highly dependent on one's environment but makes the point that these intuitions are still quite useful (Bruner, 1960). Specifically, Bruner makes the case that while formal education tends to stress the importance of analytic thinking, intuitions are of paramount importance in everyday life and in mathematics and science. Furthermore, using intuitive thinking often occurs only because an individual has deep knowledge of a given domain, and need not employ step-by-step analytic reasoning to arrive at the solution to a given problem.

In summary, prior research on creativity and innovation indicates that solutions to complex problems may appear as unexplained reasoning or behaviors. These insights may be unexplained from the perspective of their producer, but can oftentimes be predicted based on the individual's prior experiences, prior knowledge, and the context of the problem. In the section to follow we continue the discussion about the influence that prior experiences, prior knowledge, and the problem context has on student problem solving from

the perspective of cognitive science. More specifically, we highlight background literature in analogical problem solving which more closely analyzes the intersection between problem solving strategies and learning.

Analogical Problem Solving

Several researchers have chronicled the approaches that students use in different education-related problem solving contexts (Anderson, Greeno, Kline, & Neves, 1981; Carbonell, 1982; Gentner & Holyoak, 1997; Gick & Holyoak, 1980, 1983; Polya, 1945). In particular, these scholars examined the ways that students leverage similarities between a prior problem, or solution, and the current problem, in order to formulate a solution. Foundational work by Gick & Holyoak (1980, 1983) coined the term "analogical problem solving," and influenced several later instantiations of analogical problem solving (e.g., case-based reasoning (Kolodner, 1992) and learning-by-analogy (Carbonell, 1982; Gentner & Holyoak, 1997)). The initial research on analogical problem solving was based on problem solving scenarios in which participants were provided with a story whose essence could be used to solve a target problem. The researchers then examined how well students could apply the principle portrayed in one solution to solve a problem from a different context. In most studies students were presented with Duncker's (1945) "radiation problem" which asks

> Suppose you are a doctor faced with a patient who has an inoperable stomach tumor. You have at your disposal rays that can destroy human tissue when directed with sufficient intensity. How can you use these rays to destroy the tumor without destroying the surrounding healthy tissue?

The solution to this problem is to have several low-intensity rays converge on the tumor. This ensures that the healthy tissue is not damaged, while also enabling a sufficiently intense ray to destroy the tumor. In most of Gick and Holyoak's experiments, one or more of the experimental groups was presented with the solution to the Attack–Dispersion problem, in which a military commander disperses his troops and has them converge on the enemy from several directions. Gick and Holyoak (1980) conclude that presenting the solution to an analogous problem significantly improves the likelihood that students will succeed. However, merely presenting the solution is not sufficient. Instead, students need to be told that the solution to the Attack–Dispersion problem provides a crucial insight on how to solve the radiation problem. Additionally, Gick and Holyoak found that the level of correspondence between the source problem and the target problem has an important impact on how well students are able to transfer from one problem to the other. Most importantly, though, is the idea that analogy retrieval and analogy use are two distinct processes. Hence, even though a student may be able to retrieve a prior experience, they may not know when, or how, to use it. Similarly, students may be able to use a prior experience that they did not spontaneously generate, which is what frequently occurred in Gick and Holyoak (1980).

Gick and Holyoak (1983) take the research one step further by disentangling the role that schema abstraction plays in predicting student success on the radiation problem. In particular, the authors note that analogical problem solving can involve mapping between two concepts, mapping between a concept and a schema, or the application of a schema that was abstracted from several examples. Accordingly, the authors wished to study the relative affordances of each type of mapping with the realization that operating on either extreme of the concrete–abstract spectrum is non-optimal. In fact, analogical problem solving typically arises through the identification of an initial mapping which is refined over time. This refinement process can involve the learner drawing new inferences and insights never explicitly presented to the learner. Furthermore, the authors note the importance of everyday understanding in the analogical problem solving context. Through a series of experiments, one of which included a variant of Maier's two-string problem, Gick and Holyoak conclude that students who develop better schemas (i.e., mappings between the source problem and the target problem) perform much better on the activity. They also find that simply presenting the principle is not the most effective way to promote transfer, and that the impact of presenting the underlying principle is heavily dependent on the way that it is represented.

During the past few decades, researchers have continued to expand upon the early research of Gick and Holyoak (1980, 1983). Much of this research aims to lessen the challenges that students face when presented with the task of drawing comparisons between similar objects from markedly different contexts (Brophy & Schwartz, 1998; Medin, Goldstone, & Gentner, 1993) and when students have little domain expertise. Other research compared the effects of students being exposed to different representations, multiple examples, multiple questions, different levels of solution, and/or problem specificity, and the principles that underlie a given example (Colhoun, Gentner, & Loewenstein, 2008; Gentner, 2004; Gentner, Loewenstein, & Thompson, 2003; Loewenstein, 2010). Loewenstein (2010) deconstructs these different solution and problem formulations as being related to the ambiguity and context specificity, completeness, and featuring weighting. Encoding ambiguity and context specificity refer to how easy it is to encode an experience in such a way that the most salient elements are maintained. If an experience is encoded in a way that is highly context specific, it can be harder to use in the future, when there is a change in the context. Completeness refers to the quality of the encoding, and is closely tied to the identification of both surface features and structural features. Failure to properly ascertain which features of an

example are relevant can greatly hinder the process of mapping. Prior work has suggested that this is a primary hindrance for novices, who struggle to construct a complete encoding of the example (or problem). However, Loewenstein (2010) notes that there are ways to overcome poorly encoded source problems. Finally, feature weighting refers to the relative level of importance afforded each of principles or components of a problem or solution. Thus, even after an individual is able to properly identify the features or principles at play, he or she must consider the relative importance of each of those features.

Of greatest significance to the current study is prior work on distinguishing among different types of analogies and different levels of similarity. For example, some researchers have used the terminology of attributional similarities and relational similarities. Attributional similarities are those that relate to a characteristic or property of an object. Relations entail the relationship of one property or behavior relative to another. In order to effectively use analogical reasoning, students must uncover relational similarities (Medin et al., 1993). Chi, Glaser, and Rees (1981) describe analogs with the language of deep features and surface features. Deep features typically constitute those items that can only be recognized by individuals with extensive domain knowledge and are related to the principles that may underlie a given problem or solution. Without sufficient domain knowledge, novices are limited to identifying surface features, which may include elements of the problem context (e.g., recognizing that two problems are both about trains, but not realizing that one is about velocity while the other is concerned with force). Later work by Chi and VanLehn (2012) examined the distinction between entity cues and process cues. Again, entity cues represent the superficial surface features, whereas process cues involve the interactions that can be used to explain the relationship among the entity cues. Throughout these different formulations, what remains constant are the ideas that (1) there are some features that are easy to identify and some features that are more difficult to identify, and (2) that a fundamental part of successfully leveraging analogical transfer is rooted in the student's ability to leverage those deep, structural features. Examining how well the ideas of surface features and deep features map onto student reasoning strategies in hands-on engineering design is a key objective for this paper. More specifically, part of the thesis of this paper is that the current language of analogical problem solving is insufficient for the domain of engineering design.

