Design Heuristics as a Tool to Improve Innovation

Abstract

A recent National Academy of Engineering report stated, "To capitalize on opportunities created by scientific discoveries, the nation must have engineers who can invent new products and services, create new industries and jobs, and generate new wealth"[1]. With increased international competition, economic uncertainty, and environmental resource limitations, there is a need for trained engineers who can examine problems from different perspectives and produce innovative and practical solutions. Most engineering students, however, find creative thinking to be much more difficult than technical thinking, and may struggle to generate novel concepts. A contributing factor is the limitations in existing pedagogy on idea generation within engineering.

This paper describes research investigating the role of *Design Heuristics*, a concept generation tool used during the design ideation process to support engineers in generating multiple, diverse concepts. *Design Heuristics* have been successfully tested in engineering classrooms, and have been readily adopted by students to help them create more, more creative, and more diverse concepts. This research brings evidence, methods, and perspectives from multiple disciplines, including cognitive and social psychology, to bear on the problem of innovation in engineering design.

Introduction

In order to face the Grand Challenges in Engineering of the 21st Century[2, 3], the engineering workforce must be educated about how to accomplish innovation in design. Creative thinking during concept generation has been identified as the source of successful innovations[4, 5]; thus, techniques to support creative conceptual design are imperative in engineering education. However, teaching students to "think innovatively" has been difficult for many educators, because of a lack of effective instructional methods[6-8]. Engineering education now emphasizes project-based courses[9]; however, open-ended projects alone do not provide instruction on *how* to generate innovative concepts. In many cases, instructors encourage students to "brainstorm" to generate ideas[10], but this does not provide students with specific, systematic ways to create designs.

Innovative outcomes are often traced to concept generation, where diverse creative ideas are developed, evaluated and pursued[4, 5]. More and more varied initial ideas increase the likelihood of more innovative solutions. However, fixation often occurs when the designer sees an example of an existing solution, and then tries to create a product with similar features to the example[11-14]. For example, Ball et al.[15] found that instead of spending time and effort in searching for better alternative solutions, designers continued to address the flaws in their initially chosen design concepts. Jannson and Smith[11] observed designers replicating similar solutions to the ones that were provided to them initially, and even including the flaws pointed out by the researchers.

There are a variety of idea generation tools available, even though they are not frequently taught in engineering. *TRIZ*[16, 17] and *ASIT*[18] are based on transforming ideas through strategies derived from patents in engineering; however, these methods rely on the identification of contradictions in well-developed design concepts; thus, this method may not support the early stages of concept generation. Other transformation methods include *Lateral Thinking*[19], *Conceptual Combination*[20], and *SCAMPER*[21], which offer general suggestions for changing designs, such as, "substitute" or "combine." For stimulating the formation of an idea, *Analogical Thinking*[20, 22-25], *Morphological Analysis*[26, 27], and *Synectics*[28] are proposed. Evidence has supported the use of analogical thinking to improve engineers' designs, but is highly dependent on individuals' past knowledge and experience and the relevance of the artifact used for stimulation[29]. *Brainstorming*[10] and *Brainwriting*[30] are used for facilitating the flow of ideas in teams, but research shows them to be helpful in some cases[31, 32] but limiting in others[33, 34], referred to as 'group process loss'[35]. These ideation methods vary in their specificity, focus and usability within the design process. However, none of these methods have been grounded in studies of designers, and few have been tested in multiple experimental studies to validate their utility.

Only one idea generation method has been systematically derived from engineering designers and empirically validated in scientific studies: *Design Heuristics*. Design Heuristics are "cognitive shortcuts" that help designers explore variations in designs. They were developed through protocol studies with expert industrial designers and engineers, and through analyses of innovative product designs[36-39]. Additional studies verified their use by advanced student and expert engineers[40-42]. The resulting 77 distinct Design Heuristics are now packaged as easy-to-use prompts that guide the generation of new concepts. Each Design Heuristic can be used to initiate new concepts or transform existing ones in multiple ways. They provide specific methods that can be applied to any product design problem to produce multiple, diverse, and creative concepts[43]. In empirical studies, Design Heuristics have been successfully tested in engineering and design classrooms, and have been readily adopted by students in creating more, more diverse and more creative concepts[44, 45]. This paper reports on the development of the Design Heuristics, and illustrating our systematic research path.

