NARST 2020
Strand 1: Science Learning: Development of Student Understanding
Engineering Framework

Eliciting Students' Abstract and Multidisciplinary Thinking in a Design Review

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Abstract

In engineering, design review sessions are a common practice. However, in education, their value in eliciting student thinking and reasoning is under-utilized. In this study, we analyzed data collected during a design review session. We captured conversations between two design reviewers and ten middle school students. We examined how the design reviewers' questions helped elicit students' explanations. The analysis focused on two dimensions of explanations: a) abstract-to-concrete thinking and b) multidisciplinary thinking (trade-offs) – outlining student ideas and illustrating how the quadrant model can be used to map student ideas. Our analysis resulted in three types of transitions (experiential to first principles, experiential to design trade-offs, and experiential to first principles and design trade-offs) as well as no transition. We speculate that the fluid transitions to first principles reflect strong understandings of disciplinary core ideas while fluid transitions to design trade-offs reflect strong understandings of design practices. Design principles illustrated transitions between dimensions, while students with weak understandings relied on their experiential observations. Our findings also suggest that diverse semantic waves of student design reasoning can effectively be elicited through design review sessions. Future research can examine how such questioning strategies build on semantic quadrants to be effectively used in the classroom to help students transition across semantic dimensions.

Keywords: design reviews, engineering, legitimation code theory, trade-offs

1. Subject/Problem

The Next Generation Science Standards (NGSS) in the United States (Lead States, 2013) and its formative publication, *A Framework for K-12 Science Education* (NRC, 2012), urge for the integration of engineering design in K-12 science education. This initiative towards integration aims to prepare future generations with the ability to apply science, mathematics, and engineering principles in decision-making and problem-solving. There is an emergent body of literature that explores the integration of engineering design into science education, arguing for the benefits of such integration while cautioning about its challenges (Carroll et al., 2010; Crismond, 2001; Mentzer, 2014). This is because design is a complex task that requires an understanding of disciplinary core ideas, abilities to understand and engage in trade-off decisions, and abilities to make complex abstractions. Previous studies that have focused on understanding design practices and reasoning are typically conducted among professionals' engineers and undergraduate students (Crismond & Adams, 2012). Our study aimed to examine design reasoning of youth through questioning that helps elicit such reasoning. More specifically, we examined middle school students' semantic transitions between concrete and abstract thinking as well as disciplinary and multi-disciplinary reasoning by using the semantic dimension of the legitimation code theory (Maton, 2013).

2. Theoretical Framework

We approach design as a core practice of engineering and engineering as a multidisciplinary field. While studying discourse patterns in disciplines, Maton (2013) argues that disciplinary knowledge resembles waves of transitions as opposed to fragmented facts. With the Legitimation Code Theory (LCT), Maton explains five different ways of thinking in disciplines: autonomy, density, specialization, semantics, and temporality. The LCT model has been useful in explaining disciplinary practices in many disciplines, such as chemistry (Blackie, 2014), humanities (Jackson, 2016), and engineering (Wolmarans, 2016). In engineering, Wolmarans has used the LCT to study undergraduate students' design practices. She focused on two semantic dimensions: semantic density and semantic gravity (Wolmarans, 2016). The focus of these two semantic dimensions does not mean that they are the most important in engineering design. Instead, they are known to be the most recognizable in the engineering design process (Dong, Maton, & Carvalho, 2014). We based our theoretical framework on prior uses of LCT in design and adapted these models to our examination of middle school students' design practices. Similar to Wolmarans and Maton, we define semantic gravity as the shifts that students can make from concrete to abstract thinking (Wolmarans, 2016). Semantic density as the multidisciplinary thinking that students can use for explaining their design trade-off decisions. We specifically ask: What semantic shifts do design reviews stimulate as students justify their design decisions?

3. Design and Procedure

3.1. Sample

Ten students from seventh grade and two external reviewers participated in this study. We gathered our data in a middle school in the United States. The design task asked students to design an energy-efficient house using the Energy3D software (Energy3D, 2020). Students worked individually on their projects. During a final design review, the reviewers with expertise in engineering design interviewed students to understand students' decisions associated with their final design solutions. The interview questions were not pre-determined; however, the goal of the interview was to select the best design ideas from the student cohort. The questions differed by student depending on their design concepts, however, the design reviewer aimed to elicit both abstractions as well as trade-off decisions (which reflect multidisciplinary thinking). The reviewers first listened to one-slide pitches students presented in an auditorium and then conducted their one-on-one interviews in a room where all students gathered.