Additionally, the current study also serves to operate at the intersection of engineering design, creativity, and analogical problem solving in such a way that has not previously been conducted. For example, whereas prior research on analogical problem solving was typically conducted on problems with a single principle and/or a single correct solution, our task allows for a variety of correct solutions. At the same time, research on engineering design strategies has typically involved design-oriented strategies as opposed to engineering- or learning-oriented strategies. For example, Dow et al. (2010) compare the impact of parallel design and serial design. Specifically, they show that parallel brainstorming is a better strategy for promoting higher quality designs. Gero et al. do something similar by examining how idea generation strategies with varying levels of structure impact the ideation and design phases of group projects. Again, then, the focus is on design-oriented strategies and not on learning- and/or engineering-oriented strategies. And while work by Dow and colleagues (e.g., Dow et al., 2010) has focused on a similar intersection of engineering design, creativity, and analogical problem solving, that work operates from a perspective that is comparing the relative efficacy of two existing design approaches, as opposed to identifying a way for framing and explaining the reasoning strategies that students use when approaching engineering design tasks. Finally, compared to prior work, our study also has the benefit of involving a task where students actually build a physical artifact, something that is commonly omitted from studies in analogical problem solving, and in engineering design cognition. Hence, the current study represents a unique intersection of disciplines, but one that is becoming increasingly important for next-generation engineering design education.

Methodology

The purpose of this study is to chronicle the different strategies that students use for tackling engineering design tasks. Specifically, our research question is: "What guides students as they come up with a final artifact with limited materials and with explicit design requirements?" The study employs a grounded theory approach to developing classes of strategies, and then proceeds to provide case studies of each strategy. Within the discussion of each strategy we make reference to prior literature in analogical problem solving, creativity, and engineering design.

This study included a convenience sample of thirteen participants with different levels of prior experience. Including a population of students with different levels of experience was important for identifying common strategies, and was not motivated by a desire to distinguish among expert strategies and novice strategies. In fact, within our sample, we do not explicitly classify participants as being experts, intermediate, or novices, though we know that our sample includes individuals that span this continuum. The three most experienced students were enrolled in mechanical engineering PhD programs at the time of the experiment and had engaged in engineering practices for several years. Two of the PhD students were in the first year of their program, while the third was in her third year. The mechanical engineering students were part of a laboratory group that shared space with the authors. The least experienced

participants were 9th grade students who had limited prior knowledge or training in engineering. The five 9th grade students were joined by two 10th grade students, one 11th grade student and two 12th grade students. The ten high school students included in this study came from three San Francisco Bay Area charter schools, while the three graduate students were from an elite private university in the San Francisco Bay Area.

All participants worked individually and were presented with the challenge of supporting a small mass (< 1 kg) as high off of a table as possible. To complete this task, students were provided basic household materials: four drinking straws, five wooden Popsicle sticks, a roll of tape, and a paper plate; and were given an unlimited amount of time to reach a final structure that they were satisfied with (Figure 1). We selected these building materials because they are objects that most participants would be familiar with and would not necessarily confer a novelty effect. In considering the design of the task, we aimed to have a task that fits the characterization of design task put forth by Gero (1990): "a goal-oriented, constrained, decision-making, exploration, and learning activity which operates within a context which depends on the designer's perception of the context" (p. 2). An audio/visual recording was collected for each student.

Because no pencil and paper was provided to students, they largely perceived this as a making/tinkering task, as opposed to a traditional engineering task for which they would have been expected to develop calculations in order to answer their questions. This blending of engineering design and tinkering oftentimes characterizes the K-16 "making" experiences where the overall objective is to create a finished and functioning artifact, similar to the work of an engineer, but seldom do participants engage in rigorous mathematical calculations to support their designs (Vossoughi & Bevan, 2014b).

After completing the design task, students were asked about how they came up with the design of their structure. The interviewer was instructed to engage each participant in an informal discussion about where their design idea came from, essentially providing a means for the participant to walk the interviewer through the process of going from Function to Structure. The interviewer was given discretion in guiding the conversation[1]. Each student verbally responded to the questions posed and had their structure in front of them during the interview. The verbal responses form the basis for identifying, describing, and analyzing the four strategies referred to in this paper.

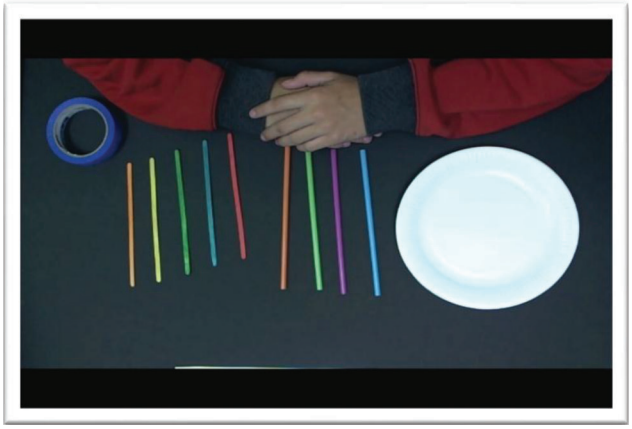


Figure 1. Materials provided for activity, which include one paper plate, four plastic draws, five wooden sticks, and unlimited tape.

Data Coding Summary

The research group used collaborative video analysis (Cockburn & Dale, 1997; Pea, Lindgren, & Rosen, 2006) to use a grounded theory approach (Glaser & Strauss, 1967) for understanding student reasoning strategies. After watching each video, we discussed the essence of each student's approach, as described by the student, and through observing their behaviors. The group then formulated and grouped responses on a whiteboard. For all participants we reached consensus about the strategies being used. An important point to note is that we are largely basing our analysis on students' responses, as opposed to our own inferences about what we observed the student doing, or a think-aloud approach. This study design decision was intentional, as some students were apprehensive about sharing their thinking in real time.

