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Semantic Fluency in Design Reasoning*

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During design, different forms of reasoning shape the designers' decision-making. As a result, the ability to fluently transition across various forms of reasoning is essential. The purpose of this study is two-fold: first is to introduce and explain the concept of *Semantic Fluency in Design Reasoning*, as the ability to transition across multiple forms of reasoning fluently. To identify these transitions, this study used the Design Reasoning Quadrants framework, which represents four quadrants: experiential observations (reasoning based on observations and experiences), trade-offs (reasoning recognizing multiple competing design requirements), first-principles (reasoning requiring disciplinary understandings), and complex abstractions (reasoning in envisioning new situations). The second purpose of this study is to illustrate semantic fluency in a design review conversation. We selected and presented three different forms of transitions identified through our analysis of conversations between students and design reviewers. Our analysis revealed evidence of semantic fluency in young designers. Mike, one of the students, demonstrated fluency across three quadrants (experiential observations, trade-offs, and first-principles). Lisa and David demonstrated two-quadrant transitions. Lisa had fluency from experiential observations to trade-offs, and David transitioned from experiential observations to first-principles. We recommend the intentional use of design reviews to elicit student reasoning in design and adopt questioning strategies to promote fluency across different forms of design reasoning.

Keywords: design reasoning; first-principles; trade-offs; engineering design; K-12; pre-college engineering

1. Introduction

Design decisions require understanding the design problem's context, trade-off considerations [1], disciplinary knowledge [2], and an ability to imagine design ideas in new situations. In addition, such decision-making necessitates fluency in transitioning between different modes of reasoning. As designers negotiate design constraints, alternative solutions, and evidence, understanding this fluency is necessary, in part because engineering design occurs at the intersection of technical and social forms of work [3]. Similarly, there is also a need to transition between context-based decisions and theoretical premises. Design problems are contextualized and demand designers to build upon their prior experiences, observations in the design practice, and knowledge regarding specific contexts. The knowledge is further used to understand design needs and solutions in new settings [4]. As a result, design decisions involve theoretical, practical, and multidisciplinary knowledge to make design decisions [5–7].

In engineering design, discursive interchanges are essential [8–10], mainly because it is one way to elicit or notice such reasoning. Discursive interchanges enable voicing and making evident the decision-making processes. To date, numerous prior studies on design decisions and engineering discourse have informed engineering education. For example, studies in undergraduate education recognize the effectiveness of design reviews in eliciting student reasoning and identifying assets and limitations [1, 2, 8, 11]. However, there is still a need for more exploration of students' transitions across different types of reasoning.

In the same way, there is also a need to examine students design reasoning in the emerging context of pre-college engineering. Our study addresses these two gaps and contributes to the field by coining a new theoretical framework, Semantic Fluency in design. Semantic fluency is the ability to transition between different modes of reasoning in design practices. By exploring how semantic fluency manifests in students' explanations, we first use the Design Reasoning Quadrants model to illustrate how a design conversation represents semantic fluency's presence, absence, or expanse. Then we describe and illustrate Semantic Fluency. Finally, we introduce analytical tools for capturing transitions across different modes of reasoning necessary for an informed design.

2. Literature Review

Prior research on design thinking and practices is key to understanding how engineers are taught and how they should be taught to design [11]. By

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focusing on design discourse, researchers revealed design practices associated with the multifaceted nature of design [12] and uncovered students' learning, challenges, and the decision-making process when designing [13]. Similarly, researchers also indicated that discursive interchanges represent a social form and an expression of professional identity [14]. Since design discourse is essential in design teaching, meaningful activities that promote rich discourse are needed. As a result, more and more researchers are encouraged to understand further discursive exchanges, the complexities in these exchanges, and how discourse influences knowledge and design [15].

Two major views characterize discourse patterns, types of discourse, and their role in design practices. One view considers semantics and language in design discourses as forms of representations. In these representations, it is possible to identify students' design reasoning. An example of this view is Lloyd and colleague's work [16], which proposes that verbal methods reveal some aspects of design reasoning. In other words, representations captured with verbal methods reflect students' reasoning. The second view characterizes design discourse as more than a tool for representation. According to Dong [15], semantic and grammatical structures are performative aspects of design discourse. In other words, forms of semantics can represent enacting design practices. In this view, researchers explored how discourse patterns can support and interfere with students' achievement of their design goals [18].

Researchers who study pre-college engineering education also investigated different aspects of design discourse. For example, Wendell, Wright, & Paugh [18] studied how discursive interaction with instructors and peers can influence students' design decisions [19, 20]. Another example is Aranda, Guzey, and Moore's research [2] which examined multidisciplinary discourses that enhance students' understanding of engineering and science concepts. At the same time, these studies focused on understanding how discourse influences design decisions. Studies in undergraduate education focused on examining transitions in students' theoretical reasoning and practical application embodied in students' discourse. These studies argued that students' theoretical and practical reasoning can impact design decisions and ultimately impact the quality of their solutions [5, 6]. For instance Wolmaran [5, 6] as well as Groen and colleagues [20] found that mechanical engineering students had difficulty explaining features of their designs with theories that influence them. Students' limited explanations in these studies reveal their difficulty in connecting design features with theory. While many of the prior studies focused on studying discourse in engineering and examined discourse to elicit student reasoning, few explored semantic fluency in students' design discourses. We describe semantic fluency as the ability to transition between different modes of reasoning. Our study aims to understand the instances where students' discourses represent semantic fluency in their design reasoning.

3. Theoretical Framework: Semantic Fluency Across Design Reasoning Quadrants

It is well recognized that design necessitates many forms of reasoning. Consequently, design reasoning labeled with pairs of descriptors such as divergent-convergent, disciplinary-multidisciplinary, theoretical-practical, and deductive-abductive [8, 21, 22]. Undoubtedly, engineering education must help develop different forms of reasoning, but even more important engineering education facilitate fluent transitions across different forms of reasoning. Thus, we developed the concept of semantic fluency in design reasoning to help represent these transitions. The following sections present the theoretical basis for this concept.

