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# Investigating the Impacts of Design Heuristics on Idea Initiation and Development

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## ABSTRACT

This paper presents an analysis of engineering students' use of Design Heuristics as part of a team project in an undergraduate engineering design course. Design Heuristics are an empirically derived set of cognitive "rules of thumb" for use in concept generation. We investigated heuristic use in the initial concept generation phase, whether heuristic-inspired concepts were carried through to later design process stages, and how concept synthesis within each team's design process related to heuristic use. The results reveal widespread use of Design Heuristics among the concepts generated by individuals and selected by teams for further development, and a prevalence of concept synthesis within approximately half of the observed teams' design processes.

**Key Words**: Design Heuristics, ideation, concept synthesis

## INTRODUCTION AND BACKGROUND

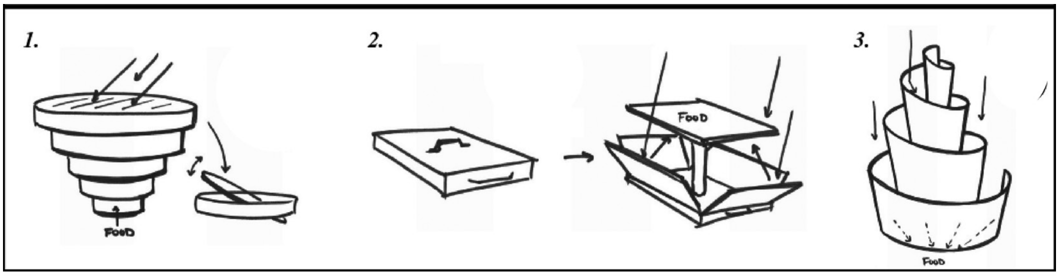
Successful innovations can often be traced to successful concept generation [1, 2] but engineering students often struggle with this stage in the design process. They experience difficulty in generating a diverse set of multiple ideas, and therefore do not fully explore the solution space [3, 4]. This challenge is partially due to a lack of formal instruction on various systematic approaches to innovative thinking and ideation [5, 6, 7, 8]. Engineering instructors, in many cases, encourage their students to generate ideas by brainstorming [9], but may not provide specific instructions on how to execute the technique, or how to leverage other tools and best practices to ideate successfully. This lack of formal instruction can prevent novice engineers from employing specific strategies as they create and develop concept ideas [4].

A number of challenges exist for engineering designers in concept generation. For example, fixation prevents engineers from a considering a breadth of potential concepts [10]. In the context of this study, two aspects of fixation associated with idea generation in engineering were important to consider. First, engineers become attached to their initial ideas early on and stop considering alternatives [11]. Ullman and colleagues [11] found that engineers did not explore multiple ideas; instead, they pursued only a single design they had settled on quickly [12]. Ball and colleagues [13] found that engineers remained fixated on their original idea, even if this idea was seriously flawed. Second, engineers became fixated when they struggled to break away from existing, well-known solutions [12]. In Jansson and Smith's [10] work, designers were given an example of an existing unsatisfactory product and were made aware of its flaws; however, when asked to design an alternative, they frequently included elements (and flaws) of the given example. Engineers are often obstructed by their own initial ideas as well as pre-existing examples, and therefore struggle to generate multiple concepts that vary in quality and originality. This results in narrowly explored solution spaces with obvious or replicated ideas rather than diverse and novel options to consider.

### Design Heuristics

Many concept generation methods have been proposed, including TRIZ [14, 15], lateral thinking [16], SCAMPER [17], conceptual combination [18], brainwriting [19], Synectics [20], SIT [21], IDEO Method Cards [22], brainstorming [9], analogical thinking [23], and Morphological Analysis [24, 25]. However, only a few ideation techniques have been empirically derived and validated. One of these is the concept generation tool called *Design Heuristics* [26, 27, 28]. Design Heuristics are a collection of strategies to assist designers in exploring a wide variety of ideas during the ideation phase [28, 29, 30]. They were developed through analyses of innovative products and protocol studies of expert engineers' and industrial designers' design processes [26, 31, 32]. Additional studies verified the success of Design Heuristics in guiding student and professional designers to generate successful concepts [33, 34, 35, 36].

The Design Heuristics are presented and packaged as easy-to-use prompts to guide concept generation in the initial stages of design. They can be used individually and in combination to initiate




*Adjust function through movement*
*Layer*
*Telescope*

*Expand or collapse*
*Flatten*

*Convert 2-D to 3-D*
*Twist*

***Figure 1. Three example concepts using Design Heuristics as a generative aid in ideation. Here, first-year engineering students were given a set of heuristic cards and asked to design a solar-powered cooking device. The Design Heuristics used in each student's concept are noted below the image. [33]***

the creation of a new concept or to transform existing concepts. Their use has been shown to produce multiple, diverse, and creative concepts for a variety of product design problems [33, 37]. As an example of the various ways Design Heuristics can be used in concept generation and development, consider the ideas (Figures 1 and 2) generated by engineering students. Figure 1 shows ideas generated by students who were asked to use Design Heuristics *generatively* (i.e. to spark new ideas). Figure 2 shows ideas generated by students who were asked to use Design Heuristics *transformatively* (i.e. to alter ideas they had previously generated). Both approaches resulted in novel design outcomes.

Each Design Heuristic prompt appears on a 4˝ x 6˝ card. Each card is numbered in the top right corner based on its alphabetical placement among the 77 cards. On the front of the card, a descriptive title and text description give instructions on how to use the heuristic to generate a new idea or to modify an existing idea. An abstract image is included, depicting the heuristic visually. The back of each card shows two examples of existing consumer products: one is always a seating device and the other is of a varied set of consumer products. The inclusion of both product examples shows that each heuristic can be applied to a wide range of products as well as to the same product category, demonstrating each Design Heuristic's breadth and depth of applicability. An example Design Heuristic card is shown in Figure 3.

The complete list of the 77 Design Heuristics is shown in Figure 4, representing the nature and range of heuristic prompts. The strategies are organized alphabetically.

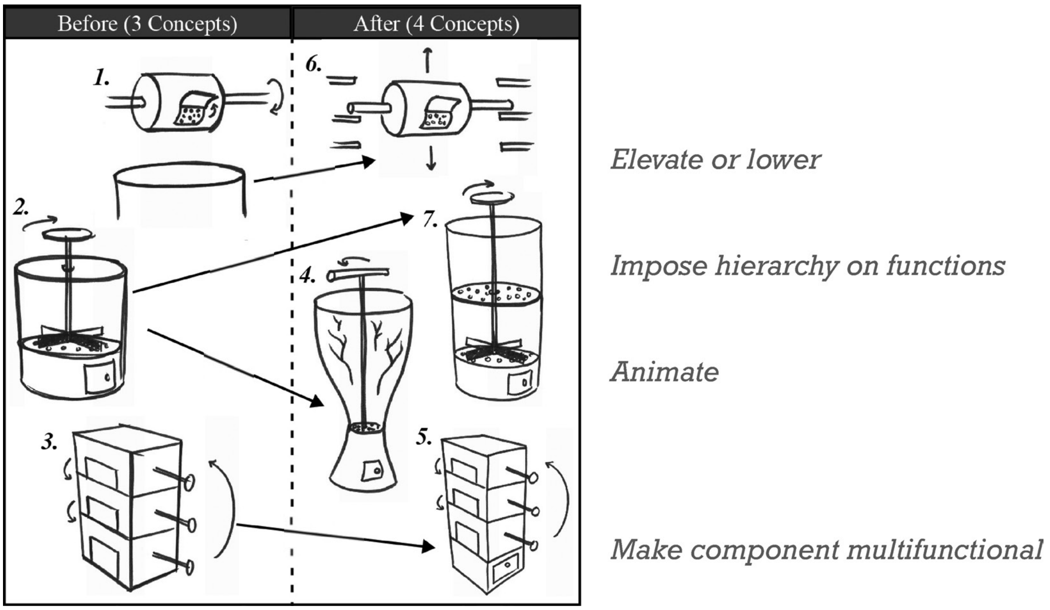



***Figure 2. Examples of four Design Heuristics used to transform concepts during ideation. Here, first-year engineering students were given a set of heuristic cards (after an initial ideation session) for use in designing a composting system. The Design Heuristics used to transform each concept are noted next to the image. [33]***