Because our main research question was "what strategies do students use to approach engineering design tasks?" we began by grouping together all responses in which a respondent was unsure of the origins of their idea (unexplained reasoning). This was readily apparent, as these students would immediately respond that they were not sure about the source of their design idea. We then focused our attention on analyzing the remaining responses, which we grouped based on the presence or absence of a reference to deep structural features (e.g., triangles or other structural principles from engineering) (principle-based reasoning). Part of the insight for even paying attention to this was based on an observation made when conducting and reviewing the interviews. Namely, we noticed that several students referred to triangles as being strong, whereas others frequently mentioned a real-world object or structure in their response. At the onset we used a very specific categorization where referring to triangles was treated differently from referring to symmetry, for example. However, we eventually realized that it would be best to collapse "principle-related" ideas into a single category, and reserve another category for ideas based on familiar real-world objects. These two categories have some semblance to prior

[1] In a follow-up study ($N = 54$) we used a more systematic approach for asking each student about the origins of their idea and saw consistent findings. However, given that the objective of this initial study was to chronicle the different approaches used, we took the liberty of framing the questions as an informal conversation.

research in analogical problem solving (i.e., surface features and structural (or deep) features). Initially, we found these three codes (unknown, example-based, principle-based) to be sufficient for describing the various responses that students created. However, after some discussion we noticed that the responses that mentioned real-world structures did so at two different levels. Some students made reference to the specific materials used for the activity, and how those materials reminded them of some other object (materials-based reasoning), while other students made reference to real-world objects that were not among the provided building materials (example-based reasoning). After coming up with these four groupings we carefully studied a few prototypical responses from each category, some of which are included in the descriptive sections of each reasoning strategy. Analysis of the prototypical responses aided in the eventual naming and defining of each category. As previously noted we avoided using the current naming constructs from analogical problem solving (structural features and surface features; or surface features and deep features) because these two terms fail to fully capture the differences that exist among materials-based reasoning, example-based reasoning, and principle-based reasoning. Whereas surface features have commonly been used for any class that falls outside of the deep features category, disaggregating into example-based reasoning and materials-based reasoning is an important distinction, especially given that deep features about the materials may subsequently trigger the student to identify an example structure whose surface features guide the student in their reasoning, for example. Additionally, as previously noted, we use the term "reasoning" in following with prior work in engineering design (e.g., Dorst & Vermaas, 2005). A description of each reasoning strategy is included below.

Unexplained reasoning – instances where the students stated that they did not know where their idea came from.

Materials-based reasoning – instances where the student indicates that one or more properties of the building materials provided the basis for their idea.

Example-based reasoning – instances where the student based their idea on a structure or item from a prior experience. A particular focus is on items from the student's home, community, or school.

Principle-based reasoning – instances where the student based their design on principles or concepts from science or engineering.

In broad terms, principle-based reasoning involves working forward from deep structural features, whereas example-based reasoning tends to involve working backwards from an exemplar. Similarly, example-based reasoning involves drawing analogies between an entire structure and a given task, while materials-based reasoning is more constrained, and normally involves component-level analogs. Finally, unexplained reasoning encompasses ideas whose origin is unknown to the originator or too difficult to articulate, or instances where the participant does not wish to describe the origins of their idea.

In the sections to follow, we provide detailed examples of each reasoning strategy based on the data from our study. Importantly, for each strategy we include excerpts and, in some cases, images to help the reader understand the essence of that strategy, as well as its potential strengths and weaknesses. Additionally, we conclude each description with a brief explanation of how that strategy could be interpreted by the FBS ontology. We do not purport that the FBS interpretations provided are the only possible interpretations. On the contrary, in many cases alternatives absolutely do exist, especially in instances where we interpret students going directly from function to structure, as this pathway remains a source of debate within the larger engineering design community (Dorst & Vermaas, 2005; Gero & Kannengiesser, 2002). Similarly, one can argue about if the structure triggers behaviors, or if the behaviors are pieced together in order to identify and define the structure.

Reasoning Strategies

Unexplained Reasoning

Of all of the strategies, unexplained reasoning is likely the easiest to recognize. Below are two dialogues with 9th graders that provide concrete instances of unexplained reasoning.

Dialogue 1

Interviewer: How'd you come up with that idea?
Student: I don't know. I really don't.
Interviewer: Have you seen anything that looks like that?
Student: No. It kind of looks like [turns it over]…I don't know.

Dialogue 2

Interviewer: So what inspired your design?
Student: I don't know, I just started doing it.
Interviewer: But you had no initial thoughts?
Student: Not really.

The source of these two students' ideas remains unexplained. While this may seem inconsequential, it may be indicative of a lack of engagement, or a lack of a clear

direction. This, in turn, could create challenges for the student. For example, following an unknown approach can result in the students having considerable trouble in debugging or fixing their structures. Without a clear understanding of the intermediate impact that a given action will have, students might find it difficult to complete the task and/or effectively interpret the feedback that they get from testing their structure.

In considering unexplained reasoning, it is important to note that this approach is not at all unexpected, nor is it necessarily deleterious. Prior research on creativity and innovation highlighted unexplained reasoning (Epstein, 1999; Maier, 1931) and intuitive reasoning (Bruner, 1960) as common in both human and animal cognition. Nonetheless, as the reader will soon observe, this approach is a stark contrast to principle-based reasoning, which gives the student some foundational ground rules for analyzing their design; and example-based reasoning where students are at least working towards a template. Similarly, with materials-based reasoning, there is typically at least a portion of the design that the student can recognize as being "correct" in the sense that the material is operating in accordance with its analog. In the case of unexplained reasoning, this is less likely to occur.

In the language of FBS, it is as if students went directly from function to structure, without an explicit or easily identifiable reasoning process (Figure 2), which may curtail their ability to draw connections between a structure's design and its behavior.

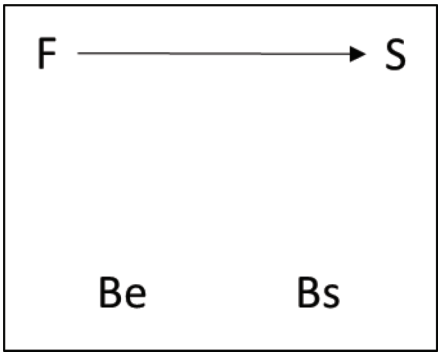


Figure 2. FBS interpretation of unexplained insight where the student effectively goes from function to structure with no intermediate steps.