3.1 Semantic Fluency and Design Reasoning Quadrants Model

Semantic fluency is the ability to seamlessly transition across different modes of reasoning in design. Some argue that two modes of reasoning are needed for design: practical and theoretical reasoning. According to Houkes [23], the theories engineers use help engineers fulfill the practical purposes of their designs. Crismond and Adams [24] also highlight practical reasoning among beginner designers. Beginner designers can provide solutions that mainly focus on superficial aspects. The use of experience as a form of reasoning could be why students have the tendency to focus on surface features a practical aspects and illustrate lesser concern for other aspects such as theoretical justifications or trade-off considerations in their design. While theoretical reasoning requires depth in disciplinary understanding, reasoning in trade-offs requires breadth in multi-disciplinary knowledge.

Goldstein and colleagues [25] suggest that to reveal trade-offs, it is essential that students have the terminology and concepts to understand competing criteria and outcomes in relation to their design. Furthermore, trade-offs reasoning demonstrates multidisciplinary understandings through recognition of risks and benefits, advantages and disadvantages of design decisions, as well as homing design decisions based on disciplinary core ideas (e.g., [2, 26]). We further add the importance of complex abstractions as another essential form of reasoning, which is necessary to make predictions, despite uncertainty, about the behavior of a designed artifact in the future. While prior literature explored the significance of practical reasoning, recognizing trade-offs, and the crucial role of disciplinary and theoretical reasoning in design, the concept of semantic fluency across these forms of reasoning has not been the main focus of any of these studies.

3.2 Design Reasoning Quadrants at the Intersection of Semantic Gravity and Density

The *Design Reasoning Quadrants for Design Reasoning* model encompasses four modes of reasoning, as presented in Fig. 1. These four modes of reasoning are visualized at the intersection of semantic gravity and semantic density, which are terms coined by Maton [27, 28] as part of the Legitimation Code Theory and later applied to design education by Dong [29] and Wolmaran [6]. Semantic Density (SD) indicates the levels of multidisciplinary perspectives reflected in disciplinary discourse [6]. The semantic density is strongest when multiple disciplines are represented in a cohesive and well-connected discourse (commonly notated as SD++). In contrast, semantic density is weaker when the disciplinary ideas are discussed in isolation (SD−) or only one discipline used in explanations (SD−−). The + and −− notations do not mean lower or higher quality discourse but rather somewhat differing condensations of meaning that are expected to occur in authentic disciplinary discourse. In Fig. 1, the diagonal-upward axis represents semantic density which connects disciplinary and multidisciplinary reasoning.

Engineering requires disciplinary and multidisciplinary knowledge necessary to understand and solve complex problems [7, 23, 30–32]. The disciplinary-multidisciplinary spectrum, called semantic density (SD), captures levels of isolation (SD−−, SD−), condensation, and interconnection (SD++, SD+) between disciplines. In engineering practices, as argued by Dong [30], discourse is not unique to one discipline but occurs at the intersection of different discourses from multiple disciplines. The design reasoning quadrants framework captures different condensation levels of meaning and encompasses both isolated disciplinary discourse and more condensed multi-disciplinary discourse.

Semantic Gravity (SG) indicates practical reasoning and context dependency in one direction (SG++) and decontextualized theoretical reasoning in the other direction (SG−−). Semantic gravity is stronger when discourse is dependent on context, with highly descriptive explanations based on experiential observations and loaded with subjective judgment. Semantic gravity is weaker when explanations are decoupled from context and based on theory. There are two forms of negative semantic gravity [SG−/SG−−]. The negative sign means that the discourse is less connected to the current design experience and instead supported theoretically. The two forms of positive semantic gravity [SG++/SG+] indicate strong use of prior experiences and subjective values to explain design decisions in the discourse. In Fig. 1, the downward axis represents semantic gravity which captures theoretical and practical reasoning. Engineering practices also require the ability to connect theoretical knowledge and prior experiences to explain observed behaviors of technological systems.

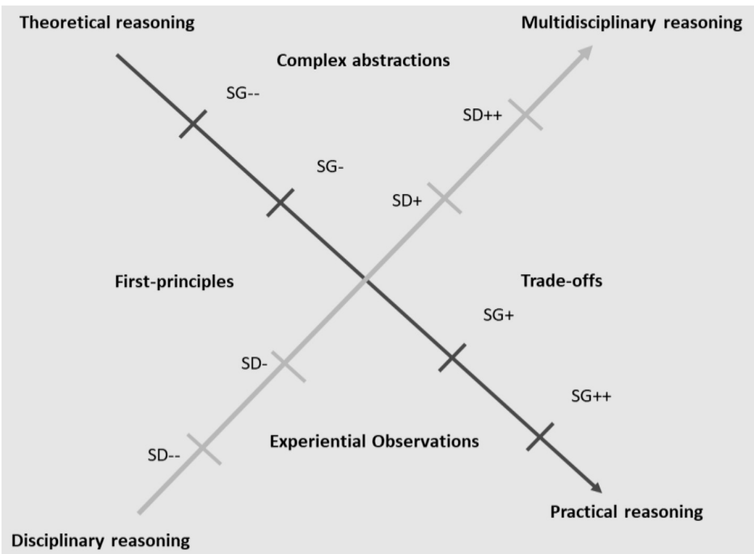


Fig. 1. Design Reasoning Quadrants model [18].

We further expand on the prior works of Dong [29] and Wolmaran [6] by visualizing the intersection of semantic gravity and semantic density with the *Design Reasoning Quadrants* model represented in Fig. 1. This model has three key elements: (a) an upward axis that connects disciplinary and multidisciplinary reasoning (semantic density, SD); (b) a downward axis that represents theoretical and practical reasoning (semantic gravity, SG); and (c) four quadrants that are situated at the intersection of the two axes.

