Making Smarter not Harder:

Using Principle-based Reasoning to Promote Object Closeness and Improve Making

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ABSTRACT

Constructionism and the Maker Movement are becoming increasingly prevalent and increasingly popular. Makerspaces and Fablabs are being developed in schools, libraries, museums and community centers around the world. However, as this movement grows it is important to continue researching, refining and improving the best practices within these innovative environments. In this paper we present a pair of studies that document 1) common strategies that students use in hands-on learning, and 2) how those strategies impact student performance and learning. Specifically, we show that students who engage in a short principle-based reasoning intervention, outperform their peers who use example-based reasoning both in terms of the quality of their designs, and in terms of knowledge construction. Based on the results of these studies we propose that short, appropriately targeted, generative activities be more broadly used in constructionist learning environments. The generative activities will help promote "object closeness" and improve the current state of making in education.

Categories and Subject Descriptors

K.3.m [**Computers and Education**]: Computer Uses in Education – *miscellaneous.*

General Terms

Performance, Design, Experimentation, Human Factors

Keywords

Constructionism, Reasoning Strategies, Engineering, Expertise

1. INTRODUCTION

Recent history has seen a significant surge in the number of organizations that feature digital fabrication technology. These Fablabs and Makerspaces are becoming a place where children, and adults, alike, have the opportunity to engage in learning through the process of developing personally meaningful artifacts. Significant prior research has discussed the merits of these student-centered environments for fostering learning (e.g. [1-6]) and is the context for the Biennial Constructionism Conference. However, few papers have ventured to identify and analyze the types of strategies that promote success and learning in these spaces. Additionally, prior research has not examined how different approaches garner differential results in terms of student learning and project success. In this paper, we address both of these gaps. Specifically, we 1) describe common strategies that students use to approach constructionist learning and 2) show how priming students with different strategies garners different results in the quality of their design and what they learn.

2. PRIOR LITERATURE

2.1 Constructionism and Process

At a high level, this research is situated within the constructionist [7] paradigm and builds on theoretical frameworks that emphasizes studying processes [8, 9] and micro genetic analysis [10]. For example, [8] describes learning as a conversation with materials in which the student repeatedly modifies and processes feedback from the materials that they are working with. Hence, one way to examine the learning and designing process is to closely study the artifact being created. This is one approach that we'll use for comparing the effectiveness of different strategies. We differ from other researchers that have conducted seemingly similar research [11, 12, 13] in that we are analyzing a markedly different set of strategies, and are more concerned with strategy at a macro-level, as opposed to a micro-level.

2.2 Analogical Problem Solving

The two strategies that will receive the greatest attention during this paper, example-based reasoning and principle-based reasoning, are ones that have ties to prior work on analogical problem solving (e.g. [14]), case-based reasoning [15] and surface and learning by analogy [16]. The analogical problem solving research also informs our hypotheses about the relative efficacy of principle-based reasoning and example-based reasoning, since the former is typically associated with greater expertise, and the latter with less expertise [17-20]. Beyond this link to expertise, however, we will suggest that principle-based reasoning has connections to "object closeness," in that an individual improves her ability to relate to the objects that she interacts with [21, 22].

3. STRATEGIES

In the paragraphs that follows I describe four approaches that student use when completing an engineering design challenge.

3.1 Participants

Identification of the four strategies that I identify is based on a study of thirteen participants with very different levels of prior experience. The most experienced students were currently enrolled in Engineering PhD programs and had engaged in engineering practices for several years in both formal and informal environments. The least experienced included 9th grade students who had limited prior experience in engineering.

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3.2 Task Description

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, one roll of tape and a paper plate and given an unlimited amount of time to reach a final structure that they were satisfied with.

3.3 Interview Protocol

At the conclusion of the activity students were asked to respond to the questions, "what made you think of your design? How did you come up with it? Responses to these question are the central basis for identifying and describing the four common strategies referred to in this dissertation.

3.4 Strategies

Analysis revealed four strategies: 1) u*nexplained spontaneous insight* – instances where the student is unable to state where the idea came from; 2) *materials-based reasoning* – instances where the student indicates that one or more properties of the materials provided the basis for their idea; 3) e*xample-based reasoning* – instances where the student based their idea on a structure or item from a prior experience; 4) *principle-based reasoning* – instances where the student based their design on principles or concepts from science or engineering.

The reasoning strategies need not be mutually exclusive. Instead one form of reasoning may give birth to a different form of reasoning. For example, materials-based reasoning may cause the student to recognize an entire example structure that can help solve the challenge in question. Similarly, a student may be able to extract the principles from an example, and in so doing transition from example-based reasoning to principle-based reasoning.