Table 1. *Engineering Design Coding Protocol for Semantic Density and Gravity*

Code	Definition	Example
SD++	Strong density- Multidisciplinary thinking and recognizing competing trade-offs in explanations.	"When my net energy reached -200 KWH, I started to focus on reducing cost by adjusting the light entering the house and the size of the walls."
SD--	Weak density- Single disciplinary focus.	"So, my first house was a rectangle, I selected a simple, common shape"
0	Simply facts or numeric answers without an explicit rationale.	"I put there three trees"
SG++	Strong gravity- Reasoning is based on concrete clues, not linked to theory.	"…Yes, I changed the windows and the roof to mess around with the cost and try to see what affected the cost."
SG--	Weak gravity- reasoning is theoretical and remains abstracted	"Heat transfer is the movement of thermal energy from one thing to another"

3.2. Data Analysis

We analyzed students' answers to the design reviewer questions through a discourse analysis and by using a coding protocol. The *Engineering Design Coding Protocol for Semantic Density and Semantic Gravity* is presented in Table 1. This protocol defines the different degrees of strength related to each semantic dimension, ranging from strong semantic gravity (SG++) and density (SD++) to weak semantic gravity (SG--) and density (SD--). It is important to note that weak density and gravity do not mean low-quality explanation; rather, the richness of the explanations are reflected in transitions across these dimensions. Furthermore, we mapped the coded answers using our model of semanatic dimensions of engineering design (Quintana-Cifuentes, Purzer, & Goldstein, 2019). In our model, we included four quadrants that cut across the semantic dimensions (See Figure 1): experiential, first principles, design trade-offs, and complex abstractions

The data were separately coded for semantic density and semantic gravity dimensions. To evaluate inter-rater reliability, three researchers used the coding protocol to analyze a sample of the data. We repeated this process until the analysis resulted in a consistent rating for each semantic dimension.

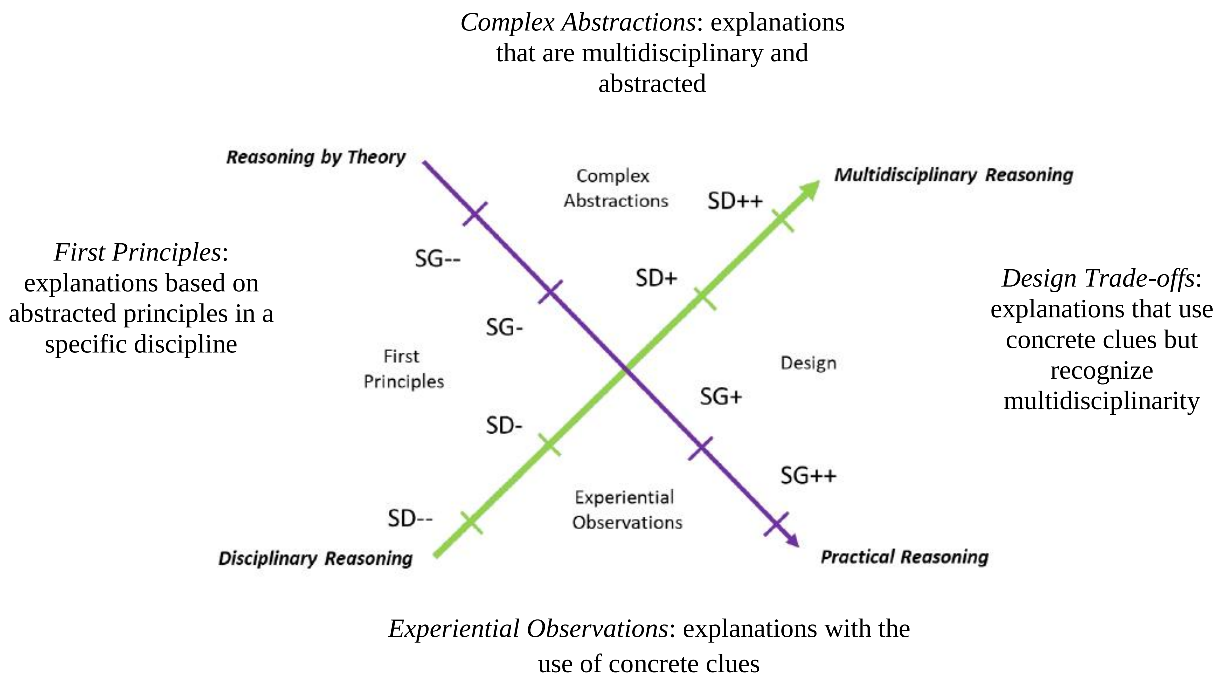
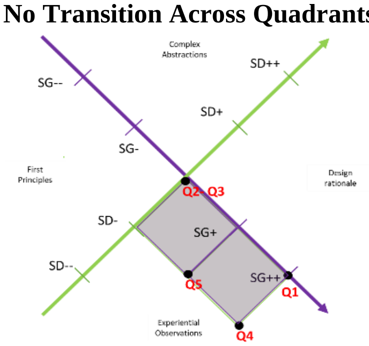
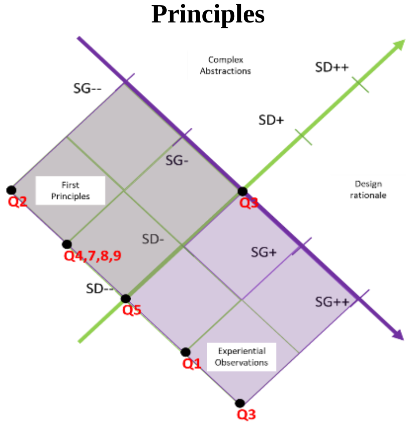