Four quadrants of design reasoning are located at the intersection of semantic density (disciplinary-multidisciplinary reasoning) and semantic gravity (practical-theoretical reasoning). These quadrants include experiential observations, trade-offs, first-principles, and complex abstractions.

- *Experiential Observations Reasoning Quadrant* is located at the bottom of Fig. 1 and represents the intersection of the least condensed disciplinary reasoning and practical reasoning. In design discourse, such reasoning reflects high use of experience, observational knowledge, subjective values, and beliefs, as well as descriptions of overt design features to explain design decisions.
- *Trade-offs Reasoning Quadrant* is represented at the intersection of strong semantic density (multidisciplinary thinking necessary to balance design requirements) and strong semantic gravity (prior design practices or newly gained observations). Trade-offs reasoning is understanding multiple design requirements that need to be explored and weighted when designing.
- *First-principles Reasoning Quadrant* represents the use of disciplinary core ideas. Weak semantic gravity represents a high theoretical content and disciplinary understandings in the discourse.
- *Complex Abstractions Reasoning Quadrant* is located across the experiential observations quadrants and represents the most complex mode of design reasoning. In this quadrant, which occurs at the intersection of theoretical and multidisciplinary reasoning, the discourse represents designers' ability to envision their designs in new situations.

4. Method

This study examined patterns of semantic fluency in middle school students' justification of their design decisions.

4.1 Study Context

The research took place in a middle school located in a suburban town in the United States. Students from the seventh-grade cohort (about 400 students) participated in a design project with the guidance of four middle school teachers. Students worked individually on their design projects over two weeks.

Students designed a single-family house with solar panels that met four design criteria:

(1) minimize the energy needed to keep the building comfortable on a sunny day or a cold night (and ideally meet negative net energy),
(2) minimize the total cost of the building,
(3) comfortably accommodate a family of four (approximately 2200 ft^2 or 204 m^2), and
(4) have an attractive exterior.

The students were also provided with design constraints, including that the cost cannot exceed $250,000 in building materials, the number of solar panels cannot exceed 40, and each side of the house must have at least one window.

4.2 Data Analysis

The data analysis occurred in three stages. First, data were coded independently for semantic gravity. Second, the same data were coded for semantic density (See Figs. 2 and 3). These semantic code pairs for gravity and density are akin to coordinates on a map. This effort resulted in a semantic fluency map (See section 4.2.3). Those answers that were clarifying information or did not present evidence or reasoning were coded as zero and located at the center of the fluency map.

4.2.1 Coding Semantic Density

A coding book was developed based on our theoretical framework to capture semantic density in students' answers. In Fig. 2, we provide descriptions of each semantic level represented in the axis of semantic density (disciplinary vs. multidisciplinary reasoning). Fig. 2 presents the code definition from data for SD++ and SD−−. The four condensation levels of disciplinary discourse shown in Fig. 2 included two forms of negative semantic density [SD−/SD−−]. This negative sign is not a connotation of an adverse form of discourse, but it is an indication of the level of condensation. It means that the condensation between different disciplines is lower or unidentifiable from the design discourse. Conversely, the two forms of positive semantic density [SD++/SD+] indicate a strong connection between different disciplines in design discourses.

4.2.2 Coding Semantic Gravity

The semantic gravity axis of the design reasoning quadrants was developed to code semantic gravity. Fig 3 presents the coding protocol used

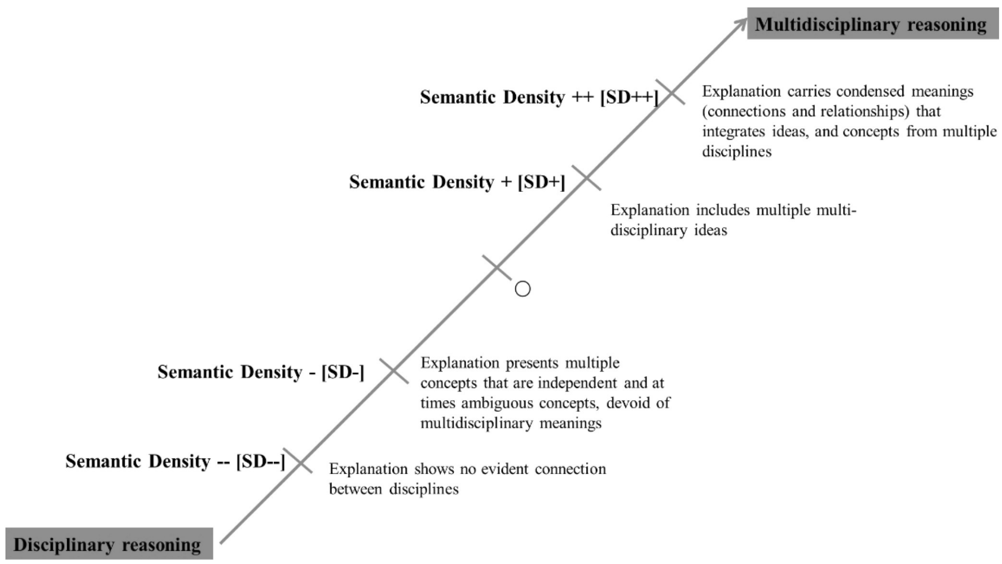


Fig. 2. Axis of Semantic Density (disciplinary vs. multidisciplinary reasoning) in the Design Reasoning Quadrants.

to analyze students' answers at each semantic gravity level.