3.4.1 Principle-Based Reasoning

Within this specific study, students whose strategy were primarily classified as being principle-based, commonly used triangles and circles throughout their design. One student when asked what inspired his design 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." This 9th grade student's structure was among the best of all of the participants. However, principle-based reasoning does not always result in success, hence one should not assume that principle-based reasoning necessarily confers a favorable outcome despite having ties to [23, 24].

3.4.2 Example-Based Reasoning

In example-based reasoning it is commonplace for students to create a structure that closely resembles a real-world object. More importantly, though, example-based reasoning often involves an example object from the individual's home, community or school. For example, one student in the study described how a chair from his home motivated his design. He drew upon similarities between a real-world object from his home and the engineering design task. The ability to transfer knowledge from the problem domain, to a potential solution domain has clear advantages to being unable to articulate a response, or having your ideas couched in the properties of the material.

3.4.3 Materials-Based Reasoning

Like example-based reasoning, materials-based reasoning also provided a powerful tool for helping student launch into the activity. However, instances of materials-based reasoning tended to occur alongside example-based reasoning. For example, when asked to describe the origins of his design one 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, in that the materials trigger the student to think of or do something. This is in contrast to the previously mentioned example-based reasoning because in example-based reasoning the tendency is to start by thinking of example structures that solve the same problem as the one posed by the specific challenge. In materials-based reasoning the student starts from the materials, instead of starting from the problem. When comparing materials-based reasoning and example-based reasoning, the two may lead to the same overall design, but represent different initial motivations.

Materials-based reasoning is also distinct from principle-based reasoning. One example of how this is different is the fact 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 matches the material, hence the direction of idea generation is not the same. As an example of this, one student described how the materials provided weren't a good "fit", and attributed his struggles to that lack of "fit." In many respects he was 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 mentality encapsulates the materials-based reasoning strategy and highlights some of its limitations. Without appropriate cues from the materials this student would not have succeeded.

3.4.4 Unexplained Spontaneous Insight

Of all of the strategies, unexplained spontaneous insight is likely the easiest to recognize. Students whose responses were classified as being unexplained were either unwilling or unable to articulate the origins of their idea. Being unwilling to explain the origins of their ideas may be suggestive of a lack of engagement. Being unable to identify the sources of one's ideas can result from not having the scientific knowledge to describe one's ideas or may result from having an expert level understanding, such that responses are intuitive and immediate. In this particular study students who failed to explain the origins of their idea did not appear to have expert level knowledge.

4. IMPACT OF STRATEGIES

In the previous section we identified four strategies that students use for approaching engineering design tasks. In this section we compare the success, learning and process and students complete between participants in a principle-based reasoning condition and an example-based reasoning condition. This comparison will occur two additional studies, Study A and Stay B.

4.1 Participants

For study A the population of students included forty high school students from around the United States who were participating in a summer program at Stanford. This implementation was largely akin to that of a classroom in that the entire population of students worked on the task at the same time. Each student received a worksheet with instructions for their specific intervention. For the second study, the population of students included local high school students and Stanford undergraduate students. The distribution of high school students and undergraduate students was the same across the two conditions. Study B followed a semi-structured clinical interview protocol with each pair of students completing the activity at different times, and a research assistant closely watching the process.

4.2 Task Description

All participants worked in pairs 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, 4ft of garden wire and a paper plate. They were given fifteen minutes to complete the task. Prior to this 15 minutes, participants completed other tasks, such that the entire experiment lasted approximately one hour.

4.3 Experimental Design

During the study participants completed the following activities: pre-test; intervention; initial design drawing; basic building activity; a post-test and reflection. The pre- and post-test were identical and challenged students to generate as many ideas as possible to make an unstable structure, more stable. Students were given access to their pre-test during the post-test process.

4.4 Experimental Conditions

Students were split into an example-based reasoning condition and a principle-based reasoning condition. Both conditions went through a short intervention. During each intervention students were first shown a picture of a bridge, a ladder and an igloo. After seeing the three picture, 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. 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. The intervention task was three minutes in duration for both conditions.

4.5 Analysis

When studying the pairs of students, particular attention was paid to the quality of their structure and how much they learned (based on a pre-/post-test).

For the pre- and post-test, student responses were code for the presence or absence of important engineering principles. These important principles were derived from analysis of a previous data set.