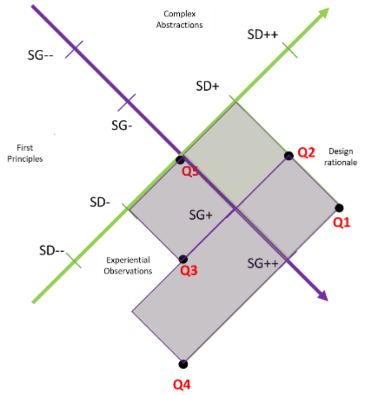
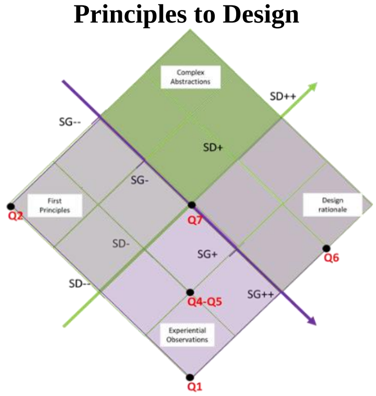
Figure 1. *Semantic quadrants (Author, 2019)*

4. Results

Our findings resulted in three types of transitions, as well as no transition (See Table 2). The reviewer questions started in the Experiential Observation quadrant. This reflected the reviewer's anchoring of the first questions to the surface features of student design. Hence, students' answers started with Experiential Observation (representing weak semantic density and strong semantic gravity) as well. As shown in Table 1, Oliver's answers only rely on his explanation of his experiential observations. When transitions were observed they occurred between two quadrants. The *Experiential to First Principles* transition was observed with one student (Tori). A more fluent transition was from *Experiential to Design Trade-offs*, which was observed in the explanations of four students.

Table 2. *Students' Transitions Across Semantic Quadrants*

<table>
<tr><th>Transition types</th><th>Design reviewer questions and student answers</th><th>Cases</th></tr>
<tr><td>No Transition Across Quadrants

Oliver</td><td>Q4: "What made this one hit the magic?"
Oliver: "Well, I finally figured out that you can right-click stuff, and I changed the efficiency all the way to 20 %, and that significantly. The other houses, I wasn't trying as much I was more trying to figure out how the program worked and what was needed."
Coded: SD-/SG++</td><td>Oliver
Wil
Jessy</td></tr>
<tr><td>Transition: Experiential to First Principles