4.2.3 *Design Reasoning Quadrants and Semantic Fluency Maps*

The intersection of semantic density and gravity axes represents the four design reasoning quadrants: experiential observation, trade-offs, first-principles, and complex abstractions quadrants. Once students' statements were coded separately for semantic gravity and density, we placed them in an appropriate semantic quadrant, as illustrated in Fig. 4. For example, the intersection of semantic gravity (SG+) and semantic density (SD++) is located in the trade-offs quadrant. A trade-offs quadrant statement means that the explanation recognizes the interplay of multiple design criteria requiring multidisciplinary reasoning supported with experiential, empirical testing evidence.

4.3 *Selection of Case Studies*

Initially, science teachers identified fifteen students to present their designs to the external design reviewers based on quality in design performance, student effort, completeness, and presentation. Two external design reviewers interviewed the students during the final design review. These interviews aimed to understand students' design decisions before selecting the best designs among the group. The interview questions were unstructured, and

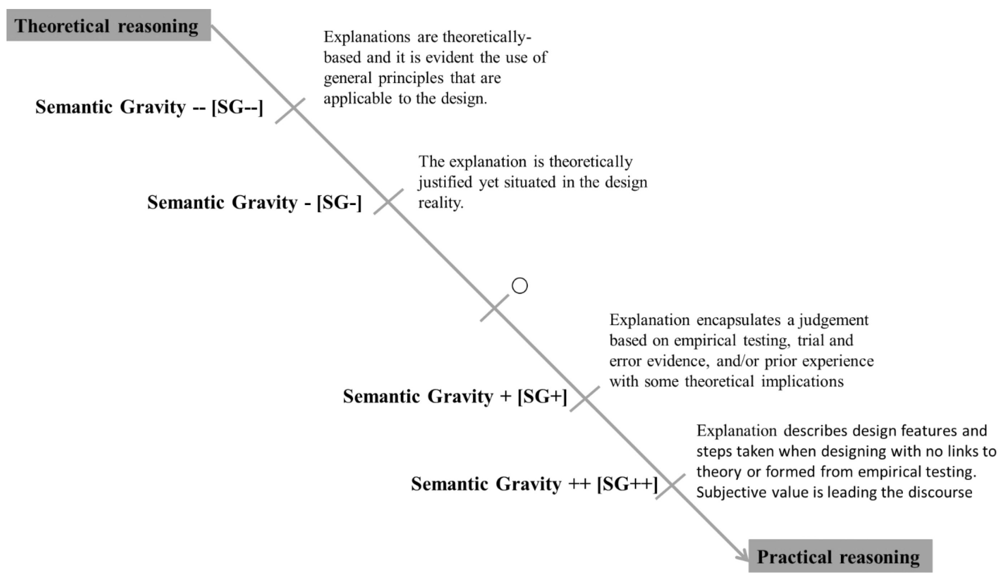


Fig. 3. Axis of Semantic Gravity (practical vs. theoretical reasoning) in the Design Reasoning Quadrants model.

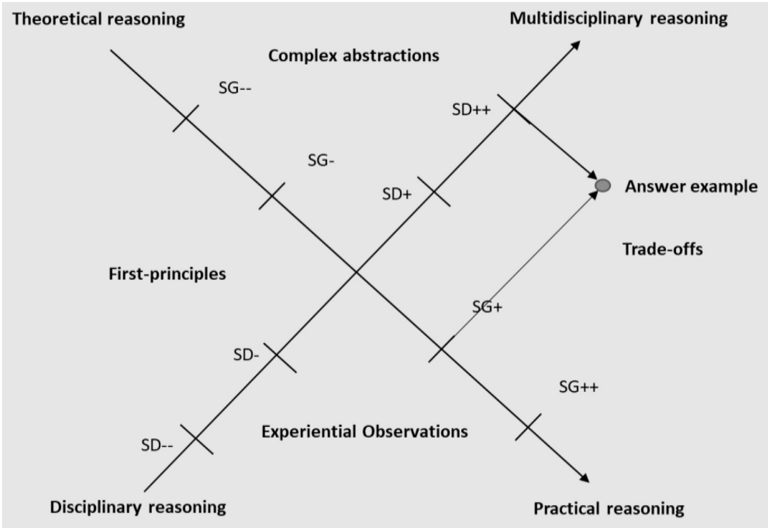


Fig. 4. Mapping semantic gravity and density.

most of the questions focused on students' final presentations, features in students' designs, and the reasoning behind design decisions. Our main data source was transcripts from the audio recordings of eleven interviews and the slides students used in their three-minute pitch presentations.

Among the eleven students, six students transitioned across two quadrants. Five of the students transitioned between the experiential observations and the first-principles quadrants. Two students transitioned between experiential and trade-offs quadrants. Two students transitioned between three quadrants, experiential observations, first-principles, and trade-offs. Finally, two students did not transition to other quadrants and only used experiential observations. We selected three cases (Mike, David, and Lisa) to illustrate fluency through two-quadrant and three-quadrant transitions.

5. Results

The careful examination of the conversations between the students and the design reviewers resulted in evidence of semantic fluency in students' design reasoning. In particular, we identified fluency across two and three reasoning quadrants.

5.1 Students' Semantic Fluency and Features of their Design Artifacts

The following section explains features of buildings designed by each student and their detailed conversations with the design reviewers. In Table 1, we introduce the fluency maps of Mike, David, and Lisa, along with the 3D sketches and the performance metrics of the houses they designed. In the fluency maps, students' answers are presented with the "A" abbreviation for answer followed by the order of student's answer, which is represented with a number. A1, for example, indicates the first answer provided by the students.