Materials-based Reasoning

Materials-based reasoning provides a powerful tool for helping students start building their structures. Instances of materials-based reasoning tended to occur alongside example-based reasoning. For instance, when asked to describe the origins of his design one first year mechanical engineering graduate student remarked, "a table, I saw the plate and thought of making a table of some sort." The second phrase, "I saw the plate and thought of…" captures the central idea of materials-based reasoning. The materials and objects available trigger the student to think in particular ways. This is in contrast to example-based reasoning where the tendency is to start by thinking of example structures that solve a similar problem. As described, materials-based reasoning has apparent ties to Epstein's comparison of long and short objects in the two-string problem. In that case, as with materials-based reasoning, student reasoning is greatly impacted by the materials provided. When comparing materials-based reasoning and example-based reasoning, the two often lead to similar designs, but represent different initial strategies. Materials-based reasoning is also distinct from principle-based reasoning. One example of this is that principle-based reasoning typically involves the student adapting or contorting the material to fit a principle. In materials-based reasoning, the student is trying to find the principle that "fits" the material; hence the directions of idea generation are opposite.

To further ground the idea of materials-based reasoning, we present an excerpt from the dialogue of another 9th grade student.

Dialogue 3a

> Interviewer: So, where'd your idea come from?
> Student: I saw how these [sticks] had the flat ends and started stabbing the thing to make it go in.

Here the student has taken an action based on an observed property of the material, namely the flat ends. He later goes on to describe that he put the sticks and straws together because the sticks fit inside the straws.

Dialogue 3b

> Student: But that didn't really like, stick in there, so I pulled the tape out and put the things in and wrapped it around it. And to make that taller, those (the sticks) fit inside these (the straws), so I just put it on top and made it. […]
> Interviewer: You mentioned earlier that the materials don't fit. What would have been better? What would have been ideal materials to build with?
> Student: I mean that what I meant by that was like, I wanted something to have a fatter, what is it? Like a beginning, more like…
> Interviewer: Tapered? Or fatter straws?
> Student: Yeah so it would have been the, the beginning would have been more stable.
> Interviewer: Oh at the bottom?
> Student: Yeah. Cause my initial thing was to put the straws in like, a square and have these on top of it, like a flat like, boat type thing. Then have the tape and then that.

The student described the materials as not being a good "fit" for the activity. In this sense he may have been

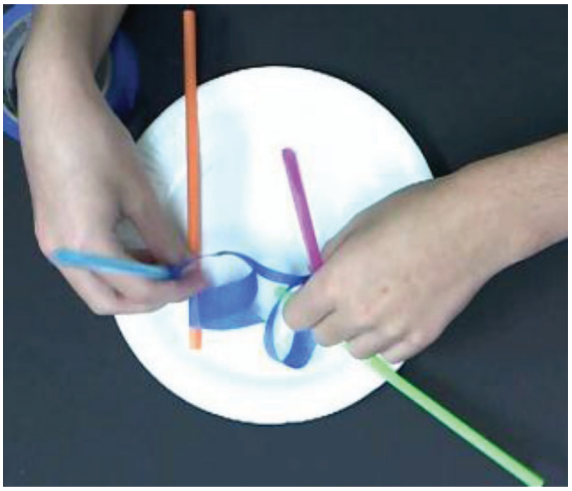


Figure 3. Student design before materials-based insight about the roll of tape. The student is struggling to get the straws affixed to the tape and also maintain a circular shape.

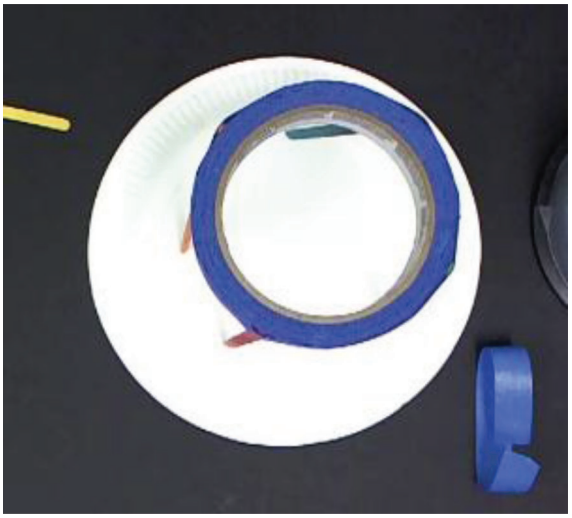


Figure 4. Student design after materials-based insight that the roll of tape could be a crucial piece of this design because of its rigidity and well-defined shape.

looking for the materials to dictate what he should do, as opposed to thinking about ways to use the provided materials to complete his idea. This approach encapsulates the materials-based reasoning strategy and highlights some of its limitations. Without appropriate cues from the materials this student probably would not have succeeded. And, in fact, this student significantly struggled until he found a clever way to use the roll of tape as a component in his final structure. Figure 3 shows the student's structure before this insight. The student eventually abandons that idea because it is unstable, and moves on to the design in Figure 4.

As an additional note, the above reference to a "boat type thing" and "make the bottom stable" are more instances of how a student may invoke several of the reasoning strategies within the same explanation. The student is describing

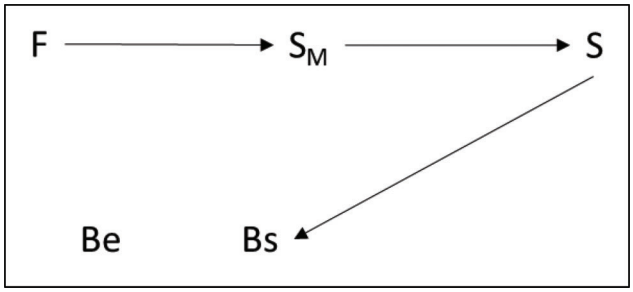


Figure 5. FBS interpretation of materials-based reasoning where the materials provided (S_M) trigger the student to think about an exemplar which they copy for their eventual structure (S).

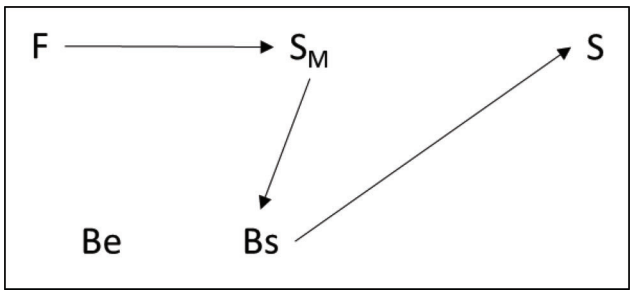


Figure 6. FBS interpretation of materials-based reasoning where the materials provided (S_M) and their behaviors (Bs) trigger the student to think about an exemplar which they copy for their eventual structure (S).

ideas that could reasonably fit under example-based reasoning (mentioning a boat-like structure) and principle-based reasoning (arranging the straws such that the structure will have a wider base). Accordingly, it makes evident that the reasoning strategies can provide bridges between one another even over relatively short time-scales.