In psychology, a heuristic is defined as a simple, efficient rule used to generate a judgment or decision, especially for complex problems[46]. Kahneman et al.[47] discovered heuristics in human decision makers, as people rely on simplified heuristics while judging under uncertainty. Heuristics provide readily accessible information to guide problem solving[48] and serve to identify and explore relevant problem aspects, assumptions, questions, or solutions strategies[49]. However, they do not guarantee one determinate solution, as in the case of an algorithm; rather, they lead to "best guesses," resulting in quick and easy outcomes based on past experiences[50, 51].

'Heuristic' is a term used in other domains; for example, Moustakas[52] described a heuristic methodology as a systematic form of qualitative research, Ulrich[49] proposed heuristics used in system evaluation, Riel[53] identified heuristics for computer scientists, Koen[54] described the engineering method through the heuristics he observed, and Nielsen[55] used heuristic evaluation as a usability-testing technique. These definitions share the identification of strategies that are based on past experience in a domain that lead to quick solutions, but not necessarily "correct" ones.

With Design Heuristics, we use the term to capture the "quick and dirty" insights of designers based on their experiences with varied designs. We propose these Design Heuristics can be useful as cognitive "prompts" to encourage the exploration of possible design solutions during concept generation[39, 43, 56, 57]. They are intended to help designers move through a “space” of possible solutions, helping designers to intentionally introduce variations within their designs so as to generate non-obvious ideas that are also different from one other. They are also likely to support designers in becoming “unstuck” or removing fixation when they have worked on a task for a long time, and are struggling to generate more, and different, ideas. Design Heuristics can be applied repeatedly, and in combination, to produce a variety of novel and original design ideas. As a tool, Design Heuristics can help a designer generate multiple creative and diverse ideas so that they will have explored the full space of potential designs.

Research Questions

Questions that guided our work on this project included: What strategies guide successful engineers in generating novel products? How do heuristics impact the quality of design solutions? And, how does heuristic use differ among designers from different disciplines?

Design Heuristics were derived from three empirical studies: (1) Analyses of over 400 award-winning product concepts, (2) a case study of a long-term project including over 200 concepts by a professional designer, and (3) 48 “think aloud” experimental sessions with design students and experts creating novel concepts. For each of these studies, our main objective was to look for evidence of heuristic use. In additional studies, we investigated how experts and novice differed in their use of heuristics, and how heuristics are applied in different design domains. We summarize our key extraction studies below.

Studies to Identify Design Heuristics

Our studies, summarized in Figure 1, accumulated evidence for the use of Design Heuristics in innovative designs. We began with a detailed investigation of approximately 400 award-winning product concepts. For each concept, the major design elements and key features were examined for functionality, form, and user-interaction features and specific heuristics were extracted. Each heuristic was described so as to capture a guideline for how to create a concept in terms that could be applied to different design problems. This “extraction” process (described more fully below) resulted in the identification of forty Design Heuristics[38].

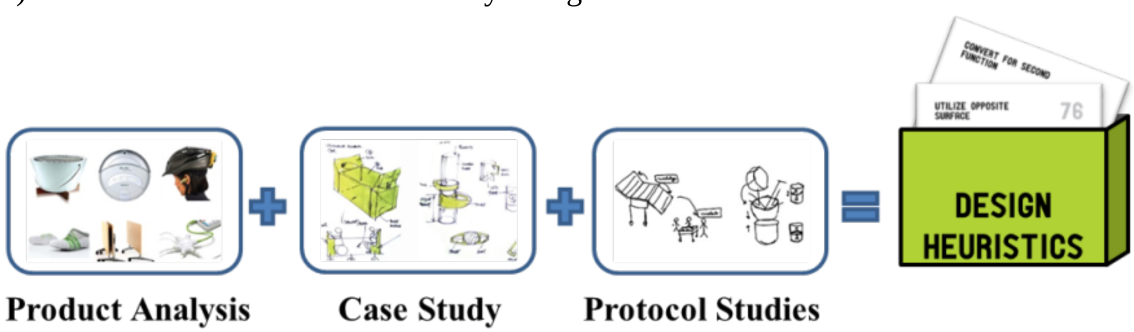

Figure 1. The schema of the studies

In a second study, over 200 concepts created sequentially by a single, very experienced professional designer over a two year period were analyzed. The design problem was to create a universal access bathroom to be installed in private homes. By examining the transitions between concepts in the sequence of creation, we were able to identify specific heuristics that captured the ways some concepts were changed[39, 58]. Across this set of designs, we observed specific Design Heuristics that appeared repeatedly in this designer's work. In sum, over thirty new Design Heuristics were identified.