Before comparing each student's design reasoning fluency, we present each student's design details to provide information that is not visible in the figure presented by them:

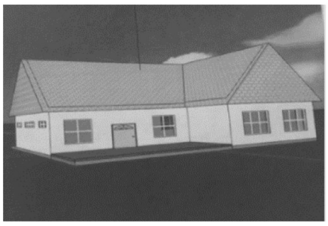
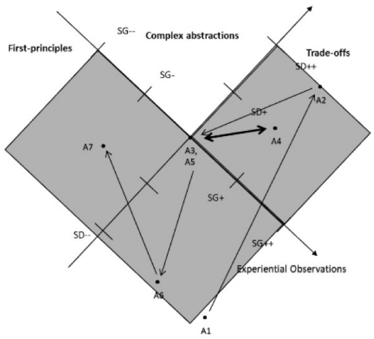
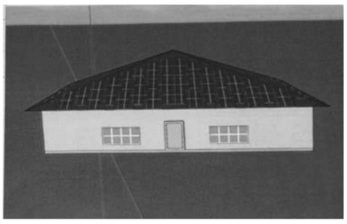
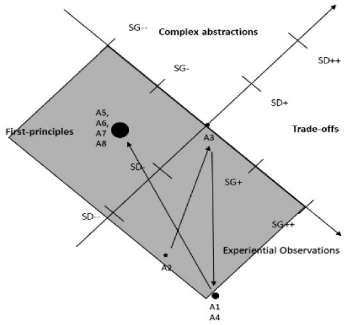
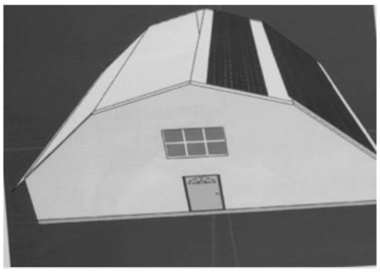
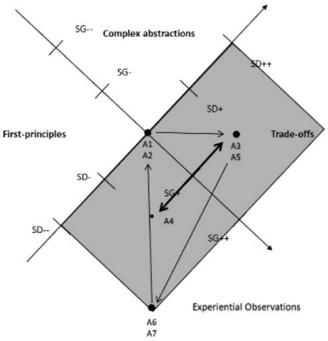
Mike's building design: The house designed by Mike is a single-story, "L" shaped house with 2000 square feet. This north-facing house contains four windows at the front of the house, a garage door and window on the west side, and three small windows on the east side. At the back of the house, two windows and three solar reflectors are placed. The angled roof contains 13 solar panels on the west side and 13 panels on the south side.

David's building design: The house designed by David is also a single-story building with more than 2100 square feet. This south-facing house also has solar panels located on the south side. In addition, David's house has two windows in the back and one on each side that is longer but narrower than the two on the back and at the front.

Lisa's building design: The house designed by Lisa is a single-story, barn-shaped home with 2000 square feet of living space. This house is west-facing and contains one window at the front, three in the back, and two on each side of the house. The roof is angled and contains 40 solar panels facing South.

Mike transitioned across three reasoning quadrants. Unlike those used by David and Lisa, the quadrants that Mike used were first-principles and

Table 1. Overview of the three students' design performance and fluency type

Students' house models designed in Energy3D	Design features & performance metrics descriptions by students	Fluency maps
Mike's house design 	*Area of the house: 188 m²* *Annual energy: -6580 kWh* *Total cost: $236,416* *Special features:* *Cut out the front lawn, two-car garage, 26 max efficiency solar panels*	**Three quadrants of semantic fluency: Experiential observations, trade-offs, and first principles.** 
David's house design 	*Area of the house: 198 m²* *Annual energy: -13,175 kWh* *Total cost: $222,229* *Special features:* *The walls are monochromatic. The door stands out. You cannot see the solar panels from the ground, but if you were nine meters tall, they just blend into the roof. Short enough that you can retrieve whatever it is that your child just threw onto the roof. Tinted windows so that the floors (or rooms with windows) don't overheat*	**Two quadrants of semantic fluency: Experiential Observations to First Principles** 
Lisa's house design 	*Area of the house: 192 m²* *Annual energy: -32806 kWh* *Total cost: $239,127* *Special features:* *My house is full of special features. My yellow door attracts the eye to the front house. The farmhouse style is very unique and eye-catching…*	**Transition: Experiential observations to Trade offs** 

trade-offs. The main difference between Mike and David with regard to the first-principles was the fluency in which David transitioned into this quadrant compared to Mike. For example, the design reviewer elicited Mike's reasoning with a sequence of questions to surface his understanding of thermodynamics concepts associated with having a large roof. Eventually, Mike was able to explain these disciplinary concepts. In contrast, David's answers had evidence of the use of scientific concepts even when questions were not explicitly targeting first-principles. An example is David's answer to question 4 (See section 5.3.1.). While Mike's understanding of scientific concepts that influence his design was evident when explained the role of energy in his design iterations and decisions, for David's answers used scientific concepts even if the question was not related to energy.

Both Lisa and Mike reasoned through trade-offs. Lisa's trade-offs answers were deliberate on making sure the panels were located strategically to collect energy and, at the same time, not be visible. However, Mike's trade-offs answers were more broadly connecting building size, energy performance, and aesthetics. All three students reasoned through experiential observations. However, each one used different prior experiences and subjective values as a source for their reasoning. For example, Mike mainly used his design experience with the previous version of his building design (e.g., the circle house, a previous version of his building design featuring a circular house). In contrast, David focused on describing his trial-and-error process with the current house, mainly focusing on testing features that can help him meet the design criteria. Lisa also used trial and error testing in experiential observations. However, she was less systematic in changing design features to meet requirements compared to David.

Finally, David and Lisa tinted their windows black, although for different reasons. Lisa decided to do it because she saw that the tinting was helping her energy in her experiments; however, she did not provide further evidence supporting this decision. In contrast, David explained his decision to tint the windows from the perspective of energy concepts. In this case, the guiding concepts in David's discourse were his understanding of how color influences his energy depending on the season.

5.2 Fluency Across Three Quadrants (Mike)

The highest level of reasoning fluency observed in our sample was the three-quadrant fluency. The house Mike designed met the negative energy criterion and the cost constraint. However, the house may be viewed as too small to fit a family of four comfortably.