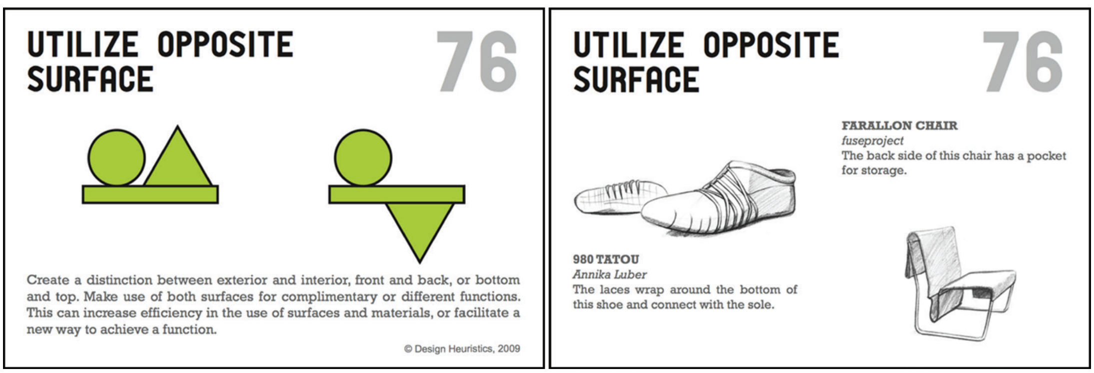



***Figure 3. Design Heuristic card example: Utilize Opposite Surface.***

**Design Heuristics Research**

Design Heuristics have been tested with designers of different levels of expertise and in varying contexts. In a study of first-year engineering students, we introduced Design Heuristics during a ten-minute instructional session, and then asked the students to generate concepts for a given

| | | | |
|---|---|---|---|
| 1 Add levels | 20 Change geometry | 39 Incorporate environment | 58 Scale up or down |
| 2 Add motion | 21 Change product lifetime | 40 Incorporate user input | 59 Separate functions |
| 3 Add natural features | 22 Change surface properties | 41 Layer | 60 Simplify |
| 4 Add to existing product | 23 Compartmentalize | 42 Make components attachable/detachable | 61 Slide |
| 5 Adjust function through movement | 24 Contextualize | 43 Make multifunctional | 62 Stack |
| 6 Adjust functions for specific users | 25 Convert 2-D material to 3-D object | 44 Make product recyclable | 63 Substitute way achieving function |
| 7 Align components around center | 26 Convert for second function | 45 Merge surfaces | 64 Synthesize functions |
| 8 Allow user to assemble | 27 Cover or wrap | 46 Mimic natural mechanisms | 65 Telescope |
| 9 Allow user to customize | 28 Create service | 47 Mirror or array | 66 Twist |
| 10 Allow user to rearrange | 29 Create system | 48 Nest | 67 Unify |
| 11 Allow user to reorient | 30 Divide continuous surface | 49 Offer optional components | 68 Use common base to hold components |
| 12 Animate | 31 Elevate or lower | 50 Provide sensory feedback | 69 Use continuous material |
| 13 Apply existing mechanism in new way | 32 Expand or collapse | 51 Reconfigure | 70 Use different energy source |
| 14 Attach independent functional components | 33 Expose interior | 52 Redefine joints | 71 Use human-generated power |
| 15 Attach product to user | 34 Extend surface | 53 Reduce material | 72 Use multiple components for one function |
| 16 Bend | 35 Flatten | 54 Repeat | 73 Use packaging as functional component |
| 17 Build user community | 36 Fold | 55 Repurpose packaging | 74 Use repurposed or recycled materials |
| 18 Change direction of access | 37 Hollow out | 56 Roll | 75 Utilize inner space |
| 19 Change flexibility | 38 Impose hierarchy on functions | 57 Rotate | 76 Utilize opposite surface |
| | | | 77 Visually distinguish functions |

***Figure 4. The 77 Design Heuristics.***

design task [34, 38]. The analysis of these conceptual solutions showed that concepts using the Design Heuristics were more creative compared to the concepts that did not show any evidence of Design Heuristic use. The concepts generated without Design Heuristics were less developed, and were often either replications of known ideas or minor changes to existing products. In another study of two groups of first-year engineering students, we provided two instructional sessions on Design Heuristics, emphasizing their value as (1) a concept generation technique and (2) a concept transformation technique [33]. Following both sessions, Design Heuristics improved students' concept development and elaboration.

In another study, we asked sophomore industrial design students to ideate using a set of twelve Design Heuristic cards on a presented problem, and the Design Heuristics led to more diverse and creative concepts [35]. We have also investigated the effectiveness of Design Heuristics in ideation for professional designers. A professional engineering team within a manufacturing company [36] worked in small groups to successfully apply Design Heuristics to their existing products. The professionals reported that the cards not only stimulated novel thinking, but also helped them realize new opportunities for their product line. These results demonstrated that novice engineering and design students as well as professionals can successfully learn to use Design Heuristics following a short instructional lesson, and can apply them successfully to support creative and diverse idea generation.

Based on this evidence, Design Heuristics can be a useful tool to assist engineers in generating initial ideas for given problems. Recently, we conducted a more situated study of upper-level student design teams defining their own term projects using Design Heuristics [39]. This study revealed the effectiveness of Design Heuristics across diverse, self-generated problems. In addition, the findings showed that ideas developed with Design Heuristics during initial concept generation were incorporated into the final team prototypes. Based on these findings, we set out to determine how initial ideas change as the team works to their final project completion. The focus of this present study was on how individual ideas generated at the beginning of a project are incorporated into subsequent designs, and how the use of Design Heuristics may assist in this process. We did not address patterns of teamwork or team ideation; instead, we focused on the changes in concepts throughout students' design processes.

This paper presents the results of an empirical study demonstrating how initial ideas were developed in a sophomore level engineering design course, and how these concepts evolved throughout the life of the project. To examine concept evolution, we collected data from the student teams at several points in the term. First, the students in the class were introduced to Design Heuristics early in the semester in an individual concept generation session. Individual student design ideas were collected after this session. Next, students worked in teams to develop their ideas, and information about their progress was collected at two later time points (mid-term and final presentations). The analysis addressed the use of Design Heuristics evident in each team's design process from initial individual ideation to team concept development to final design. We sought to reveal patterns in Design Heuristic use over the team design process. In particular, the pattern of synthesis emerged in our analysis and we continued to explore the presence of synthesis (or lack thereof) of both heuristic-inspired and non-heuristic-inspired concepts in the teams' concept development processes.

## MOTIVATION AND RESEARCH QUESTIONS

The motivation for this study was to investigate how Design Heuristics were used among undergraduate engineering students as they worked through a design process. Our focus was to explore how concepts evolved from individual ideation through team concept development to a completed final design. We were interested in exploring the degree to which individuals in a team adopted Design Heuristics, how the teams synthesized concepts with and without Design Heuristics, and how Design Heuristics might be carried through the design process.

