Assessing the "Makers": The Impact of Principle-Based Reasoning on Hands-on, Project-Based Learning

Marcelo Worsley, Paulo Blikstein, Stanford University, 520 Galvez Mall, CERAS 102, Stanford, CA 94305
mworsley@stanford.edu, paulob@stanford.edu

Abstract: Prior research suggests that experts and novices employ markedly different approaches to engineering design tasks. For example, novice designers commonly use trial and error, which researchers liken to backward-reasoning. Experts use forward-reasoning, which allows them to accurately predict the impact of certain decisions. In this paper, we present a complementary conceptualization for how experience affects design approaches. We liken backward-reasoning to example-based reasoning, and forward-reasoning to principle-based reasoning. In study 1 (N=13) students complete an engineering design activity. A qualitative analysis shows clear instances of example- and principle-based reasoning strategies. Study 2 (N=20) compares the efficacy of the two approaches by using a between-subject design. We find that principle-based reasoning improves the quality of designs ($p < 0.01$) and learning of important engineering principles ($p < 0.001$). This suggests that hands-on learning environments may benefit from encouraging students to employ principle-based reasoning.

Introduction

With the rise of Makerspaces and Fablabs in education, constructionist (Papert, 1980) and project-based learning is experiencing a revival. Schools, community centers and museums around the world are spending millions of dollars to create spaces where students can engage in design and invention activities (New York Hall of Science, 2012, Blikstein, 2013). Amidst this resurgence, however, are questions about how to effectively implement hands-on learning in a way that foments Science, Technology, Engineering and Mathematics (STEM) learning. For museums, they must address questions about how to promote changes in students STEM intuitions through short-lived constructionist activities (see "Keychain Syndrome", Blikstein 2013 for an example). At the same time, schools have to consider how to produce measurable learning gains through engaging, hands-on activities. In this paper, we begin to address these concerns through two studies. In Study 1 we describe two common approaches to solving open-ended engineering tasks. We refer to these approaches as *example-* and *principle-based reasoning*. These two approaches share resemblance to prior literature on learning by analogy and expert/novice design strategies (e.g. Ahmed Wallace & Blessing, 2003, Gentner, 1997, Cardonell, 1983). Study 2 shows that principle-based reasoning produces superior designs and greater recognition of engineering principles among non-expert students relative to example-based reasoning.

Our approach draws from studies of engineering education (e.g. Atman & Bursic, 1998, 2007; Russ et al., 2008, Lau, Oehlberg & Agogino, 2009, Worsley & Blikstein, 2011), the role of analogy in supporting learning (e.g. Gentner & Holyoke, 1997, Cardonell, 1983, Lakoff & Nunez, 2000, Polya, 1945) and prior work on expertise (e.g. Ericsson, Krampe, & Tesch-Römer, 1993, Chi, Glaser & Rees 1981, Cross & Cross 1998, Atman et al. 1999).

Study 1

Study 1 examines engineering design approaches of students with different levels of experience. Students are presented with a mechanical engineering challenge that requires them to use their intuitions and prior knowledge about forces. Ten 9th- through 12th-grade students and three graduate students participated in this study. This variance in experience was a primary component in pre-defining student experience levels, i.e. low, medium, high, and expert (a detailed description of the user population can be found in Worsley & Blikstein, 2013.)

Students worked individually using common household materials: one paper plate, one ping-pong ball, a roll of tape, four drinking straws and five wooden Popsicle sticks. The objective was to use the materials provided to create a structure that could support approximately 2-3 pounds. Participants were also asked to support the weight as high off the table as possible. Students were instructed that they would receive ten minutes to complete the task, but were permitted to work for as long as they wanted. Total participation time ranged from 8 to 52 minutes.