The design review conversation with Mike started with the reviewer noticing and pointing out Mike's house realistic look. Experiential reasoning is evident in Mike's answers to the first and sixth questions. Mike provides his reasons for selecting a specific form for his house in his first answer. Next, he refers to the forms his peers have chosen, resulting in a design decision based on his experiential observations of houses in his neighborhood and surroundings.

Reviewer	Question 1: "*I like how you were describing your presentation that for you, this was a mix of traditional and modern. Really, I was struck looking at the house. It looks like one you could see in a neighborhood. What other kinds of houses and shapes did you explore first?*"	
Mike	**Answer 1: "*So, a few of the first houses that I tried were basically rectangles, but I saw when I looked around the room, a lot of people were already doing rectangles. And I am not going to follow the trend, so I pasted off a lot of the houses in my neighborhood. A lot of my house has a side garage, and then they have different rooms to the left of the house facing. So, I explored a lot of designs, I even tried a circle house, but it did not work out because the roof did not attach right. I decided on this one because it was more related; you know, it was familiar to me.*"**	**SD−− and SG++** **Experiential Quadrant**
Reviewer	Question 2: "*Ok, very interesting, so it was again one way to look at the design. Did you look at the energy performance of the different homes?*"	
Mike	**Answer 2**: "***Definitely the circle one, because the roof on the circle one, it allowed a lot of sunlight to hit a lot of areas on the roof, and by putting a lot of solar panels down, I could maximize the efficiency, so it was around negative three, thirty-five thousand kilowatts per hours, but it looked like a muffin, so I didn't really like that. So, basically, I came to a conclusion the more roof space that the sunlight hit, the more kilowatt per hour, the less kilowatt per hour.***"	**SD++ and SG+** **Trade-offs Quadrant**
Reviewer	Question 3: "*So, to follow up on the more roof, you mean the area?*"	
Mike	**Answer 3: "*Yeah, the surface area.*"**	**Coded as zero**
Reviewer	Question 4: "*So, what are the trade-offs? You were able to put more solar panels, but what are the disadvantages of having more roof area?*"	
Mike	**Answer 4: "*One of the disadvantages of having a lot of surface area is. . . I guess you could say because there is so much surface area on them. I will give the circle house as an example. You could practically place it in any position you wanted because it has much surface area, but that led to a lot of problems with (solar panels). First of all, if you have an awkward facing house, the light comes in a different direction, and it kind of bothers the house throughout the day and temperature was also another problem because a lot of it. . . not only in the***	**SD+ and SG+** **Trade-offs Quadrant**

	program, but I thought about different things just like the weather and stuff like that, but by putting it in different directions, it caused a lot of problems surprisingly. I don't know how to explain it exactly. **"**	
Reviewer	Question 5: "*So, let me ask differently. Let's imagine you don't have any solar panels. Which one would you think will be a better design decision if there is not a solar panel, having a big surface roof, or smaller surface roof?*"	
Mike	**Answer 5: "*. . . No solar panels, bigger surface area.*"**	**Coded as zero**
Reviewer	Question 6: "*And tell me why?*"	
Mike	**Answer 6: "*Because. . . I usually say the bigger the roof the bigger the house. I like big houses. . . I guess I don't know how to put it.*"**	**SD−− and SG+ Experiential Quadrant**
Reviewer	Question 7: "*So yes, it would actually. . .yes. Think about heat transfer and the possible impact.*"	
Mike	**Answer 7: "*Oh yeah!! Yeah. . . the larger the surface area in summer, it could consequently make the roof very hot, which can basically increase AC usage, which is something that will. . .Because in my first test that was actually one of the first issues the AC skyrocketed when up like the nineties and in December drop. So, I think actually both of them have disadvantages one of the disadvantages is AC usage, but the advantage more room for solar panels, so that the conclusion.*"**	**SD−− and SG− First-principles Quadrant**

In Mike's answer to the second question, he transitions into the trade-offs quadrant. Interestingly, this conversation centers on a design feature that he explored as an alternative (i.e., the circle house) but was not incorporated into his final design. Thus, without explicit prompting, Mike naturally starts to explain the advantages and disadvantages of the circle house concerning two design criteria: energy performance and aesthetics, resulting in a trade-offs answer.

Question 3 was a clarification question, and it was not coded in any quadrant due to its nature. This type of question aims to clarify information, resulting in being located at the center of the semantic quadrant map and being coded as zero.

In question 4, the design reviewer explicitly asks about trade-offs, likely to elicit Mike's thoughts on the cost of building a large roof, one of the design criteria not yet mentioned in Mike's answers (see. Design conversation above). Mike does not mention building costs; instead, he expresses the displeasure house residents would face with constant exposure to the sunlight. Mike's answers connected the disciplinary concepts of energy and aesthetics and recognized the scientific and aesthetic factors that influenced his design. However, his answer to the sixth question brings him back to the experiential quadrant when he presents his subjective view about selecting a roof size.

What made Mike's design review session stand out among other students was that he also transitioned into the first-principles quadrant. In Table 1, we provided the fluency map that illustrates Mike's transitions across three quadrants. This transition was facilitated with explicit prompting from the design reviewer. For example, the question asks Mike to imagine a roof with no solar panels and evaluate if choosing a large roof would still be advantageous if he could not install any solar panels. The reviewer further prompts us to think in terms of heat transfer. Mike recognizes the disadvantage of having a large roof area in summer when solar panels are not used, answering as a first-principles explanation.

5.3 Fluency Across Two Quadrants (David and Lisa)

We found that students also fluently transitioned between two quadrants. For example, in one case, David demonstrated semantic fluency between experiential observations and first-principles quadrants. In another case, Lisa transitioned from experiential observations to trade-offs quadrants while explaining her design to reviewers. We describe each case below and provide data excerpts for each case.