In a third set of studies, a "think aloud" protocol was used. A novel problem was given to both student and expert engineers: To design a solar oven for use in a rural setting. We explored how these 48 engineers generated and transformed their concepts during this novel concept generation task[59]. Their protocols and design concepts were then systematically coded for the presence of possible heuristics, resulting in evidence for 60 different Design Heuristics.

Compiling evidence from all three of our studies resulted in the identification of 77 distinct Design Heuristics. Each heuristic was observed in use multiple times, was used by several independent engineers, and was observed across these multiple design problem contexts. Table 1 summarizes the research questions, data collection and outcomes of our Design Heuristic identification studies. Next, we describe each of the three studies in more detail in order to explain how heuristics were identified from the evidence collected in each.

Table 1. Design Heuristics Identification Studies

	Research Question	**Data Collection**	**Results**
Study 1. Product Analysis	What are the strategies that successful engineers use to generate a novel product?	400 award-winning products from a diverse range of design domains	40 Design Heuristics were extracted following the development of a heuristic extraction method
Study 2. Case Study	Are heuristics involved in creating multiple, varied designs? How do heuristics impact the quality of design solutions?	218 concepts developed by an expert designer over two years for a single design project	34 additional Design Heuristics were extracted using the same method. Application of multiple heuristics was observed. The creativity of concepts was found to be related to the number of heuristics used.
Study 3. Protocol Analysis	How does heuristic application differ among designers from differing disciplines and levels of expertise?	36 engineers and 12 industrial designers at various levels of expertise talk aloud while designing concepts for a novel problem	The number of heuristics used by designers from both domains was similar, though the way they approached the design problem varied. Both experts and novices showed heuristic use in their protocols.

Study 1 – Product Analysis

Method: Identifying innovations in product design

We identified designs through existing, independent award competitions and published compendiums of well-known, successful products (e.g., Red Dot Design Awards, books on design such as Design Secrets: Products by IDSA). The information available about each product included product descriptions, design criteria, constraints, scenarios, and sometimes critiques provided by professional designers.

From these sources, we narrowed the designs to include based on the following selection criteria: the product was (1) easy to understand through reading its description, (2) designed for the consumer market, (3) available in the marketplace, and (4) innovative in both its functionality and its interaction with the user. This left us with 400 products for a detailed investigation. Major elements and key features of the products were identified for functionality, form, user-interaction, and physical state. We then performed a content analysis of the needs, design criteria, and the design solution. After the products were analyzed, the ones with the same design features were grouped and compared in order to explore the commonalities.

Analysis: Extracting Design Heuristics

For the extraction of the heuristics, we followed a process for each of the products that were in our original list. We started with randomly selecting one the products, defined functions and key features we recognized in the design, hypothesized potential heuristics, identified design criteria associated with it, selected other products that share the same criteria, and finally, confirmed the hypothesized heuristics by comparing the heuristic applications among all of the products.

Clearly, subjective interpretation is necessary to derive a potential heuristic from the description of a finished product. The data provided included no intermediate steps, competing concepts considered, or process trace of the designer's work. It is also possible that the designer may not agree with our characterization of the derived heuristic. However, the success of this extraction approach is determined by whether the proposed heuristic is observed in other product designs, and whether it appears to offer a strategy that can be successfully applied to create novel designs.

Results: Defining Design Heuristics

The analysis of the 400 products resulted in the observation of 40 different heuristics; some heuristic strategies add functionality, suggest use of fewer resources, save space, provide ideas about visual consistency, and form relationships among the design elements. These more specific heuristics go beyond simple transformations to identify why a particular one might be advantageous. Below are two examples demonstrating the extraction of heuristics from the set of innovative products in the study:

Figure 2a & 2b. Example designs for Design Heuristic: *Use packaging as a functional component within the product*

Heuristic Example 1. *Use packaging as a functional component within the product.*
In Figure 2a, a set of colored pencils is located inside a package that also serves as a stand during use. In Figure 2b, the lighting unit is packed in a way that it is enclosed inside a wrapped form made out of the same material. When opened, the package supports the structure, and functions as a necessary shade component rather than a separate, unused feature. The packaging was embedded within the product, where the packaging performs a different function, such as creating a shell or covering for a component or the entire product.