Our project was guided by the following research questions:

1. How do students incorporate heuristics into their initial ideas?
2. How do elements inspired by heuristics manifest in students' later concepts?
3. What patterns are evident in concept development with and without the use of Design Heuristics?

## METHODS

### Participants

Thirty teams in a sophomore-level engineering design course at a large Midwestern university participated in the study. Three teams were excluded from this analysis due to lack of data on their final designs. The twenty-seven student design teams included in the analysis were composed of mechanical engineering students with either three or four members per team, for a total of 105 students.

### Design Project Description

The goal of the course project was to design and build a remote-controlled vehicle to compete in a ball-collecting competition. The game board (Figure 5), constructed specifically for the course, included a tower, a wave field, and two scoring holes. Several ping pong balls, squash balls, and sand-filled squash balls were placed around the game board. The two competing

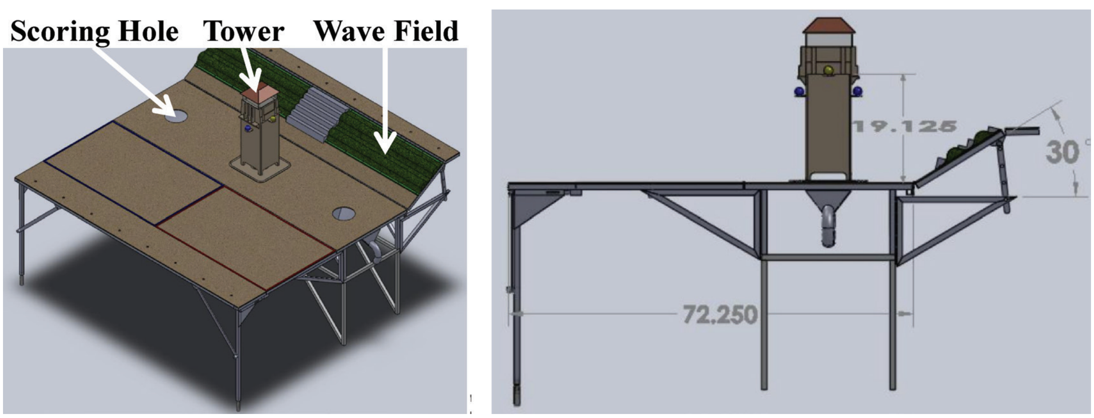



*Figure 5. The game board used in the course competition. Dimensions are in inches and degrees.*

vehicles would each have ninety seconds to collect the largest mass of balls possible. Each team independently defined their strategy for competing in the game, and built their vehicles to meet this strategy.

The machine size was limited to starting dimensions of 18 x 18 x 12 inches. Teams were given stock materials from which to construct their machine (including aluminum, acrylic and Delrin plates, PVC, threaded rod, springs, hinges, gears, fasteners, motors, polypropylene wheels, a ball caster, electrical components, and other assorted building materials), but were also allowed to purchase materials not included in the stock (e.g. extra ball casters).

### Data Collection

We collected samples of the students' coursework at three points during the term:

**Gate 1: Individual Ideation.** Early in the semester, students spent one class session (50 minutes) learning and then applying the Design Heuristics in a concept generation session. In this session, students were given background instruction on ideation and on Design Heuristics. A video that represents the type of training students received is available online, as shown in Figure 6. After working through practice ideation exercises for an unrelated design problem (the design of a seating device), each student was given a set of fifteen Design Heuristics cards. They used these cards to ideate individually on the vehicle design for the game. We collected copies of students' individually–generated, hand-drawn preliminary concept sketches for the vehicle.

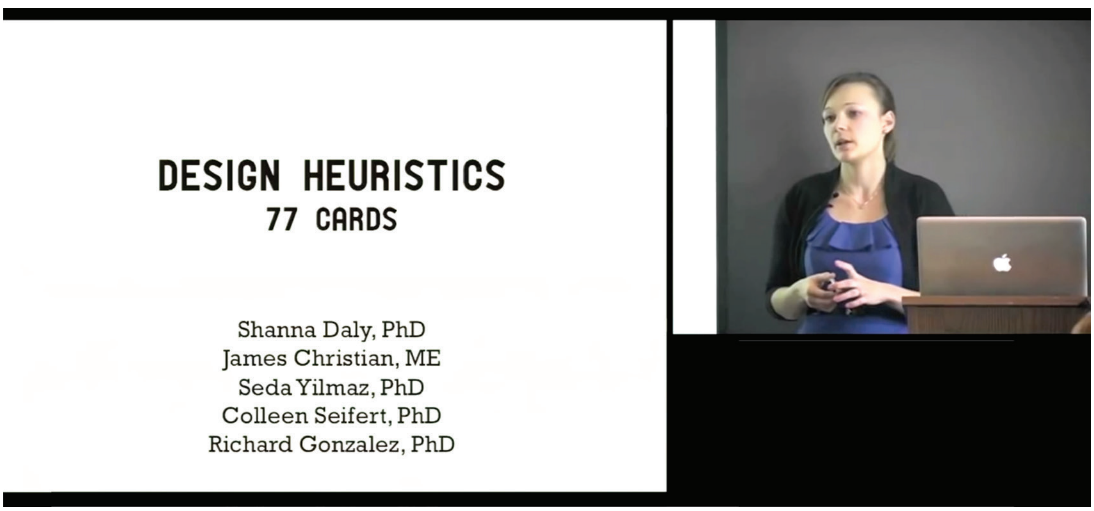



*Figure 6. Video of Design Heuristics instructional session. Available online at: https://www.youtube.com/watch?v=SM8yDD1fAVo&feature=youtu.be*

**Gate 2: Team Concept Selection.** We then collected their subsequent team designs at the mid-term Design Review (week 7). These were represented as sketches with written descriptions, including decision-making matrices (Pugh charts) [40]. We also collected student designs, along with their explanations and justifications for decisions, in the form of oral reports and presentations given in class.

**Gate 3: Final Design Presentation.** These data were collected from the Design Expo held in the final week of the course (week 14). We collected the initial team prototype schematics (hand-drawn sketch and computer-generated solid model), and final team prototype design (physically constructed model, collected in the form of a photograph). We also collected their explanations and justifications for decisions, in the form of oral reports and presentations given in class.

These materials were then assembled into timelines detailing the progression of each team's design process. Figure 7 below shows the phases of data collection.