Engineering Strategies

As we analyzed each video, we paid particular attention to the post-activity interviews. During this interview students were asked questions about the motivation for their design. We were intrigued by how some students' designs were motivated by those of real-world objects, while others relied on geometric properties and more fundamental principles from engineering. As such, our goal in this section is to briefly demonstrate the existence of the example-based and the principle-based approaches in the data—these two approaches do not represent all strategies that students used, but constitute the majority. In what follows we present short case studies of each approach.

Example-Based Reasoning

The first example that we present is of a student who successfully modeled their structure after a chair (Figure 1). More importantly, though, we learn that this was not modeled after just any chair, but after a chair that the student has at home. The student emphasizes this point when responding to a question about the inspiration for the design: "It's like a form of a chair… Plus. Um. Just like a chair, because I have a chair like that… at home."

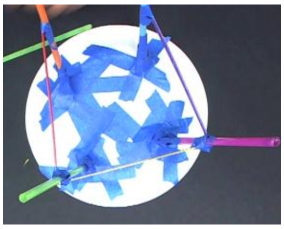

Figure 1. Successful Example-based Design

This student has drawn a connection to a real-world object from his home as a way for approaching the task. As the student continues to describe the motivation for the design, he indicates that he had briefly entertained another idea. This other idea very closely resembled his current structure but did not have wooden sticks connecting the legs. When asked why he didn't pursue the other design he said that the other idea "was dumb." While he may have been hinting at principles in engineering design, he does not articulate them at this point. As we examine the line of reasoning offered by students who employed principle-based reasoning, we will see an apparent difference in the extent of mechanistic reasoning that the students employ (Russ et al., 2008).

Principle-Based Reasoning

Among students that exhibited principle-based reasoning it was common to find structures laden with triangles and circles. This was the case for structure pictured in Figure and Figure 5.

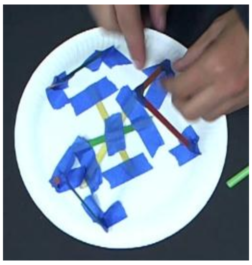

Figure 2. Successful Principle-Based Design

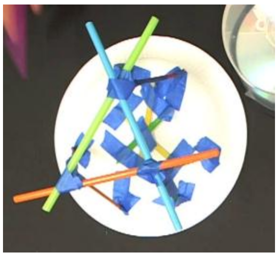

Figure 3. Successful Principle-Based Design

Figures 2 and 3 contain the underside of the structure of one particular student in this group. In Figure 2 we see the early stages of the base. This base features two levels of triangles. The first is the shape of each leg, and the second is the triangular base that the three legs define. Figure 3 makes the second level of triangles more explicit with the addition of three straws that form a triangle. When asked about his inspiration for the 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: "It'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." The student was very confident in his reasoning, and provided a strong justification for his design. Furthermore, in contrast to the example-based designs, this structure bears little resemblance to any real-world object.

Discussion

Study 1 was designed to identify the ways that students would naturally go about handling an open-ended engineering design challenge. It offers a glimpse into the types of experiences that students may have when approaching unscripted, hands-on, "maker," learning activities. Examining these practices is of particular relevance given the rise of "making" that is taking place in several types of formal and informal learning environments. Within these constructionist environments, some students attain success by drawing on real-world examples (Gentner, 1997; Cardonell, 1983; Kolodner, 1997). Identifying real-world examples gives students an entry point into constructing their design. It also challenges students to consider ways for generalizing the objectives of the challenge to structures that are salient in their individual lives. Other students approach the task from the perspective of engineering principles. When both designing and troubleshooting their structure, they draw upon fundamental engineering principles to guide their thinking and their actions. Just like the example-based approach, the principle-based approach yields mixed results. Nonetheless, these two approaches appear to align with prior literature on expertise in open-ended design activities (Ahmed, Wallace & Blessing, 2003). The example-based approach is akin to backward reasoning, where the individual begins with a structure and works backwards to deduce its feasibility and quality. The principle-based approach is in line with forward reasoning—students identify the inner workings of a design before concerning themselves with their larger, overall design. While it was not our objective to align these practices with levels of expertise, this is something that loosely emerged from the qualitative observations. This perceived difference in who is using the different techniques motivates the design of Study 2.