Figure 3a & 3b. Example designs for Design Heuristic: *Hide / Collapse / Flatten design elements not in use using by nesting*

Heuristic Example 2. *Hide / Collapse / Flatten design elements not in use using by nesting.*
In Figure 3a, the earphone cable is kept inside of the cable management accessory when not in use. In Figure 3b, the different sized bowls and accessories are nested inside each other for compactness and saving storage space when they are not in use. An object was placed inside another object entirely or partially, wherein the internal geometry of the containing object is similar to the external geometry of the contained object.

Each of the forty identified heuristics[38] was observed in at least four different products of over 400 in the database. In some of the products, multiple heuristics were observed. The results of the product design analysis demonstrated a methodology for identifying design heuristics in existing products. The process also included comparing multiple applications of individual heuristics in order to identify key components. The outcome of the analysis was a set of 40 heuristics that were used as a starting place for our other studies as well as one data source for our final triangulation of data to determine our final list of heuristics.

Study 2 – Case Study: An expert designer's design process

Method: Examining a longitudinal project on a single design problem

In order to triangulate with our initial set of 40 design heuristics, we decided to analyze another data point: A sample work from a single expert industrial designer, a sixty-year old male. This designer has established a long and distinguished record for highly successful and innovative product designs, and taught a variety of design courses (including project-based studio courses) in a university industrial design program for over thirty years.

The design project selected for this study involved developing a home bathroom for elderly people and their caregivers. An additional focus was a modular approach, with the goal of planning a self-contained product to be placed as a whole into existing homes. Key issues identified for the design problem were overall configuration, lighting, visual and audible cues, storage, safety, modularity, patient transfer, and maintenance. The designer worked on the project over a period of approximately two years. He worked using a paper scroll to keep a record of each design concept as the work progressed, providing a serial record of the progression of designs generated.

Analysis: Extracting Design Heuristics

For the content analysis, two hundred and eighteen separate concept sketches were included on the scroll. By examining the first fifty concepts, a set of potential heuristics[58], was generated. Whenever a change in concepts was identified, a heuristic describing the change was labeled. Each heuristic identified included a specific change to the concept that added variation to the previous concept. For example, one heuristic addressed a change in how the functions of the product were controlled. This strategy was then considered for how it may play a role in other designs, and a more general description created, such as, *Adjust / Control functions by moving the product's parts*. Each heuristic was described so as to be (1) readily observable as a new element within a given concept, and (2) applicable to many different design concepts. For example, the heuristic, *Use a common element for a variety of functions*, encourages the strategy of holding an element constant while attempting to incorporate additional functions. A total of 21 heuristics were devised from the first fifty concepts. Six of the heuristics were pretested in a study with novice designers[56], and found to be easy to apply within a new design problem.

Next, two independent coders, both design professionals with master's degrees in art and design, conducted an examination of the first fifty concepts on the scroll in an order. The coders were uninformed about the nature of the study and its hypotheses. First, the coders were verbally instructed about each heuristic, and written descriptions were provided for review as needed. Copies of the sketches were provided, sequentially ordered, and each sketch was numbered. The coders were asked to identify which, if any, of the 21 proposed heuristics appeared in the transition from one concept to the next, or in changes depicted within a concept drawing. The visual data analysis started with identifying the changes among the sequence of concepts using the form, labels, and context provided in the sketches. Each concept design was coded for new elements, focusing on aspects of the form (i.e., change the configuration, reverse, repeat, etc.)

and aspects of more specific, context-oriented functions (i.e., changing how the user physically interacts with the system, adjustability according to different users' needs, etc.).

Each drawing received a score on each of the heuristics to determine how frequently the heuristics were observed, and how consistently the set of heuristics could be applied to the sketches. The agreement between the two coders (the percent of the observations where both coders positively scored a given sketch as containing a specific heuristic, or inter-rater reliability) was 91% overall.

Results: Defining Design Heuristics

The analysis of the designer's concepts on this project resulted in a total of 21 new heuristics. The set of 40 design heuristics from the initial Product Analysis study[38] were added to the coding scheme. This merged set of heuristics was used to code the entire set of 218 separate concepts. The goal of this analysis was to identify the patterns of heuristic use in the sequential concepts generated while using an extended set of possible heuristics. Once the final set of heuristics had been identified through the analysis, a second pass through each of the concepts ensured that each discovered heuristic had been identified in the overall set of 218 concepts.