### Data Analysis

Data analysis included identifying the presence of Design Heuristics, the influence of previous concepts on later concepts, and the patterns in concept development over a period of time. Students indicated their use (or not) of Design Heuristic strategies for each concept they generated during the initial ideation session. From these data, we were able to attribute a particular characteristic or function of a concept to the use of a heuristic, and we determined if this function or characteristic was present or absent in later concepts, as well as in the final physical prototype. This allowed us to determine which concepts were heuristic-inspired. To explore the influence from previous concepts, we documented the common design elements observed across two or more concepts from individual ideation (Gate 1), team concept selection (Gate

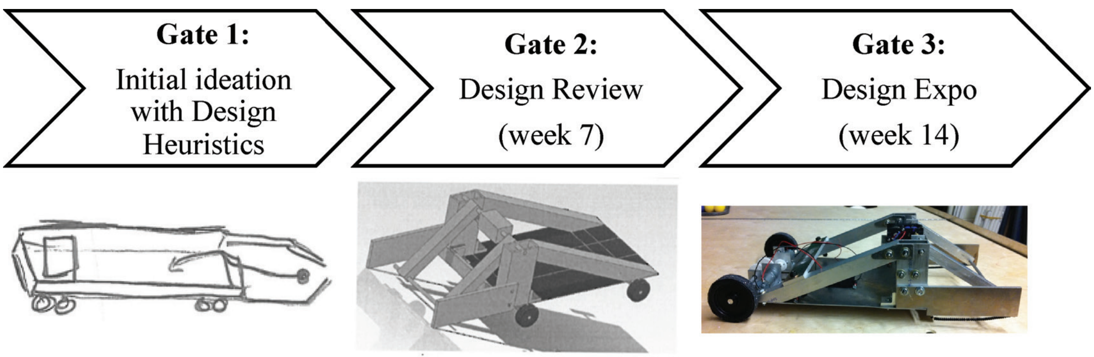
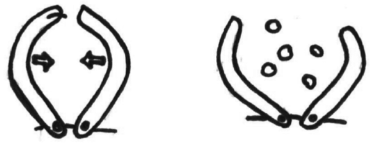
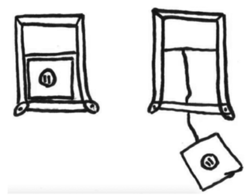



***Figure 7. Diagram of data collection with examples of data (from Team 2) collected.***

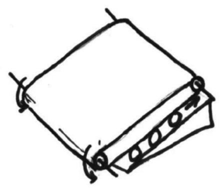
**Note: we have referred to each point of data collection as a "Gate".**



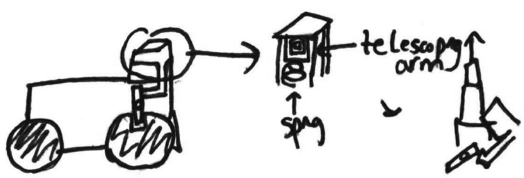
Participant from Team 5
**CLAW**
"Can be used to grip and pull. If large enough, can also collect and gather balls"
No stated use of Design Heuristics



Participant from Team 14
**SPLIT BOT**
"Bot splits in two to accomplish two tasks at once. One bot (larger) collects and deposits balls. The other bot drops into opponent's hole, blocking scoring."
Use of *Nest*



Participant from Team 17
**CONVEYOR**
"This is a conveyor belt pick up system that takes a 2D piece of rubber and transforms it into a 3D belt loop that engages on the balls and collects them"
Use of *Convert 2D material to 3D object*



Participant from Team 22
**THE QUICK ARM**
"The machine starts with its telescoping arm in a compressed state to conserve space. Simply by starting to move the machine, the wheel releases the lock on the telescoping arm on the machine, allowing the spring to extend it very quickly (allows arm without separate motor to extend)"
Use of *Adjust function through movement* and *Telescope*

***Figure 8. Examples of concepts generated during the initial Design Heuristic ideation session.***

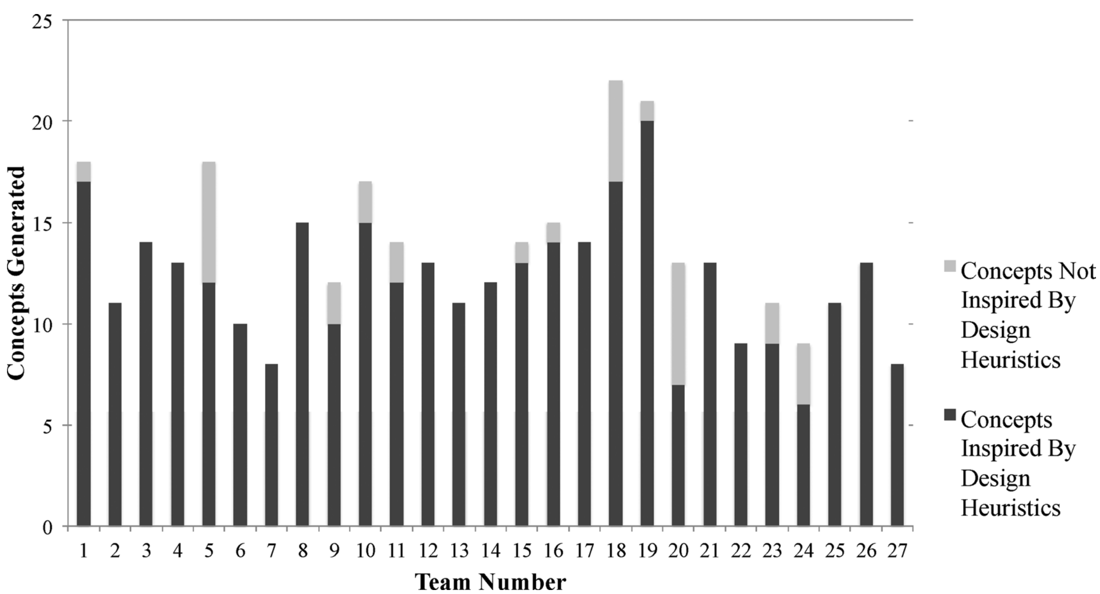
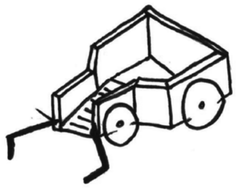
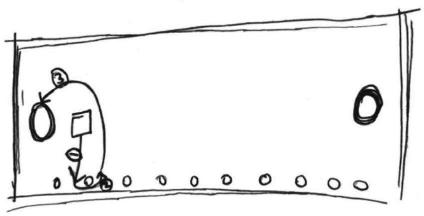



***Figure 9. Design Heuristics present in the individual ideation phase (Gate 1).***

***Create system***

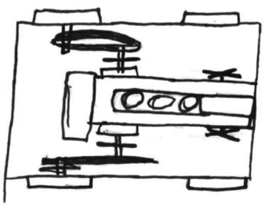


Participant from Team 10
"Uses an arm to collect balls, it can open and close. The balls will be pushed onto a conveyor belt which will put the balls into the back of the machine where they can be held."

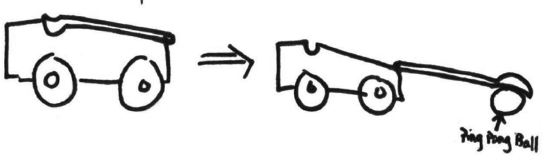


Participant from Team 3
**A PLANNED APPROACH**
"To play the game, the balls have to be pushed into a hole. Hence the system will be to:
1) Collect the balls
2) Drive to the hole
3) Drop off balls"

***Nest***



Participant from Team 6
**NESTED VEHICLE**
"Smaller vehicle inside larger one to go up wave field"




Participant from Team 4
**HIDDEN ARM**
"With the size boundary of our project, I would use nesting to have an extending arm fit into the robot. The arm could grab ping pong balls and drag them. Without nesting, the device would be too big! Also, opponent wouldn't know about arm until the last minute"

***Figure 10. Examples of initial individual concepts generated using the same heuristic cards ("Create system" and "Nest").***

2), and final prototype design (Gate 3). By identifying elements of the designs at each gate and comparing across gates, we were able to document patterns in maintaining, discarding, and synthesizing design elements.

## FINDINGS

### RQ1: Incorporation of Design Heuristics

The 105 participants in the initial individual concept generation in Gate 1 produced 359 different concepts, averaging 3.4 concepts per student (Table 1). Examples of initial individual concepts generated with and without Design Heuristics are shown in Figure 8. These drawings and subsequent figures are enhanced versions of the student-drawn sketches.