As it relates to the FBS ontology, materials-based reasoning can take on a couple of different interpretations (Figures 5 and 6). In Figure 5 we see the case where the specified function caused the student to focus on a property of one of the provided materials (S_M) (e.g., a plate). The plate then triggered the student to think about another structure (S) (e.g., a table), which has certain behaviors that appear to satisfy the functional requirement specified.

In other cases (Figure 6), the function may cause the student to think about the materials provided (e.g., straws) and their behaviors (e.g., symmetric and thin, but still rigid), subsequently resulting in the student thinking about using the straws as legs of a table, which again has behaviors that satisfy the functional requirements of the artifact. Thus, materials-based reasoning has the general pattern of a sub-component triggering a particular exemplar that may eventually serve as a template.

Example-based Reasoning

In example-based reasoning, students create a structure that closely resembles a real-world object. More importantly, though, example-based designs are often modelled

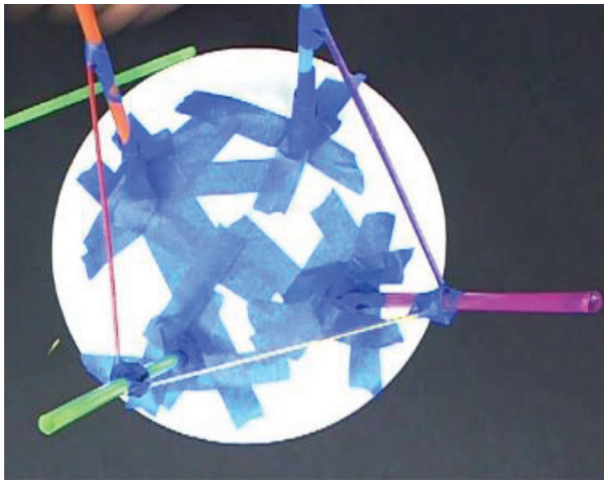


Figure 7. Successful example-based design that was modeled after a chair from the student's home.

after a specific item that the student has frequently interacted with as seen in the following dialogue with a 9th grade student.

Dialogue 4a

> Interviewer: So how'd you come up with your design? What inspired it?
> Student: Uh…It's like the form of a chair. Plus. Yeah just like a chair…'cause I have a chair like that…at home.

This student draws on similarities between a real-world object from his home and the engineering design task. He recognizes that a chair satisfies many of the same requirements as this particular task, and therefore elects to use a chair as the basis for his design (Figure 7). In the language of analogical problem solving, the student constructed a mapping between the capabilities of the chair and the need to create a structure that is stable.

As the student continues to describe the motivation for the design, he indicates that he had briefly entertained another idea.

Dialogue 4b

> Interviewer: Did you consider any other designs?
> Student: Nah. Oh. Oh yeah. And I'm like… Oh that's dumb.
> Interviewer: Why? What way was that?
> Student: That was um, just putting the straws straight up. And then putting the sticks inside. But like…let's use the sticks for something else.
> Interviewer: So what do you think, what would have happened if you had gone with the other design?
> Student: It would have fell, probably.

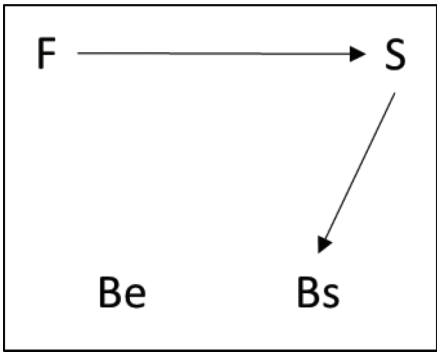


Figure 8. FBS interpretation of example-based reasoning where the functional requirements trigger the student to think about an example structure that has certain behaviors that meet the specifications.

The student's initial idea very closely resembled his eventual structure but did not have wooden sticks connecting the legs. In other words, he refined his initial mapping in order to address its perceived shortcomings. When asked why he did not pursue the other design he says that the other idea "was dumb." While he may have been hinting at engineering principles, he does not articulate the supporting schema for his idea refinement. For this reason, it is hard to state whether this student was using surface features or deep features. It may be that he was using elements of both. Regardless, there is a need for a complementary taxonomy, beyond surface features and structural features, for describing how this student develops his idea. As it relates to the other strategies, the ability to transfer knowledge from a problem to a potential solution has advantages to being unable to articulate a response (unexplained reasoning) (Gick & Holyoak, 1983), or having ideas couched in the properties of the available material and objects at hand (materials-based reasoning) (Epstein, 1999; Gick & Holyoak, 1983). The example-based line of reasoning is also distinct from the in-depth, principle-informed comments of the principle-based reasoning examples that we describe in the next section.

In the FBS ontology, example-based reasoning could be represented as a subset of materials-based reasoning. As seen in Figure 8, instead of having an intermediate structure, the student bypasses that step and goes immediately to the structure of the exemplar, which has a set of behaviors that meet the functional requirements of the design task.

Principle-based Reasoning

Within this specific study, students whose strategies were classified as being principle-based ones commonly used triangles and circles throughout their design. This was the case for the structures pictured in Figures 9 and Figure 10, which contain the underside of a student's design.

In Figure 9 we see the early stages of the base. This base features two levels of triangles. The first is the shape of each leg. The second is the triangular base that the three

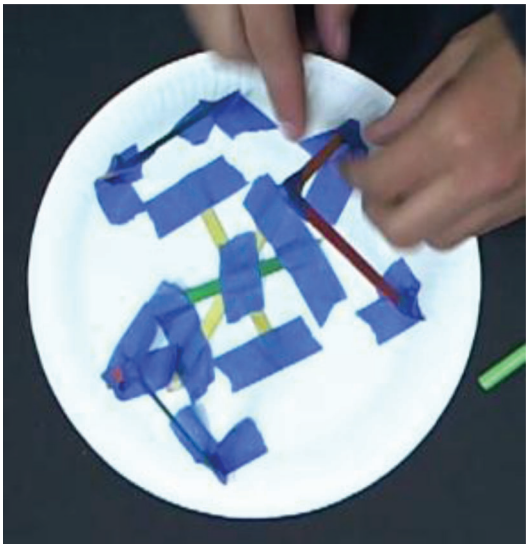


Figure 9. Sample principle-based design where the student has made three triangle-shaped legs.