Study 2

In Study 2 we prompt participants to use either an example- or principle-based approach when completing the challenge. This allows us to examine the impact of the two reasoning strategies on student success and on student learning. Study 2 also differs from Study 1 because participants work in pairs, instead of individually. This change in design was adopted to foster more natural verbalization of students' thoughts and strategies.

Prior to the study, we had two main hypotheses. The first hypothesis was that principle-based reasoning prompt would cause students to be more aware of the mechanisms that conferred stability. Moreover, as we observed in Study 1, we anticipated that when students focused on mechanisms, they would be more cognizant of weaknesses in their design. This, in turn, would result in the principle-based reasoning condition being more successful in building their structures. At the same time, we hypothesized that the example-based group would mirror the novices in Study 1 and create structures that resembled real-world structures. However, in so doing, we expect for many students to overlook one or more important engineering principles because they are primarily thinking at the macroscopic level.

Twelve 9th- through 12th-grade students and eight undergraduate students participated in this study. Pairs of students were randomly assigned to each condition, after controlling for prior education experience. Students worked with common household materials: one paper plate, 4 ft. of garden wire, four drinking straws and five wooden Popsicle sticks. Students were also given scissors. The objective was to use the materials provided to create a structure that could support a weight of approximately half a pound. Participants were also asked to support the weight as high off the table as possible. Students were instructed that they would receive fifteen minutes to complete the task, but were permitted to work for as long as they wanted. Changes from the Study 1 protocol were adopted to avoid some of the superficial troubleshooting strategies observed in study one. For example, tape was taken away because during Study 1 several students used excessive amounts of tape in order to compensate for unstable structural designs.

Activity Sequence

The set of activities that students completed included: a pre-test; introduction to the design challenge; an intervention, i.e. one of the two conditions; a preliminary design drawing; a hands-on, paired, building activity; a post-test; and reflection. For both the pre- and post-test, students were asked to generate as many ways as possible to easily reinforce an unstable structure. For the post-test, students were permitted to both review and refer back to their pre-test responses.

During the intervention, students were first shown a picture of a bridge, a ladder and an igloo. 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 current task. Students received three minutes to generate and draw three ideas. In the principle-based condition students were asked to generate three mechanisms, or engineering principles, that cause one or more of the three items pictured (the bridge, the ladder and the igloo) to be structurally sound. Again, students were given three minutes to generate three mechanisms.

One key observation from Study 1 was the failure to recognize important engineering principles, or mechanisms, among the example-based reasoning group. Most common was for students to overlook the importance of connecting the legs of the structure, especially when using slanted legs. In Study 2 we adopted a coding scheme that explicitly classified pre- and post-tests based on the presence of connected legs and slanted legs. In order for an item to be coded as having connected legs, there must be something that connects the legs at some place other than the top or bottom of the structure. Identifying the presence of slanted legs was based on the presence of a non-90-degree angle between the legs of the structure and the upper portion of the structure. When coding student pre- and post-tests, the presence of slanted legs resulted in a scoring of -1, and the presence of connected legs resulted in a scoring of +1. Accordingly, a given test could be coded as -1, 0 or 1. Each design drawing was coded by two research assistants. An analysis of inter-rater reliability analysis yielded a Fleiss' Kappa of 0.76. In addition to coding the pre- and post-test, an explicit metric of success was used to rate the quality of each structure. In order to be deemed a success, the structure was required to hold the half-pound mass for at least one minute.

Results

We first examine the correlation between success and the two conditions. A binomial test (probability of success = 0.1 – based on prior work) confirms that the principle-based condition (M: 0.6, SD: 0.52) significantly outperforms the baseline probability ($p < 0.01$), while the example-based reasoning condition (M: 0.2, SD: 0.42) does not outperform the baseline probability ($p < 0.40$).