5.3.1 Fluency Between Experiential Observations and First-principles Quadrants: David

David's discourse illustrates the fluency between experiential observations and first-principles. What made David stand out from other students who frequently transitioned to first-principles to illustrate their design decisions is the premise that he used to connect to his design decisions. We present his conversation with the design reviewer below, and we also represent David's design performance and semantic fluency map in Table 1.

Reviewer	Question 1: "*Ok, so something . . . interesting house, and I like the name too, of you going with the features of the house, so it looks like a good design. You said, and this stuck out with me, and I wanted to follow up with you; you were frustrated with the requirements*".	
David	**Answer 1: "*Like, getting to zero or low for the energy was kind of easy, but then matching the cost with it, and also having zero or below was pretty difficult.*"**	**SD−− and SG++ Experiential Observations Quadrant**
Reviewer	Question 2: "*. . . in this house, what was the main area that you were trying to optimize? What was that one? You said you started with energy, and that was easy to do*".	

David	**Answer 2: "*Yes, but once I got to [indistinct] that everything else on to the requirement section. I was, kind of, went to the very limit of the other areas to see how far I could go with my energy, like how far I can get below zero, and that is how I ended up with exactly two hundred and fifty thousand dollars and like it was almost exactly a hundred thirty-five square meters like just at the very edges, not meeting all the requirements.*"**	**SD− and SG+ Experiential observations Quadrant**
Reviewer	Question 3: "*Then, how many windows do you have?*"	
David	**Answer 3: "*Six*"**	**Coded as zero**
Reviewer	Question 4: "*I also noticed that you do not have any trees. Was there a specific decision, you had not included trees?*"	
David	**Answer 4: "*Not really, it was just. I couldn't figure out how to get to the shades to line up with the window so that it would actually help me out, so I decided not to use them.*"**	**SD− and SG− First-principles Quadrant**
Reviewer	Question 5: "*And going back to the windows, how do the windows impact energy? You really target it to focus on energy and to get a very negative number.*"	
David	Answer 5: "*Well, I tinted them a different color to keep the house either cool or warm depending on the season, so that way the air conditioner or heater will take less energy.*"	**SD− and SG− First-principles Quadrant**
Reviewer	Question 6: "*So, how does the color impact energy?*"	
David	**Answer 6: "*Well, I tinted it white. It reflects heat.*"**	**SD− and SG− First-principles Quadrant**
Reviewer	Question 7: "*So, it works in summer? Or winter? How does it work?*"	
David	**Answer 7: "*Oh, winter... Cause, oh no, sorry in summer because it reflects some of the hot air, so it doesn't need to work as hard [indistinct.]*"**	**SD− and SG− First-principles Quadrant**
Reviewer	Question 8: "*Do you think that would be a problem in winter, the color?*"	
David	**Answer 8: "*Well yeah, it would because it will also reflect the heat that would be brought into the house, but in winter, that is not very much light . . . the amount of heat that is coming into the house already is not that much. I feel that if I chose black in winter would of made a bigger negative impact in the summer than having white having a negative impact with energy.*"**	**SD− and SG− First-principles Quadrant**

Design reviewers initiated the conversation with David by asking what was frustrating while dealing with the design requirements. In answer 1, detailed in the design conversation, David explained that low energy usage was easy to achieve. However, it was hard to match the energy efficiency with the cost of the building to get the energy usage to zero or below. David's experiential reasoning was evident from the first set of answers, answers one through four. For example, in question 2, David's answer evidenced his testing process while modifying each design feature. This process helps David to identify how each design feature would impact energy efficiency. While David's answer might look to be in a trade-offs quadrant, the answer does not provide evidence of the given trade-offs behind his answer or for trade-offs to be the main trigger of his decision. Instead, testing different features helps him to meet the design criteria provided in the design task. In this first set of questions, there was no evidence of semantic fluency, and only one question, question 3, was coded as zero, considering that this question only provided information.

David transitioned to the first-principles quadrant in question 5. In this question, the design reviewer asks about the role of the windows in David's house energy performance. In addition, the reviewer asks this question likely to elicit David's reason for using windows to manage energy consumption. David's answer focused on explaining how the tinted windows can help to reduce or increase the energy consumption of an AC or heater, depending on the season. David's answers' focus on energy presents evidence of disciplinary knowledge, resulting in being mainly guided by the first-principle quadrant.

David's answers to questions five through eight represent David's use of first-principles reasoning to explain his design decisions. In question 6, reviewers request more details on how color impacts energy. David again uses the first-principles quadrant to justify how white is more beneficial for reflecting the heat. He also suggests that the color will be impactful to differing degrees depending on the season. For example, David explains that having a black color in winter will not be as beneficial as white. This type of answer evidences a strong understanding of scientific concepts used to inform decisions on the selection of design features. David provides this type of answer throughout the rest of the conversation while explaining how color is beneficial in different seasons (answer 7, answer 8).

5.3.2 Fluency between Experiential Observations and Trade-off quadrants: Lisa

Lisa demonstrates semantic fluency between experiential and trade-off quadrants. Lisa designed a house where all the solar panels are located on one side. We present answers in the two quadrants that exhibit her transition in the conversation below.