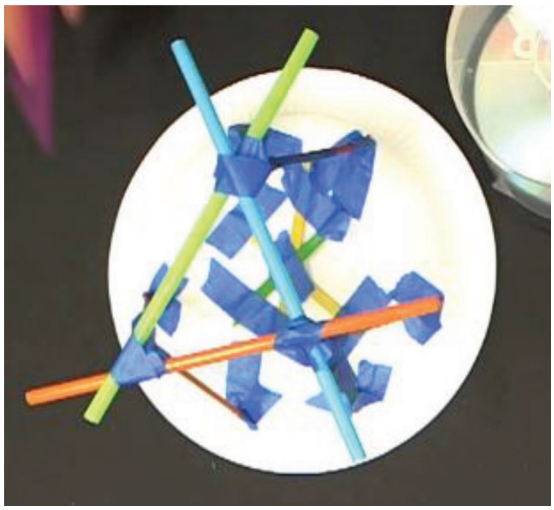


Figure 10. Sample principle-based design as in Figure 9, but with the addition of a triangle made out of straws to connect and brace the triangular legs.

legs define. Figure 10 makes the second level of triangles more explicit with the addition of three straws that form a triangle. When asked what inspired his design the student responded: "Well triangles are strong. And so, I decided to use as many triangles as I could." Upon further probing about the importance of triangles the student offered the following explanation: "[i]t's the most secure shape because, uhh, none of the angles can change once you have three sides in place. Whereas a lot of other shapes, they can tilt around and change."

This was a 9th grader at a local high school who spent considerable time on engineering-related projects outside of school. His structure was among the best of all of the participants in terms of stability, and his process underscores his approach of working forward from his understanding of principles in order to complete his design.

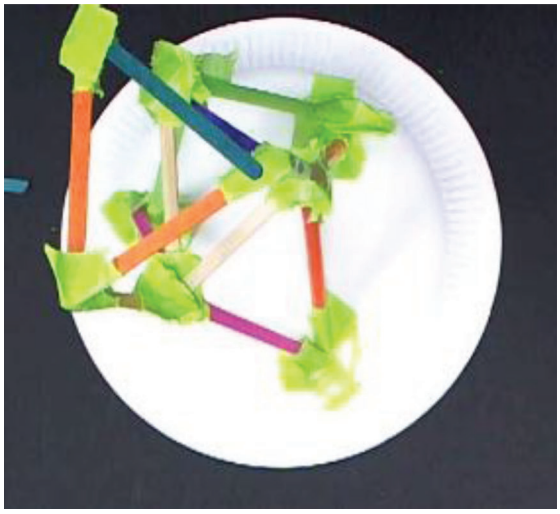


Figure 11. Unsuccessful principle-based design.

In a previous paper, we showed that principle-based reasoning correlated with higher quality designs and better learning (Worsley & Blikstein, 2014b). However, principle-based reasoning does not always coincide with these benefits. Figure 11 depicts a structure that failed to meet the requirements. This structure was made by a PhD student in mechanical engineering. When asked about what motivated the design, the student described the central role that triangles played in the structure.

Dialogue 5

> Interviewer: So what, what motivated your design?
> Student: Triangles…
> Interviewer: Triangles?
> Student: Uhh, the strongest structure is triangles. So I started with these triangles [pointing to the base of the structure] and figured out how to do more triangles… kind of like building a truss system.

We again see a principled approach to designing and building. She later reconfirms her principled orientation in describing why the structure failed and how she went about testing it. Specifically, she explains that the structure failed due to poorly constructed connections between the pieces of wood (Figure 12).

Furthermore, her approach for troubleshooting, which consisted of carefully applying a uniform force to the top of the structure in order to identify weak points, also represents a focus on principles. She essentially undertakes to simulate placing the weight on the top in order to apply enough stress so that she can determine the locations of the structure's instabilities. In this way she is demonstrating knowledge of the current shortcomings of her design, as well as knowledge about how to systematically test her design.

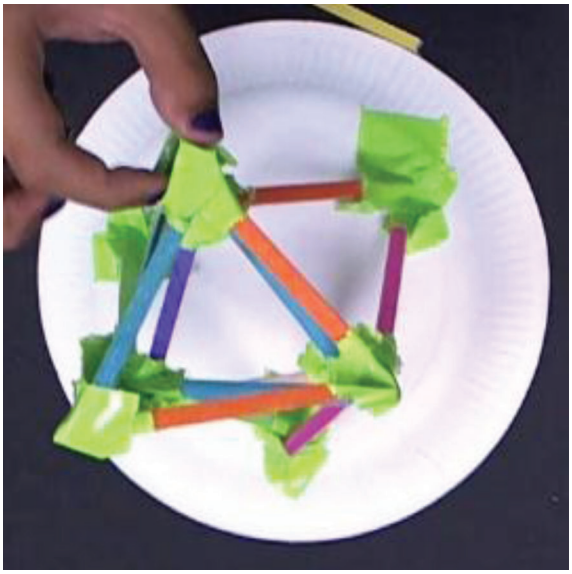


Figure 12. Student identifying weakness in their design.

Thus, from these excerpts we see that the student is using engineering principles at both the design and debugging stages. The fact that she uses the same underlying ideas to design and troubleshoot provides additional justification for referring to these approaches as reasoning strategies, as they appear to help the student reason through various portions of the challenge. Finally, the depth of explanation provided is analogous to the constructs of mechanistic reasoning and causal reasoning (e.g., Lehrer & Schauble, 1998; Russ, Coffey, Hammer, & Hutchison, 2009), builds on deep structural features (Chi et al., 1981), and appears to leverage robustly encoded schemas (Colhoun et al., 2008; Gick & Holyoak, 1983;Loewenstein, 2010).

In considering the FBS ontology, we typify principle-based reasoning as shown in Figure 13. The functional requirements cause students to immediately consider design elements (wide base, symmetric, triangular) whose expected behaviors satisfy the function requirements. They then utilize the microstructural elements to construct the larger structure, and iterate over the design as needed based on the actual behavior of their structure. In troubleshooting their macrostructure, they will continue to leverage and refine the microstructural design elements as needed.