Of the 359 concepts generated, 327 (91%) were heuristic-inspired, as reported by the students. 103 students (98%) used Design Heuristics in at least one of their initial concepts. The number of individual concepts generated with and without the Design Heuristics is shown (by team) in Figure 9.

During the initial concept generation, it was apparent that individuals made use of Design Heuristics in a variety of ways. Figure 10 shows examples of individual designs where students employed the same Design Heuristic card, yet came up with very distinct concepts.

**RQ2: Continued Maintenance of Design Heuristics in Later Concepts**

In the team concept selection stage (Gate 2), each team selected three concepts to pursue, and then used a Pugh chart [40] to select one concept to continue to develop. Of the twenty-seven teams, twenty teams selected concepts in Gate 2 from their initial individual concepts that included Design Heuristics (these findings are shown in Table 1), and only two teams (Teams 20 and 23) chose an initial concept with no evidence of Design Heuristic use. The other five teams (Teams 3, 7, 10, 16, and 21) selected concepts that were not clearly related to any of their initial individual concepts, and therefore were likely generated after the initial in-class ideation session.

The five teams that did not base their Gate 2 (team) designs on their Gate 1 (individual) concepts *did* follow their Gate 2 concept choice through to Gate 3. With the exception of Team 3, this meant that these teams (Teams 7, 10, 16, and 21) did not show any evidence of heuristics in their final designs. Team 3, however, synthesized a heuristic-inspired concept from Gate 1 back into their Gate 3 prototype, despite choosing to pursue a concept not inspired by Design Heuristics during Gate 2. None of the teams used the Design Heuristic cards again after the initial ideation session (it was not made available as a resource), so any concepts generated outside of the initial session were not counted as “heuristic-inspired.”

All twenty-seven teams pursued their selected concept from Gate 2 through to the final product phase in Gate 3. In the final design prototype produced for Gate 3, the same twenty teams who chose to pursue an initial individual concept that used Design Heuristics had final designs still showing evidence of Design Heuristics. As previously mentioned, two teams (Teams 20 and 23) carried forward an individually-generated concept from the initial ideation session that was not based on a Design Heuristic, and one team (Team 3) produced a new final design showing evidence of Design Heuristics. Therefore, in total, 78% of final team concepts showed evidence of Design Heuristic use. Table 1 summarizes each team's performance and their use of Design Heuristics with respect to the three design process phases.

Evidence of Design Heuristic use dropped off between the individual phase (Gate 1) and the team concept selection phase (Gate 2). Seven teams chose not to pursue a heuristic-inspired concept during Gate 2: two of these teams chose to pursue a non-heuristic-inspired concept from the initial ideation session (Gate 1) and five of these teams chose to pursue a concept that was not generated during the initial ideation session. Although we did not ask the students to report on this, there are several possible reasons why the teams did not use their heuristic-inspired ideas. The teams may have already had an idea of the machine design they wanted before Gate 1's initial ideation session, leading them to not choose any of the concepts generated during the heuristic session. The teams may have preferred the non-Design Heuristic concepts they generated, or they may not have been satisfied with any of their initial concepts and therefore chose to ideate as a team after the initial session.

**Summary of Findings for RQ1 and RQ2**

Our analysis of initial Design Heuristic use and maintenance of the design elements suggests that design teams found the Design Heuristic cards to be applicable and useful for generating concepts. Evidence of heuristic-driven concepts in all three phases of data collection (Table 1) suggests that heuristics support practical design outcomes. Table 1 shows the behavior of each team in Gates 1, 2, and 3. For example, in Gate 1, students in Team 1 generated eighteen concepts in total, and seventeen of them were generated with the help of Design Heuristics (labeled DH in the table). Looking across Table 1, it is evident that Team 1 maintained DH throughout their entire process; their Gate 2 concept (the concept they chose to further develop) maintained the DH of their Gate 1 concept, and their Gate 3 concept (the concept they chose to prototype) maintained these DH as well.

Over the term, the design teams went through several iterations of creating and developing concepts. At each phase, the majority of teams maintained the heuristic-driven elements of their previous concepts. This finding is especially important because engineering students tend to struggle to pursue a creative idea through the design process,leading to a creative final product [41]. In addition to increased creativity [26], Design Heuristics support practical and useful design outcomes based on the present findings.

The teams each ended up with very different concepts for the same design problem. This demonstrates that Design Heuristics can be applied in a variety of ways, even on the same problem, and lead to a diverse range of solutions.

| | Gate 1: Individual Ideation (many concepts) | | | | Gate 2: Team Concept Selection (one concept) | | Gate 3: Final Prototype (one concept) | |
|---|---|---|---|---|---|---|---|---|
| Team | Total students | Students using DH | Total concepts | Concepts using DH | Based on Gate 1 concept | Showed DH | Based on Gate 2 concept | Showed DH |
| 1 | 4 | 4 | 18 | 17 | Y | Y | Y | Y |
| 2 | 4 | 4 | 11 | 11 | Y | Y | Y | Y |
| 3 | 4 | 4 | 14 | 14 | N | N | Y | Y |
| 4 | 3 | 3 | 13 | 13 | Y | Y | Y | Y |
| 5 | 4 | 4 | 18 | 12 | Y | Y | Y | Y |
| 6 | 4 | 4 | 10 | 10 | Y | Y | Y | Y |
| 7 | 4 | 4 | 8 | 8 | N | N | Y | N |
| 8 | 4 | 4 | 15 | 15 | Y | Y | Y | Y |
| 9 | 4 | 3 | 12 | 10 | Y | Y | Y | Y |
| 10 | 4 | 4 | 17 | 15 | N | N | Y | N |
| 11 | 4 | 4 | 14 | 12 | Y | Y | Y | Y |
| 12 | 4 | 4 | 13 | 13 | Y | Y | Y | Y |
| 13 | 4 | 4 | 11 | 11 | Y | Y | Y | Y |
| 14 | 4 | 4 | 12 | 12 | Y | Y | Y | Y |
| 15 | 4 | 3 | 14 | 13 | Y | Y | Y | Y |
| 16 | 4 | 4 | 15 | 14 | N | N | Y | N |
| 17 | 4 | 4 | 14 | 14 | Y | Y | Y | Y |
| 18 | 4 | 4 | 22 | 17 | Y | Y | Y | Y |
| 19 | 4 | 4 | 21 | 20 | Y | Y | Y | Y |
| 20 | 4 | 4 | 13 | 7 | Y | N | Y | N |
| 21 | 4 | 4 | 13 | 13 | N | N | Y | N |
| 22 | 3 | 3 | 9 | 9 | Y | Y | Y | Y |
| 23 | 4 | 4 | 11 | 9 | Y | N | Y | N |
| 24 | 4 | 4 | 9 | 6 | Y | Y | Y | Y |
| 25 | 4 | 4 | 11 | 11 | Y | Y | Y | Y |
| 26 | 4 | 4 | 13 | 13 | Y | Y | Y | Y |
| 27 | 3 | 3 | 8 | 8 | Y | Y | Y | Y |
| **Total** | 105 | 103 | 359 | 327 | 22 | 20 | 27 | 21 |

***Table 1. Evidence of Design Heuristics (DH) use at three design phases.***

**Note: shaded cells indicate "Yes" or "Y".**

**RQ3: Synthesis (and Lack Thereof) as a Primary Process Pattern**

We investigated how the teams incorporated their initial individual design concepts (Gate 1) – both inspired and not inspired by Design Heuristics – into their team design processes. We also investigated patterns that occurred in their team design processes as they developed later designs for Gates 2 and 3. In our investigation, we noticed three design process patterns. Within their teams, (1) students could simply pool their concepts from Gate 1 and choose one to pursue for further development. Alternatively, (2) the team could generate an entirely new concept to pursue. A third pattern is (3) "synthesis," or the combination of separate elements of different concepts into a single design. Synthesis emerged as a dominant pattern in the teams' design processes. We assessed synthesis at the two different team design phases: the team concept selection phase (Gate 2) and the final prototype phase (Gate 3). We examined the number and diversity of concepts synthesized, and the different ways the teams combined their ideas.