The other value that we compared is coded values for slanted legs and connected legs. When we perform a student t-test on this data we find a significant difference ($t(18)=3.46$, $p < 0.003$). Students in the principle-based reasoning condition were more likely to include only connected legs, while the example-based condition was more likely to only include slanted legs. This is important because the slanted leg configuration in the absence of connected legs will typically result in failure. On the other hand, using connecting legs has utility across several leg configurations and orientations. Thus it means that after doing the hands-on activity, students in the example-based reasoning condition were more likely to propose a design solution that included slanted legs, without connecting the legs. This suggested that they were less likely to attribute structural failures to having slanted legs or having unconnected legs, whereas the principle-based reasoning group was more likely to correctly make this association.

One concern is that this observation is a function of the student's prior knowledge of structural engineering. Accordingly, we coded the pre-tests as well as the initial design drawings (recall that each student completed a design drawing immediately after having finished the intervention). From both of these, we find no significant difference in the averaged coded value for slanted legs-connected legs either immediately before the intervention or immediately after the intervention (pre-test - $p < 0.23$, initial design drawing - $p < 0.13$). Of particular note is that connecting the legs was more common in the example-based reasoning group ($p=0.6$) than in the principle-based reasoning group ($p=0.4$) when comparing design drawings made immediately following the intervention and preceding the building activity. This suggests that the observed difference on the post-test is not a function of the intervention alone, nor is it a function of prior knowledge, but is mediated through the hands-on activity.

Discussion

Through studies 1 and 2, we highlighted the existence and importance of different approaches for completing engineering design tasks. We found that students who employ principle-based reasoning were more successful in completing the task, and also identified important mechanisms in the post-test. On the other hand, students who used example-based reasoning were less likely to succeed in their designs. We attribute these differences to students in the example-based reasoning condition overlooking important engineering principles that were integral to the stability of their example structure. As an example of this, consider students Mike and Tom. These two students modeled their structure after a water tower. They include several of components of a water tower in their structure. However, their structure failed because they do not recognize the importance of connecting the legs of their structure together. Ironically, these two included connected legs in their design drawings, but still did not recognize their importance. Unfortunately, we do not have sufficient post-interview data to confirm that all students in the principle-based reasoning condition that included connected legs fully understood the implications of including reinforcements or braces. Anecdotally, we observed that a number of students in the principle-based reasoning condition made reference to connecting the legs during the activity, but because this was not explicitly tested for all participants this inference is only speculative.

As we consider next steps one area for further research is to leverage an approach from our prior research that more explicitly studies user action patterns (Worsley and Blikstein, 2013). Within this paradigm, we would be interested in studying how the process differed between the two conditions. As a part of this analysis, we would look to identify if the example- and principle-based reasoning cause students to use substantively different iteration cycles and troubleshooting strategies. Moreover, several previous research studies have highlighted differences in how experts and novices complete engineering design tasks. While we have seen that principle-based reasoning helps students be more successful, there is the additional question of whether or not this approach actually helps students behave more like experts when examining more fine-grained action sequence. Related to this is another possible study that tries to more definitively delineate the mechanics that mediate success for the principle-based reasoning group, again through process-based measures.

Conclusion

In this paper we presented two studies that investigate how to improve the quality of hands-on learning experiences. In Study 1 we provided a short qualitative analysis of two engineering design approaches: example- and principle-based reasoning. We argued that these two approaches are in line with prior research in engineering education, expertise, and learning by analogy. Moreover, we described how example-based reasoning is commonly used among novices as they confront new engineering design tasks. Study 2 was a controlled study where we compared the efficacy of the two approaches in terms of the quality of designs, and in terms of what students learn. Here we found that principle-based reasoning is associated with better quality designs, and better recognition of important engineering mechanisms. As described in this paper, priming students to use principle-based reasoning could conceivably be enacted in the variety of constructionist learning environments that are currently found in community centers, museums and schools. As such, adopting this approach could foster significant improvement to the quality of constructionist learning. More generally though, this paper echoes previous research that highlights the importance of pushing students to draw on the depth of their conceptual intuitions. While some prior work has cautioned that students intuitions may contain non-scientifically valid principles and concepts, in the case of this study, this concern was far less impactful than the positive benefits conferred by promoting principle-based reasoning.