Discussion

Despite the wealth of individuality that students bring to engineering design, clear commonalities exist in how students approach these tasks. The commonalities that we identified fall into four categories, namely unexplained reasoning, materials-based reasoning, example-based reasoning, and principle-based reasoning, which we described through individual case studies. Principle-based reasoning involves working forward from deep structural features, whereas example-based reasoning tends to involve working

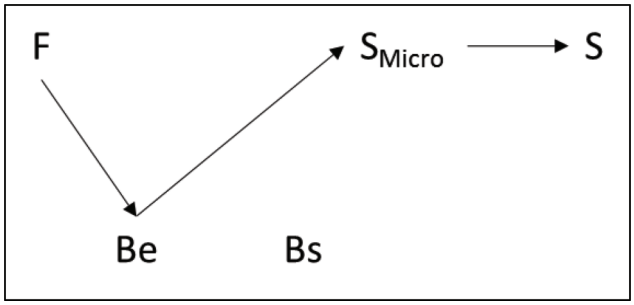


Figure 13. FBS interpretation of principle-based reasoning where the functional requirements cause the student to consider the expected behaviors, and subsequently the set of microstructural elements (S_{Micro}) that can be used to achieve those expected behaviors. The microstructural elements are then used to create the eventual structure (S).

backwards from an exemplar. Similarly, example-based reasoning involves drawing analogies between an entire structure and a given task, while materials-based reasoning is more constrained, and normally involves component-level analogs. Finally, unexplained reasoning encompasses ideas whose origin is unknown to the originator or too difficult to articulate, or instances where the participant does not wish to describe the origins of their idea.

Identification of the four strategies sheds an important light on the different ways that prior knowledge is incorporated into design cognition, and extends prior work on analogical problem solving, which is a central component in many design activities (Dorst & Vermaas, 2005; Gero, 1990). Additionally, the four strategies provide a more easily identifiable set of approaches through which to provide feedback and instruction.

Concretely, this paper provides three key extensions to prior research on analogical problem solving and the use of experiential knowledge in engineering design. First, the very notion of materials-based reasoning is one that does not appear in the literature on analogical problem solving. Recall that materials-based reasoning entailed the students' ideas being triggered by one or more of the materials provided. It may be that since most prior work on analogical problem solving was devoid of hands-on tasks, materials-based reasoning never surfaced as an important part of the problem-solving process. In addition to the mere existence of materials-based reasoning in engineering design, the case studies provide an initial indication that materials-based reasoning may serve as a pathway for enabling example-based reasoning and principle-based reasoning. This is particularly important because prior research has reiterated that novices often have trouble developing meaningful analogies. Accordingly, if there are ways for students to start one step before example-based reasoning, we may be able to help students improve their ability to effectively leverage their prior knowledge. Finally, the emergence of these reasoning strategies gives teachers and practitioners a more effective means for diagnosing student problem solving difficulties. For example, instead of simply

suggesting that a student chose a non-productive example analog, practitioners may be able to probe and discover the more immediate origins of a student's idea and more appropriately intervene.

Second, while three of the four strategies bear resemblance to analogical problem solving, we also saw clear distinctions among the strategies. In materials-based reasoning, the student is drawing analogies, or insights, based on the properties of the materials, or the way that the materials triggers the student to recall a certain sub-component of a given structure. In example-based reasoning, the student has abstracted away from the specific materials and is drawing connections between real-world examples, and the specific problem or challenge that they are addressing. Finally, in principle-based reasoning the user has abstracted principles from several examples, or past experiences, and is drawing analogies between the current challenge and the appropriate principles. In this way there is a continuum from sub-component (materials-based reasoning), to entire real-world example (example-based reasoning), to principles common to several real-world examples (principle-based reasoning). And, in fact, we observed a portion of this continuum on a small scale among the materials-based reasoning explanations that triggered students to later employ example-based reasoning. Not surprisingly, then, prior research in analogical problem solving would categorize this continuum as representing an increase in complexity (Anderson et al., 1981; Brophy & Schwartz, 1998; Chi et al., 1981; Chi & VanLehn, 2012; Loewenstein, 2010; Moss, Kotovsky, & Cagan, 2006; VanLehn, 1996). This, however, is not to suggest that experts exclusively use principle-based reasoning. For example, Bruner (1960) makes the case that experts are often able to use intuitive thinking (an instance of unexplained reasoning), as opposed to analytic thinking, because of their deep subject matter expertise. Similarly Ahmed and Wallace (2003) note that when placed in new, complex situations experts will utilize a variety of strategies. At the same time the continuum does not suggest that non-expert students never use principle-based reasoning. Even within this small dataset we observed 9th grade students who used principle-based reasoning, and a PhD student who used materials-based reasoning. Nonetheless, there is a general expectation that as students develop they transition towards the ability to use a larger variety of the reasoning strategies (Anderson et al., 1981; Chi et al., 1981; VanLehn, 1996). Several prominent cognitive psychologists and education researchers have made a similar argument insomuch as moving towards principle-based reasoning is associated with the development of expertise, scientific reasoning, and strategies that have broad applicability (Atman, Chimka, Bursic, & Nachtmann, 1999; Brennan & Resnick, 2012; Bruner, 1960; Chi et al., 1981; Lehrer & Schauble, 1998; Moss et al., 2006; Piaget, 1973).

The idea of a continuum also emerges when we consider the four reasoning strategies in the context of FBS. In particular, we see as one moves from materials-based, to example-based to principle-based, the student needs fewer explicit real-world cues in order to trigger their reasoning from function to structure. From this perspective, then, unexplained reasoning can be seen as the most "advanced" or least "advanced" of the approaches. As an "advanced" strategy, unexplained reasoning points to a level of intuitive knowledge that obviates the need for extensive causal and teleological reasoning. The student simply knows the solution to the design challenge. On the other hand, unexplained reasoning can indicate a lack of knowledge about how to effectively approach and troubleshoot the problem. As noted earlier, being unable to evaluate the expected behavior of the sub-components of a given design can make it difficult to create a functioning artifact. One implication of this continuum, then, is that practitioners should be cautious about having students move immediately from unexplained reasoning to principle-based reasoning, to use an extreme. If a student is exhibiting the use of materials-based reasoning, and the teacher wishes to help the student move to a different level of abstraction, the results from this analysis would suggest that it is most appropriate to help the student transition to example-based reasoning, as it is the next step in the continuum.

Third, relative to prior research on analogical problem solving, the strategies presented in this paper may best serve as complementary categorizations. For example, materials-based reasoning may involve using local structural or surface features in order to identify example structures. In the same way, even when one is basing a design on an example structure, the justification for leveraging that example structure could be based on surface features, deep features, or both. Hence, a classification system that incorporates the four reasoning strategies in this article as well as the traditional frames for categorizing analogical problem solving may be most appropriate for studying engineering design processes.

Implications

An important contribution of this paper is the development of two sets of coding schemes for identifying reasoning strategies within students' responses. The first coding scheme classifies a given response based on the most complex strategy used. The second coding scheme identifies the number of times each reasoning strategy is used in a given response. Both strategies are described in detail in Appendix A. We intend for the coding schemes to be useful in helping researchers and practitioners better understand how students developed their ideas.