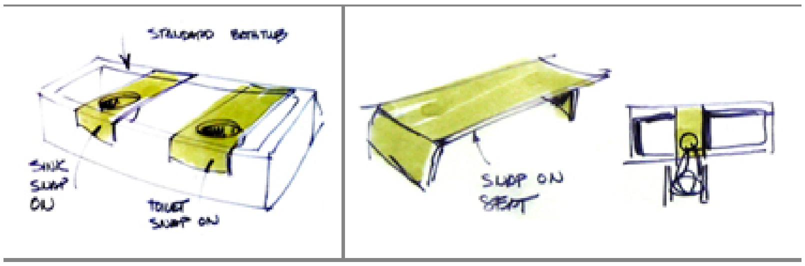

Figure 4a and 4b. Examples using the Design Heuristic *Add-on, take out, or fold away components when not in use*

To illustrate, several examples of the concept sketches are provided from the designer's scroll, followed by the narrative the designer provided in the retrospective interview, and a description of how the cognitive heuristics appear within each sketch. In a series of concept sketches, the designer explored components for a bathroom that could be added on when needed, and taken out when not needed. The labels on Figure 4a and Figure 4b indicate that the components for both the sink and toilet functions could be the same modules, and they could be snapped onto a standard tub. Using the heuristic, *Add-on, take out or fold away components when not in use*, the designer minimized the need for new materials, and created a system that integrated existing products (the tub) with the newly defined elements.

While the designer commented on portability, he identified his concern about using already existing products as a key requirement in the design problem: "… more homes in the world have existing bathtubs than have an open room. I was inventing a new toilet and but then I got practical and said you know, wait a minute, while it's fun and nice, everyone else already has a tub. So can I do some of that this way adding onto an existing tub?"

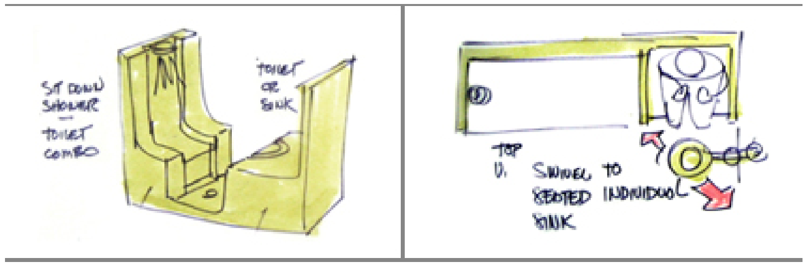

Figure 5a & 5b. Examples using the Design Heuristic *Change how the user physically interacts with the system*

In another sketch sequence, the expert seemed to focus on user interaction with the design elements, an important criterion given the physical needs of the potential users. Using the heuristic, *Change how the user physically interacts with the system as a heuristic*, the designer appeared to explore new ways of approaching elements and defining how users interact with them. Whereas Figure 5a shows stable, mounted features, the next concept (Figure 5b) indicates a swiveling motion for the seating unit, which entirely changes how the product can be used. This change in how the user accesses the elements moves the possible designs in a new direction. In the retrospective interview, the designer commented on this change as: "… shower, toilet, it is one piece; one piece molded and put in place. But then I'm thinking about swiveling."

In sum, Design Heuristics were identified 1753 times in the 218 different concepts on the scroll. This case study demonstrated that design heuristics do occur, in great numbers, in the work of an expert industrial designer. The frequent occurrence of these heuristics within the design concepts, and in the transitions among the concepts, suggested that they might be a key component of the development of expertise in design ideation. Of these, the majority (66%) were identified through the concept analysis in this study, with 1291 instances of heuristics identified from the analysis of the expert's concepts. The additional 34 heuristics from the product analysis were counted 596 times, or 34% of the observations. This shows that the heuristics derived from the independent product analysis were also frequently observed in this very different data set consisting of multiple concepts within the same design task from a single expert designer. In fact, four heuristics derived from the product design set ranked in third, fifth, sixth, and eighth in frequency of use.

This analysis of Design Heuristics provided a specific description of how design elements were changed, suggested which combinations of heuristics were important to the design process, and revealed the process of incremental vs. major changes across concept sketches. These data combined with the first study were taken to the third stage of our extraction process, where we investigated idea generation in a third way to be sure these heuristics would hold true by looking at the process of designing and considering another context.