Synthesis of concepts could provide designers with the opportunity to revisit their initial concepts developed using the Design Heuristic cards at Gate 1. It could also give designers the opportunity to combine different parts of their best ideas into one concept. The number of "links" between ideas (i.e. the presence of synthesis) has been found to correlate with a high-quality and creative design process [42]. Of the twenty-seven teams, thirteen showed evidence of synthesis at some point in their design process (either Gate 2 or 3). Twelve teams showed synthesis of their initial, individually generated concepts in Gate 2, and three teams showed evidence of further synthesis in Gate 3. Only two teams synthesized concepts at both Gates 2 and 3 (see Figure 11).

For example, Team 25 (see Figure 12) successfully synthesized several diverse initial concepts. Three individual concepts generated during the initial ideation session were used in further concept development. Concept 1a, using the *Utilize inner space* heuristic card (labeled with a blue circle in the figure), features a vehicle with a hollow bottom that can store balls between the vehicle's wheels. Concept 1b, using the *Reduce material* heuristic card, proposes a hollow vehicle body with a shutter to collect and hold balls. Concept 1c, using both the *Use continuous material* and *Change geometry* heuristic cards, presents a semi-circular vehicle front to aid in ball collection. Elements from Concepts 1a, 1b, and 1c are combined (synthesized) in Concept 2, presented at Gate 2. Concept 2

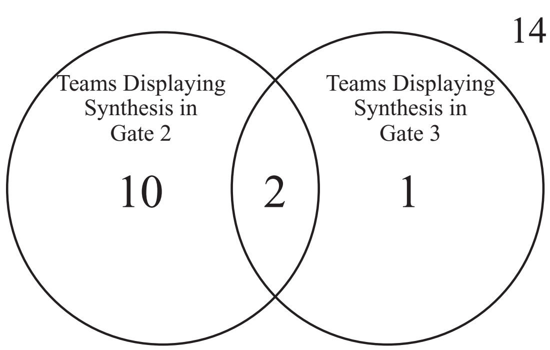



***Figure 11. Team synthesis during each Gate.*** **Note: Fourteen teams did not synthesize at all.**

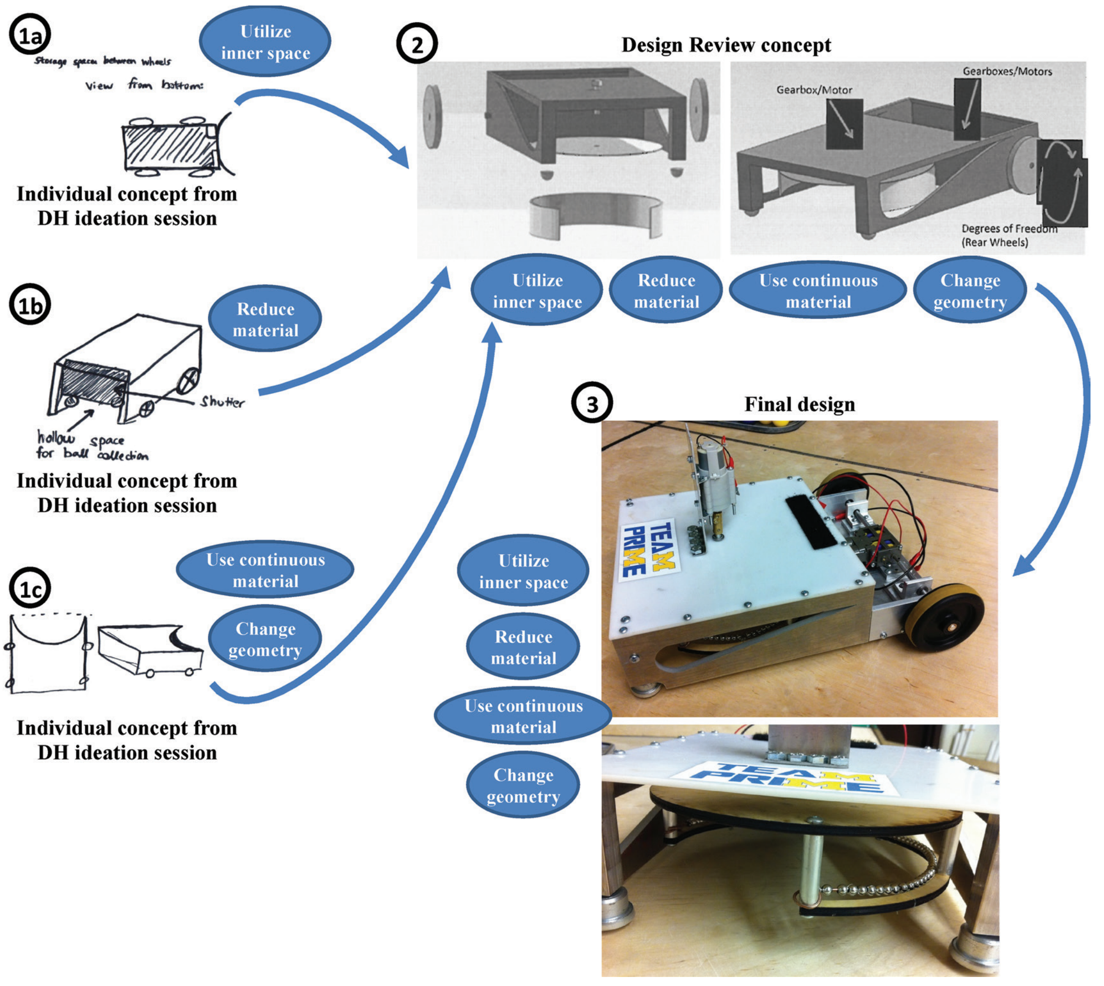



***Figure 12. Team 25's design process shows the synthesis of individual ideas (Gate 1) into resulting team concepts (Gates 2 and 3).***

**Note: Design Heuristics evident in the concepts are indicated within blue circles.**

features a hollow body and rotating semi-circular collection apparatus inside the vehicle's body. This design maintains elements of the four heuristics implemented in the initial concepts. Concept 2 was then built into a prototype and presented at the Design Expoin Gate 3 (Concept 3). Concept 3 also maintains elements of heuristic use originally present in Gate 1.