Understanding the origins of students' ideas has great relevance for helping teachers and facilitators address students' challenges in those environments, and provides an additional dimension for acknowledging each student's individual developmental trajectory. As an example of this,

imagine a teacher who is preparing to talk with a student whose project did not satisfy the student's goals. This conversation could be markedly different based on the knowledge of the reasoning strategy that the student employed. A student who based their idea on an example structure, but overlooked an important piece of that structure would differentially benefit from a different kind of discussion than a student who based their design on properties of one of the provided materials. To make this more concrete, consider the case where a student used example-based reasoning. For that student it may be best to start by having a discussion around why the student chose the particular analog real-world structure. If the analog seems appropriate the teacher may then help the student troubleshoot through deep structural features that the student overlooked, or did not construct in accordance with the example structure. However, if the analog structure itself is not appropriate for solving the particular challenge that the student is tackling, the discussion should focus on helping the student think of an example structure that better fits the goal. In contrast, if a student used principle-based reasoning, the discussion should steer towards the specific principles that the student had in mind, and how they tried to apply them to their design. It may be that they misunderstood the principle, or, perhaps, were unsuccessful in how they tried to enact the principle within their design. Hence, being aware of reasoning strategies provides a better context for interacting with students.

We also observed instances of students' responses including multiple reasoning strategies. This is important because it reinforces that the strategies are not mutually exclusive, and that individuals of all levels of expertise are likely to employ a variety of strategies depending on the context and their prior knowledge in that area. One way for considering this is through the lens of "manifold cognitive resources" (Hammer, 2004). This theory provides an important perspective by explaining that students have a variety of resources at their disposal, but oftentimes only activate those resources in certain contexts. For example, certain elements of a task, or an experience, are likely to trigger the activation of different resources and practices. Accordingly, the role of an instructor is to help elicit students' diverse cognitive faculties. As such, even in describing the students in this study, we want to emphasize that there is a difference between a student using a principle-based reasoning strategy, and classifying a student as a principle-based "reasoner." The coding schemes provided in Appendix A are intended to categorize student utterances and behaviors, and not to categorize students as a certain type of learner, since these utterances are greatly dependent on context and activation.

Conclusion

In this paper we proposed the existence of four reasoning strategies: unexplained reasoning, materials-based reasoning, example-based reasoning, and principle-based reasoning. We empirically and theoretically described, and substantiated, the nature of each reasoning strategy. One of the primary factors motivating this paper was the desire to chronicle how students go from an engineering problem to a solution in the context of a hands-on building task. These tasks are becoming increasingly prevalent with the expansion of Makerspaces and FabLabs, which often operate at a fuzzy intersection between engineering and making (Honey & Kanter, 2013; Vossoughi & Bevan, 2014b). While prior work on creativity, engineering design, and analogical problem solving has provided some insights in this space, the previous categories and taxonomies are underspecified for the context of engineering design. Accordingly, we catalogued four strategies, principle-based reasoning, example-based reasoning, materials-based reasoning, and unexplained reasoning, that can be used in conjunction with previous ontologies. Principle-based reasoning was likened to reasoning forward from deep, structural features. Example-based reasoning was presented as a way to work backwards from prior experiences and example. Materials-based reasoning consisted of an analogical problem solving strategy that was largely limited by the properties of the building material. Actions that require the individual to use common materials in uncommon ways prove to be quite challenging using materials-based reasoning. Additionally, the identification of materials-based reasoning proved to be a new dimension in the problem-solving literature that may have important implications for both theory and practice. Unexplained reasoning had two interpretations: one as an instance of being able to act without the need for significant conscious mental processing, and the other as being the result of unconscious prior conditioning. Finally, we presented use cases in which the reasoning strategies are used in concert with one another.

Through this work, we hope to have contributed to the literature on engineering education by (1) elucidating a set of strategies that students employ, (2) studying design in a context where students are building actual artifacts, and (3) describing each strategy in the language of existing work in engineering design cognition and analogical problem solving. We recognize that this is just one step in a much longer path, and that more research is needed to find more nuanced transitions between the four reasoning strategies, further deconstruct each strategy, and determine effective techniques to move students from one strategy to the next. However, given that the implementation of these new engineering education spaces in K-16 schools is very recent, so is the research on how and what students learn in those spaces. We hope to have motivated continued research on the study of the origins of students' ideas as they have broad significance in supporting innovative practices of both teachers and students as they work in project-based, student-centered, hands-on learning environments.

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Appendix A: Coding Schemes

This appendix describes the two approaches that we developed based on our qualitative and theoretical analyses.

Single Strategy Assignment

In the first a, a student response is categorized by a single strategy. The process for coding a response is as follows:

1. Does the response mention engineering or science principles, even if they are not described in complete or correct terms?
   a. If yes, label principle-based reasoning.
   b. If no, proceed to the question 2.
2. Does the response mention one or more example structures from a prior experience?
   c. If yes, label example-based reasoning.
   d. If no, proceed to question 3.
3. Does the response mention a comparison, or analogy, between one of the materials provided and another entity or property?
   e. If yes, label materials-based reasoning.
   f. If no, proceed to question 4.
4. Does the response indicate that the student is unaware of, or unwilling to state, the origin of their idea?
   g. If yes, label unexplained, reasoning.
   h. If no, label as other.

Multiple Strategy Assignment

The first coding scheme provides a simple way for classifying an entire response, without being concerned about interactions between reasoning strategies. The second coding scheme provides an additional level of complexity by identifying the presence or number of instances of each strategy type across one of more utterances. Thus, instead of assigning a single strategy to a student response, a response is described as a combination of different strategies. In this case the coder will label each individual phrase or sentence. For each phrase or sentence the coder answers the following questions:

1. Does the phrase mention engineering or science principles, even if they are not described in complete or correct terms?
   a. If yes, then increase the count of principle-based statements by 1.
   b. If no, proceed to question 2.
2. Does the phrase mention one or more example structures from the student's prior experiences?
   c. If yes, then increase the count of example-based statements by 1.
   d. If no, proceed to question 3.
3. Does the phrase mention a comparison or analogy between one of the materials provided and another entity?
   e. If yes, then increase the count of example-based statements by 1.
   f. If no, proceed to question 4.
4. Does the response indicate that the student is unaware of, or unwilling to state, the origin of their idea?
   g. If yes, increase the count of unexplained reasoning by 1.
5. Move on to the next phrase or sentence.

Depending on the hypotheses being analyzed the actual count, or a simple binary classification can be used.