Analysis of structure quality was done at both the final state, and at several intermediate points. Two measures of quality were derived from the stability of the structure while supporting the mass. If the structure remained stable for at least 30 seconds, the student's structure was coded as successful. The other means for comparing final structure quality was based on how high the mass sat above the table.

Additionally, intermediate design structures were coded based on the addition of principle-based modifications (a structure was deemed an intermediate structure if at least one of the individuals in the pair put stress on the structure to test its stability). Principle-based modification included: adding a base, adding reinforcement, adding triangles, making strong connections and adding symmetry. For this metric we looked at 1) how many principle-based items were added over the course of the activity and 2) the number of intermediate structures that received a principle-based modification.

4.6 Results

As previously noted, student structures were judged based on whether or not they could support the mass, and how high the mass sat above the ground when supported by the students' structure. Along both measures the students in the principle-based condition performed significantly better than their peers in the example-based reasoning condition. For the measure of success, students in the principle-based conditioning (M: 0.6, SD: 0.49) were more likely ($p(18)<0.01$) to succeed than students in the example-based condition (M: 0.2, SD: 0.4) as determined through a binomial test.

Using the Wilcoxon test on the height rankings we find that the principle-based condition did significantly better ($p < 0.001$).

A similar trend was found when comparing post-test scores between the two conditions. The pre-test showed no significant differences between the two conditions. However, students in the principle-based condition (M: 0.4, SD: 0.48) were more likely ($p(18)<0.01$) to include engineering principles in the ideas generated for the post-test, than their peers in the example-based reasoning condition (M:-0.4, SD: 0.48) .

Finally, when looking at the rate of principle-item inclusion in intermediate structures, the principle-based reasoning group (M: 0.45, SD:0.078) again has significantly more ($p(9)<0.05$) than their peers in the example-based reasoning condition (M:0.26, SD:0.16).

Similar results were recorded for both studies, with the results from Study B being increasingly pronounced relative to those of Study A.

5. DISCUSSION

Across all three metrics we found significantly different results between the two different strategies. Namely, the principle-based condition was associated with higher quality designs and higher learning. Based on the analysis of principle-based item inclusion, it seems probable that it was the principles that helped mediate an improved design quality. This has clear implications for constructionist spaces in that while Makerspaces may often encourage students to engage in brainstorming and extensive idea generation, students would greatly benefit from engaging in idea generation activities that push them to think more deeply about the design and problem space. All too often, students engage in a shallow form of idea generation that may result in them spending more time working harder and longer on a task, without any added benefit. While idea generation is a useful strategy, pushing students to go deeper in their idea generation can have noticeable differences on student learning and the quality of what students produce.

We would however, like to acknowledge that principle-based reasoning strategies did not uniformly produce better quality designs. In fact, the two worst performing pairs, when considering both example-based reasoning and principle-based reasoning, were from the principle-based reasoning condition. For these students the principle-based reasoning intervention served as an opportunity to make disparaging comments about their own ideas and/or their partner's ideas. As a result of this, team dynamics were noticeably poor throughout their participation in the activity. Additionally, these two pairs embarked on ideas that were not physically sound. Namely, the misconceptions that they developed during the intervention stage, may have caused their designs to suffer. This is in contrast to students in the example-based condition, who at least had a real-world example from which to base their ideas. That real world example may have helped constrain the variance in idea quality, both for better and for worse.

Hence, the reader should be aware that while principle-based reasoning does offer significant benefits to example-based reasoning, one must be attentive about how the interaction and discussion of principles and mechanisms is taking place among pairs and/or groups of students.

The final implication that we'll discuss is the idea that students are not properly equipped to adopt expert strategies. Traditional work on expertise describes an expert as having both deep subject matter knowledge and organization. In this study we challenged non-expert students to use an expert strategy, and in so doing have shown that despite not having expert knowledge or expert organization, that the students could effectively use principle-based reasoning to increase the quality of their designs and their learning, beyond that of the example-based reasoning group.

6. CONCLUSION

Constructionist learning environments are innovative spaces that place the agency of the student front and center. By supporting students as they engage in the design and implementation of meaningful, hands-on projects, constructionist learning privileges the importance of motivating individual student development. We have proposed to extend the ways in which constructionist learning centers on individual student agency. While constructionism has historically involved students performing idea generation and brainstorming, our research shows that not all idea generation practices are made equal. Instead, we have shown that pushing students to more deeply draw upon their own intuitions in engineering increased the quality of student designs, and the quality of student learning. The intervention that we used was not laborious, nor did it detract from the constructionist perspective. Instead, we suggest that challenging students to identify engineering principles promoted "object closeness."

7. REFERENCES

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