Reviewer	Question 1: "*So very interesting design; what side are the solar panels on?*"	
Lisa	**Answer 1: "*They are on this side right here.*"**	**Coded as zero**
Reviewer	Question 2: "*and do you know what side of the north, south, east, west?*"	
Lisa	**Answers 2: "*Maybe east?*"**	**Coded as zero**
Reviewer	Question 3: "*Ok, do you remember what went into deciding? How did you decide? Because I see all on one side*"	
Lisa	**Answer 3: "... 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."**	**SD+ and SG+** **Trade-offs Quadrant**
Reviewer	Question 4: "*So, your energy is really, really low, so what about this design you think to get to that?*"	
Lisa	**Answer 4: "*I think a big part of getting it low is . . . I made sure that everything was insulated and including the windows, and I tinted them black to make them like . . . I don't know. I tried it, and it helped, so I tinted my windows black, and I made the colors of my house really light because I found that would help with the energy a lot, and I also made the solar panels like maximum efficiency, and I made them black, and I feel like all that together really helped to get the energy really low.*"**	**SD– and SG+** **Experiential observations Quadrant**
Reviewer	Question 5: "*So, as you are working on energy, did it hurt other aspects of your solutions the things you were trying to do?*"	
Lisa	**Answer 5: "*Oh yeah, so when I was first working on . . . like when I first started, I had trees all around my house, and the walls were a lot tall and I found that with all that together, it was getting really close to the budget, and it was going over, when I was like adding solar panels and adding insulation. So, I ended up taking the trees away because when I did that, I found that it helped to drop my energy because they were shading the solar panels, and I made my walls shorter and I enough that it made the cost less, but they were still tall for enough people to live in the house.*"**	**SD+ and SG+** **Trade-offs Quadrant**
Reviewer	Question 6: "*So, how high is this?*"	
Lisa	**Answer 6: "*This here is about two meters, and then here is, I think, 4 meters. So, they're not super tall, but it worked out. I ended up before I built this, I changed them, like I already made this, but I made my wall taller because I had extra money after I had taken away the trees, I had extra money, so I made them taller. I don't remember what their new high is.*"**	**SD– – and SG++** **Experiential observations Quadrant**
Reviewer	Question 7: "*Why is it called daisy launch?*"	
Lisa	**Answer 7: "*The yellow door that I have here inspired that.*"**	**SD– and SG++** **Experiential observations Quadrant**

Reviewers initiated the design review session by asking where the solar panels were located. In this question, Lisa indicated where the solar panels were located by pointing at the picture in her PowerPoint slide (See section 5.1, Table 1) and indicated the cardinal location on her second answer.

As shown in the conversation above, Lisa responded to the third reviewer's questions using trade-offs reasoning. Her trade-offs reasoning is evident when she uses connections between disciplines in her justification, such as using aesthetics and energy concepts to explain why all the solar panels were on one side of her design. In this question, Lisa's reasoning also connects the multidisciplinary reasoning to her design experience while developing her design making. She also provided a rationale for her understanding of the need for the solar panels to be located strategically to gather solar energy.

When answering the design reviewers' fourth question, Lisa transitioned from trade-offs to experiential observation quadrant. In this question, Lisa focused on explaining her experience by trying different settings in the insulation, windows, and wall colors to help her energy consumption to be reduced. This experiential observation reasoning only prompts answers that explicitly use students' experiences without revealing specific connections to any disciplinary concepts. Nevertheless, she returned to the trade-offs quadrant when asked what factors hurt while getting the energy low (less usage) in question 5.

In question 5, Lisa's explanation showed evidence of connecting science principles to aesthetic considerations required in the design challenge. As a result, Lisa's answers demonstrate her understanding of balancing these requirements and influencing these requirements, such as insulation in her house and panel location.

6. Discussion

This study aimed to present the instances where students' design review sessions provided evidence of semantic fluency in design reasoning. Our findings illustrate the critical roles of practical-theoretical and disciplinary-multidisciplinary reasoning at the intersection of a weak and strong form of semantic gravity and density. According to Dong, Maton, and Carvalho [30], both strong and weak semantic gravity are necessary for applying knowledge to different situations, which literature also refers to as the transfer of knowledge. For example, Mike's exploration of creative ideas such as the circular house could be possible due to this weak and strong form of semantic gravity and density: semantic fluency. On the other hand, Dong and colleagues consider low semantic gravity (SG−) to be influential in generating creative solutions. An example of low semantic gravity is when designers bring solutions from different contexts from the problem context, such as analogies. However, this might not be the case when problems are well-defined since it might be more efficient to apply direct knowledge to the context.

Cross and Cross [32] suggested that thinking based on first-principles might be more likely to lead to innovative ideas. In our study, David and Mike used first-principles reasoning frequently to reevaluate his explanations of how roof surface area impacts their house energy performance and how window color impacts energy. However, David reveals a more advanced understanding of the scientific concepts that impact his design in his answer. In addition, David's fifth answer was coded as an experiential observation. Finally, the approach was targeted at balancing design criteria that would translate to trade-offs.

Nevertheless, at this stage in his explanation, David is only getting familiar with the negotiation he needs to make to meet design goals. It is not clear that he had already recognized outcomes in changing trade-offs. This type of explanation most likely is a way in which students become intuitively familiar with factors that interact with each other and the need to balance them. Simultaneously, it is also possible that, as Goldstein and colleagues suggest [25], students, who did not have explicit instruction on trade-offs and the interaction between them, might make a language connection while communicating with them or be aware of the particular outcomes while focusing on them.

Using semantic fluency and the design reasoning quadrant model in the design review conversations appears to highlight students' understanding of scientific concepts, the relation between trade-offs and design features. Mike, David, and Lisa's fluency in three and two different design reasoning quadrants is likely due to their cognitive abilities and the eliciting power of the design reviewers' questioning. Even though there is still a debate whether creativity happens in a weak or strong gravity or density, we argue that it is semantic fluency that facilitates effective problem solving and innovative design.

7. Conclusions and Implications

In conclusion, this study explored semantic fluency in design reasoning by examining a design review session that took place in a middle school. Our findings suggest that even among early designers, there is evidence of semantic fluency. We identified two main forms of semantic fluency in the cases presented in this study. One is where the student moves across three quadrants: experiential observations, trade-offs and first-principles quadrants. The second form of fluency takes place between two quadrants, along with two variations. One is where the student moves from experiential observations to trade-offs, and the other one is where the student moves from experiential observations to first-principles. Future research should explore ways fluency can be facilitated in engineering education and examine how different forms of reasoning impact the performance of students' design solutions.

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