The other twelve teams who exhibited synthesis in their team design processes (at Gates 2 or 3) did so in different ways. These teams selected a variety of concepts generated during the initial ideation session. Team 1 (see Figure 13) displayed synthesis at two points in their design process. Here, the team generated two initial concepts (Concepts 1a and 1b) that were synthesized into the

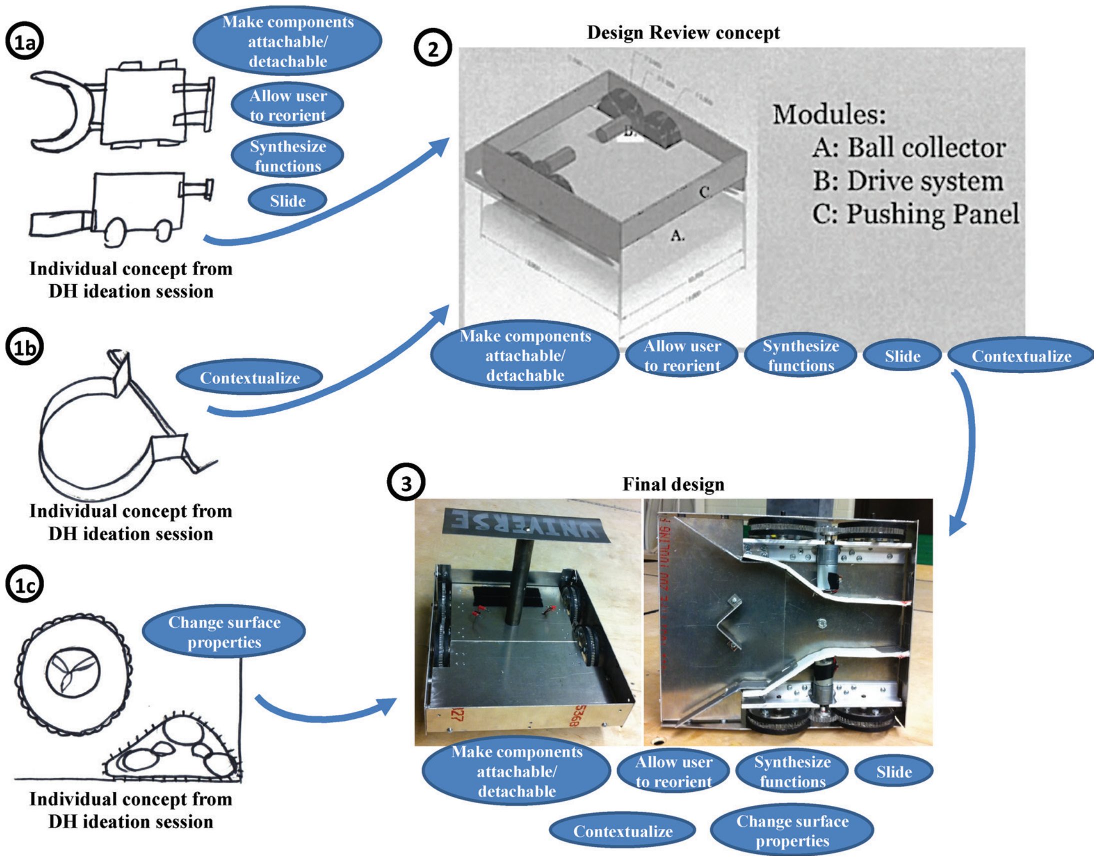



***Figure 13. Team 1's design process shows the synthesis of two individual ideas into a team selected concept at Gate 2, and then further integration of a third independent concept in the final prototype at Gate 3.***

Gate 2 concept (Concept 2). The team then synthesized another initial concept (Concept 1c) into the final design in Gate 3 (Concept 3).

In contrast, nine other teams selected an individual concept from Gate 1 and stayed with it throughout the design process, without synthesizing any of the other initial individual concepts. Two of these teams followed a Gate 1 concept that *was not* inspired by Design Heuristics, while seven teams followed a Gate 1 concept that *was* inspired by Design Heuristics. For example, Team 12 (see Figure 14) did not display any evidence of synthesis in their design process, and instead, their Gate 2 concept (Concept 2) was based on just one of their heuristic-inspired initial, individually-generated concepts (Concept 1). No other concepts were synthesized into the design, and therefore the final design presented in Gate 3 (Concept 3) was very similar to the individual idea presented initially as Concept 1.

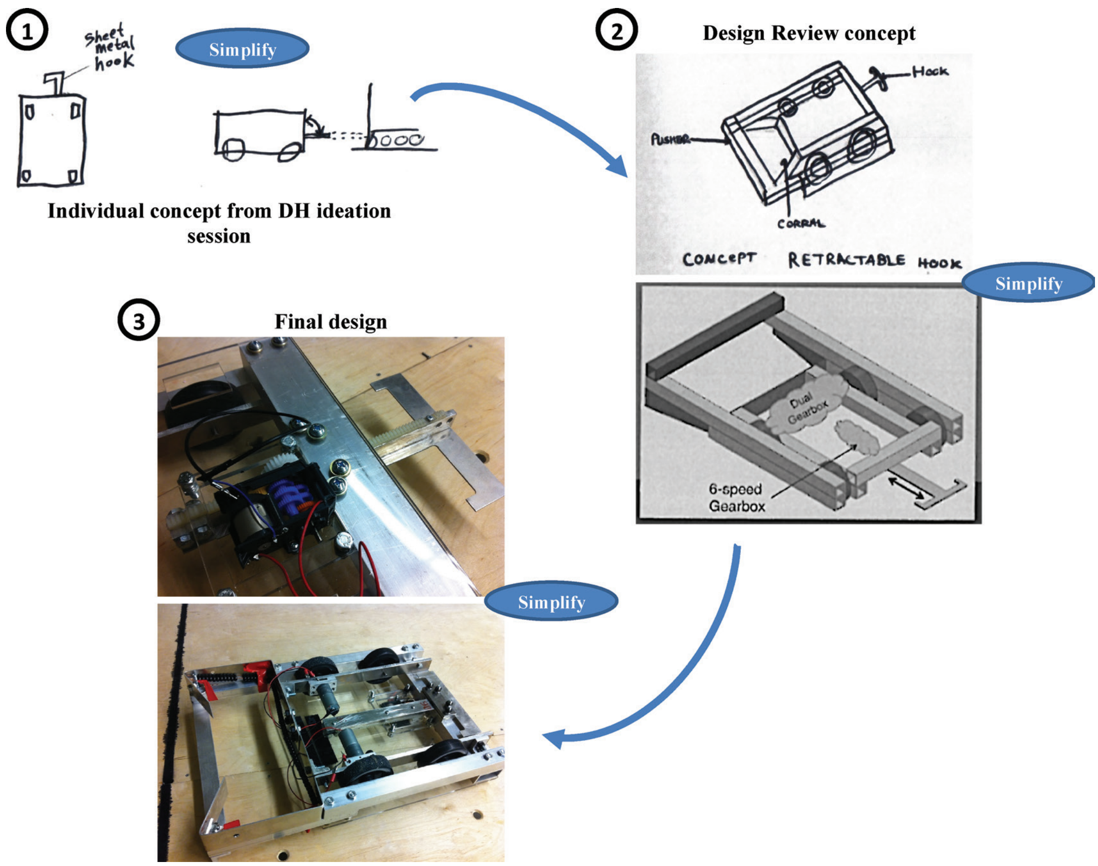



***Figure 14. Team 12's design process shows a single initial concept re-enacted in the team's selected concept in Gate 2, and in the final prototype (Gate 3).***

Finally, five teams created an entirely new concept presented at Gate 2, which could not be linked to any of the team members' initial concepts. It seems these teams chose to abandon their initial ideas and to create a new concept to develop.