Tori</td><td>Q1: I get a really nice design of the house as we were looking at. Can you tell me a little bit about what your steps were in making this house energy efficient?
Tori: Well I change the roof a lot because it was, the way it works, at first, I had the roof panels on the wrong side of the house, and then I had to move them that around a bit. I also tried to make it (the roof) flatter and other roof designs to see the way the sun reflected more.
Coded: SD--/SG+
Q2: So, when you say that your solar panel was on the wrong side, what do you mean?
Tori: "So, the sun, it wasn't in the sunlight kind of…(Indistinct)"
Coded: SD--/SG--</td><td>Tori</td></tr>
</table>

Transition types	Design reviewer questions and student answers	Cases
Transition: Experiential to Design  Lisa	**Q2:** *"Ok, do you remember what went into deciding? How did you decide? because I see all on one side."* **Lisa:** *"…so…yeah…so with the heliodome it was coming like this over the house, so most of the light would be on this side because it is going like that over, so then I decided if I put solar panels over here, they wouldn't get very much light, so if I just put them all over here they will be more efficient, and since they're on the roof you can't see them that much, from like if you were just like standing over here on the street, you wouldn't be able to see them that much, so it didn't really matter that it wasn't like completely balanced."* **Coded: SD+/SG+**	Lisa Mike Peter Ryan
Transition: Experiential to First Principles to Design  Alex	***Q1:*** *"Ok, so in your presentation, remark that the unique shape and we were also looking at that and struck by that and very interesting. Why this shape?"* ***Alex:*** *"So basically, when I started making my house, I started with a rectangle box basically, and I kept adding to it. It was obviously houses aren't rectangular. So, I looked at a lot of design of real houses, and I tried to put them into mine, and I did research on how houses like really are..."* ***Q6****: So, one more question, so if I look your energy, If I actually compare to others, your peers are not that low, and your cost is close to fifty, so did you make this decision strategically that you emphasize specific criteria?* ***Alex:*** *"So, when I first started, I was mainly focused on my energy, so I just kept trying to get my energy lower and lower, so eventually my cost was ...so for that I added to the house, and I also my cost would go up, but eventually I stuck with this design, and it was aesthetic pleasing, but my cost, it was going pretty borderline, so, I did reduce a little bit to get it there, and my energy to be on..."* **Coded SD+/SG+**	Alex David

The transition between Experiential Observation and First Principles represents weak semantic density, meaning the student was able to make abstract-to-concrete connections with explanations abstracting the concrete aspects of their solution. However, the explanations did not present evidence for multidisciplinary thinking (See Tori in Table 2). Another transition was between Experiential Observation and Design Reasoning. As it is shown in Table 2, Lisa's answers to question one (Q1) and question two (Q2) illustrated strong semantic density and semantic gravity. Students who shift between these two quadrants could use their multidisciplinary thinking to connect with concrete aspects of their designed solutions. Finally, the final variation was the transition across three quadrants. Illustrating the most advanced ways of transitions, students in this group were able to abstract their explanations but also explain the multidisciplinary aspects of a problem (i.e., trade-offs). None of the students' explanations showed transitions to Complex Abstractions, which we argue is a difficult task requiring deep disciplinary knowledge in multiple areas as well as designing experience.

5. Conclusion and Contributions

Design review sessions play an important role in eliciting student thinking. When done effectively, they reveal thinking that is not visible at the surface but necessary for reflection and learning. By framing the student responses to the design reviewer questions in four semantic quadrants, we provide evidence of waves of transitions in students' responses that may not be evident with deeper questioning related to first principles (justification of design decisions with disciplinary core ideas) and multi-disciplinary thinking (justification of trade-offs made in decisions) questions. Given the increased importance of integrating science and engineering, we believe these findings and recommendations would be of interest to the NARST membership.

Our study confirms the utility of the legitimation code theory (LCT) in eliciting student thininking in design. Theoretical constructs from Maton's argument of LCT is based on the idea that disciplinary knowledge resembles waves of transitions as opposed to fragmented facts. Future research can further examine the use of the construct, the semantic quadrant, that we have coined in this paper. Finally, our student sample was not very diverse as we conducted research in a well-resourced school district. Future research should explore the questions rasiedraised with an equity perspective and check that our findings can be elaborated with research conducted in different demographic make-up.

6. Acknowledgments

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7. PowerPoint Presentation Slides

On March 16, 2020, we organized a virtual session to present papers to an interetested group of authors. https://web.ics.purdue.edu/~spurzer/QuintanaPurzer_NARST2020_Slides.pdf

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