References

New York Hall of Science. (2012). *Design-Make-Play: Growing the Next Generation of Science Innovators*. New York, NY: New York Hall of Science.

Ahmed, S., Wallace, K. M., & Blessing, L. T. (2003). Understanding the differences between how novice and experienced designers approach design tasks. *Research in Engineering Design, 14*(1), 1-11.

Atman, C. J., Adams, R. S., Cardella, M. E., Turns, J., Mosborg, S., & Saleem, J. (2007). Engineering design processes: A comparison of students and expert practitioners. *Journal of Engineering Education, 96*(4), 359-379.

Atman, C. J., & Bursic, K. M. (1998). Verbal protocol analysis as a method to document engineering student design processes. *Journal of Engineering Education, 87*(2), 121-132.

Atman, C. J., Chimka, J. R., Bursic, K. M., & Nachtmann, H. L. (1999). A comparison of freshman and senior engineering design processes. *Design Studies, 20*(2), 131-152.

Atman, C. J., Deibel, K., & Borgford-Parnell, J. (2009). The process of engineering design: A comparison of three representations. *International Conference on Engineering Design*.

Blikstein, P. (2013). Digital Fabrication and 'Making' in Education: The Democratization of Invention. In J. Walter-Herrmann & C. Büching (Eds.), *FabLabs: Of Machines, Makers and Inventors*. Bielefeld: Transcript Publishers.

Carbonell, J. G. (1983). Learning by analog y: Formulating and generalizing plans from past experience. *Machine Learning: An Artificial Intelligence Approach*, 137-161.

Chi, M. T., Glaser, R., & Rees, E. (1981). *Expertise in Problem Solving*. Pittsburg: Learning Research and Development Center, University of Pittsburgh.

Cross, N., & Cross, A. C. (1998). Expertise in engineering design. *Research in Engineering Design*, 10(3), 141-149.

Ericsson, K. A., Krampe, R. T., & Tesch-Römer, C. (1993). The role of deliberate practice in the acquisition of expert performance. *Psychological Review, 100*(3), 363-406.

Gentner, D., & Holyoak, K. J. (1997). Reasoning and learning by analogy: Introduction. *The American Psychologist, 52*(1), 32-34.

Kolodner, J. L. (1997). Educational implications of analogy: A view from case-based reasoning. American psychologist, 52(1), 57-66.

Lakoff, G., & Núñez, R. E. (2000). *Where mathematics comes from: How the embodied mind brings mathematics into being*. Basic Books.

Lau, K., Oehlberg, L., & Agogino, A. (2009). Sketching in design journals: An analysis of visual representations in the product design process. *Engineering Design Graphics Journal, 73*(3), 23-28.

Papert, S. (1980). *Mindstorms: Children, computers, and powerful ideas*. Basic Books.

Polya, G. (1945). *How to solve it: A new aspect of mathematical model.*

Russ, R. S., Scherr, R. E., Hammer, D., & Mikeska, J. (2008). Recognizing mechanistic reasoning in student scientific inquiry: A framework for discourse analysis developed from philosophy of science. *Science Education, 92*(3), 499-525.

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 International Conference on Educational Data Mining (EDM 2011)*, 235-240.

Worsley, M. and Blikstein, P. (2013). Toward the Development of Multimodal Action Based Assessment. *Proceedings of the Third International Conference on Learning Analytics and Knowledge (LAK '13)*, 94-101.