In summarizing our findings, we did not attempt to evaluate the quality of designs; rather, we examined evidence to learn about how teams reconsidered the initial, individual concepts proposed when they converged on a single team design by Gate 2. It is clear that not all teams developed their concepts in the same way. Some simply chose among the initial concepts, but almost half of the teams synthesized multiple concepts into their designs at the team concept selection stage (Gate 2), and a few continued to synthesize new concepts into their designs in the final prototype phase (Gate 3). Some teams synthesized more, and more diverse, concepts than other teams. Thirteen teams exhibited synthesis in their design process. Of the twelve teams who synthesized individual concepts in Gate 2, nine combined two different individual concepts, and three combined three different individual concepts. Of the three teams who synthesized individual concepts with team concepts in Gate 3, all three combined two concepts (the team concept from Gate 2 plus one initial, individual concept). This suggests variation in the teams' approaches to synthesizing individual concepts. Because a large number of teams (fourteen) performed no synthesis of any concepts, they may have preferred a simpler "winner takes all" strategy [43] for concept selection, or an abandonment of individual concepts in favor of a team-generated concept. However, neither one of these approaches facilitates iteration, which is imperative in successful design practice.

These observed process patterns appeared to be independent of how the initial concepts were created. In this study, most teams either synthesized aspects inspired by Design Heuristics or maintained a single concept inspired by Design Heuristics. For teams who synthesized, the design characteristics inspired by Design Heuristics were often maintained, suggesting that students saw value in that particular element and found ways to incorporate that characteristic in the next-version concept. Teams who did not synthesize carried one concept throughout their design process, so they did not have to decide if the heuristic-inspired element was worth maintaining in a new concept. Design Heuristic use assisted students in generating a large quantity of diverse ideas for team consideration, but had no influence in teams' recognition that desirable features across multiple concepts could later be synthesized into a better concept.

## DISCUSSION

The findings show that the engineering student participants were successful in learning and applying Design Heuristics to generate a variety of different concepts within a single session. The vast majority of students created designs using the Design Heuristics, and a large majority of groups built prototypes that were inspired by Design Heuristics. It appears that the Design Heuristics successfully aid students in generating a variety of concepts students considered useful to their team projects.

This study complements the validation studies previously conducted for Design Heuristics [33, 35, 36, 38]. While previous work has documented the diversity and creativity of ideas inspired by Design Heuristics during early ideation [29, 33, 34, 35, 38], a goal of this study was to explore the influence of ideas generated using the heuristics on later team concept development. As ideation is a design phase where evaluation is to be avoided, we measured practicality by determining whether or not heuristic-inspired elements were included in a final built design. However, Design Heuristics may also contribute to creative and practical final design outcomes in a non-linear way (i.e. the cards serve as a tool to get ideas flowing or the ideas developed with heuristics become a foundation for multiple transformations where the original heuristic is no longer present or evident). This study reveals the more obvious inclusions of heuristic elements in final designs, as these inclusions are easier to trace and demonstrate. In this study, a large majority of the design teams displayed evidence of Design Heuristics in their final design deliverables, demonstrating that engineering student design teams can use Design Heuristics effectively in initial ideation and that this generation phase impacted the subsequent stages of team concept development.

In team design processes, “my idea” is often replaced by “our idea,” and this transition may occur in a variety of patterns. In some cases, teams considered the individual ideas generated, and then voted for a single concept to pursue in a “winner takes all” model. It is also possible for individually-generated concepts to be completely abandoned in favor a new, team-generated concept. A third possibility is that teams may combine individual designs, creating a synthesis of design elements from individuals’ concepts. By collecting data on designs generated (1) initially, (2) mid-term at the team selection point, and (3) in the final prototype stage, we found that the almost half of the teams synthesized ideas during their design process.

All of the teams who used synthesis in their design processes also selected concepts generated with Design Heuristics, and maintained the essence of the original Design Heuristic-based concepts in their synthesis. The findings show that Design Heuristics were helpful in initial ideation, and also at later stages throughout the concept development process. Further work is needed to investigate the link between Design Heuristics and team concept development.

### Pedagogical Implications

The findings suggest several implications. Design teams may feel pressure to converge on their concepts too soon, leading to a narrowed search of the solution space. To combat this, instructors may find better design outcomes by encouraging and holding students accountable for multiple divergent explorations [50] that lead to the exploration of a wider variety of ideas. For example, the instructor could encourage this by requiring teams to develop a large number of diverse ideas before converging, synthesizing, or selecting. Additionally, at early design reviews (Gate 2, in this course), instructors could require students to develop a few more ideas based on the feedback received. In some courses, like the one featured in this study, a core pillar of the curriculum is to keep feasibility in mind, and to prototype a product in a semester-long course. This goal can feel in competition with solution exploration and the ideation phase “rule” to avoid early evaluation [9]. Instructors may consider alternative early stage design deliverables to facilitate broader consideration of ideas without sacrificing practical outcomes. Additionally, it is the combination of courses in one’s undergraduate experience that shapes their design skills. A single course may not emphasize solution space exploration and creativity, while another course may focus more on these topics and associated strategies. It is important for instructors to align their expectations of student designs with course pedagogy and assessments.

Design teams may also benefit from instructions about how to synthesize ideas. Instruction for student teams could discuss how to compose a solution incorporating the best features of several concepts rather than simply selecting the best of the individual designs. Without synthesis across team members' concepts, the power of the group may be diluted to that of the best performing individual [44, 45, 46]. Additionally, concept synthesis is a skill individual designers must leverage in their own work, pulling together the best features of multiple ideas into a stronger one. Synthesis provides an opportunity to iterate and build on original concepts [47], and added connections or links among ideas have been shown to result in more creative and successful design outcomes [42]. Students struggle to transform their concepts, and many of the teams in the study carried one initial idea all the way through to the final design. Encouraging students to synthesize concepts could positively impact the quality of design outcomes.

A final implication is that having design teams reconsider the Design Heuristics as they progress further in the design process could facilitate concept development. By continuing to use the Design Heuristic cards, a design team may be more likely to allow their concepts to evolve and transform. Design Heuristics used at several stages in the design process may help students iterate, combating the fixation observed in novice designers [10]. Encouraging design teams to use Design Heuristics in the later design stages may improve the quality of the final outcomes and result in more successful designs.

### Limitations and Future Work

Our analysis did not consider the relative success of each team in the design competition, nor did it attempt to assess the quality of designs. Additionally, individual students used the Design Heuristics for ideation but did not use the tool for their team ideation processes. The data collection was limited to three points in the design process, and other team interactions about the concepts occurred but were not collected. Further concept generation may have followed the initial ideation session, along with intra- and inter-team interactions that may have influenced each team's process. The study was also limited to one instructional protocol for Design Heuristics and one design problem in the course, limiting the ability to draw conclusions about its effectiveness. Importantly, the Design Heuristics tool was only available to students in the initial ideation session at Gate 1. Future work may extend the use of Design Heuristics to other design problems, courses, and assignment structures, and also facilitate multiple engagements with the Design Heuristics tool throughout the team design process.

## CONCLUSIONS

This study contributes greater understanding of how novice mechanical engineering design teams develop ideas following an initial Design Heuristics ideation session. The results show that

Design Heuristics support successful individual ideation, as initial ideas developed with the Design Heuristics were often incorporated into final team selections and built designs. About half of the teams took a straightforward approach to team concept development. These teams either employed a "winner takes all" approach, which may limit the success of their design outcomes by relying on the best individual concept, or they abandoned their initial individually-generated concepts in favor of a new team-generated concept, which may limit the success of their design outcomes by taking away an opportunity for concept development. The other half of the teams attempted to synthesize concepts to create new designs combining the best features from individual concepts. This suggests that even when initial ideation is successful, student teams need more instructional support about concept development throughout the design process in order to build the skills necessary to develop and synthesize their ideas. Future work will seek to explore how Design Heuristics can be integrated into later phases of the design process for individuals and teams.

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