Study 3 – Protocol Studies

Method: Observing protocols as designers worked on a novel design problem

We recruited individuals through informal networks including engineering and industrial design students, and design practitioners from multiple institutions, workplaces, and professional conferences. A $5 gift card was provided as a token of appreciation for participation in the study. In total, we had 48 participants. Table 2 shows the participants based on their experience in design and their demographics.

Table 2. Participants' design experience and gender

	Engineering	**Industrial Design**
Undergraduate students	22 (8 female, 14 male)	7 (3 female, 4 male)
Graduate students	9 (2 female, 7 male)	2 (1 female, 1 male)
Professionals	5 (3 female, 2 male)	3 (2 female, 1 male)
TOTAL	36 (13 female, 23 male)	12 (6 female, 6 male)

Data collection involved laboratory sessions where individuals were presented with a design problem. They were asked to create concept sketches, and to "think aloud" as they worked[59]. A retrospective interview followed, where participants were asked to describe their approaches to ideation, including how they generated each concept, how they moved from one concept to another, and any strategies they used.

The design task was an open-ended, novel problem related to one of the Grand Challenges for Engineering (National Academy of Engineering, n.d.). It included a small set of criteria and constraints to keep the problem as simple as possible. Participants were given the design task in written form, asked to begin working, and instructed to include labels and descriptions on their sketches. The design task was similar to solar problems used in engineering curricula at the college level, and was stated as follows:

> *Sunlight can be a practical source of alternative energy for everyday jobs, such as cooking. Simple reflection and absorption of sunlight can generate adequate heat for this purpose. Your challenge is to develop products that utilize sunlight for heating and cooking food. The products should be portable and made of inexpensive materials. It should be able to be used by individual families, and should be practical for adults to set up in a sunny spot.*
> *Note: Specific materials for a targeted temperature can be postponed to a later stage. Do not worry about the specific quantity of heat that can be generated. Please focus on conceptual designs. Please consider both the ways of capturing the light, and the structural variety of the concepts.*

Participants were given twenty-five minutes to generate ideas. All of the engineers' drawings and verbal comments were collected using an electronic pen that tracked its own movements and simultaneously recorded verbal data. This allowed us to recreate each participant's session for analysis.

Analysis: Extracting Design Heuristics

Verbal data from the sessions were transcribed to supplement the sketching data. This collection of data was reviewed multiple times as we searched for evidence of how designers generated ideas and transitioned from one concept to another. The extraction method involved a close examination of each concept, its labels and description from the engineer, and the analysis of the flow of concepts across the session.

Two coders, both trained designers with Ph.D. credentials, analyzed all of the data separately. Any disagreements in coding were resolved through discussion. The coders examined the data from each subject session separately, examining each concept separately and in sequence, for evidence of strategy use. Coding began with a master list of 68 Design Heuristics, and each concept was examined at length and coded for the presence of specific heuristics.

In the analysis of each participant's concept set, we looked for characteristic differences between concepts; that is, the first concept was compared to all subsequent concepts, and then the second concept was compared to all subsequent concepts, and so on. We identified: 1) characteristics that differentiated each participant's ideas from each other (i.e., how one concept compared to the others in a participant's set), 2) what transformations moved participants from one concept to the next (i.e., how characteristics of a set of concepts were similar and different, as well as how participants described the transformation), 3) participants' comments on the source of their ideas as they worked through the task, and 4) participants' explanations of how they proceeded through the design task in the retrospective interview.

Results: Defining Design Heuristics

In total, the 36 engineers and 12 industrial designers generated 247 concepts. From the protocols collected for this study, we identified 62 separate Design Heuristics that participants applied to generate concepts. Fifty-three of these were identified in the previous two studies, and nine were new strategies that emerged in the analysis, and were identified as new Design Heuristics. Fifteen that were uncovered in our previous work did not appear in this design problem.

For example, one of the engineers generated seven diverse concepts (see Figure 6). For his first concept, he chose a container that could be transported by users to a larger community gathering. The second concept was a large Fresnel lens, adjustable to the angle of the sun as well as to the best angle for cooking. For his next concept, he extended the previous one by segmenting his original lens into four separate lenses. The fourth concept was a spit cooker, which utilized a lens to focus on a line of heat, rather than a point. The fifth concept was a double boiler, consisting of a system pumping hot water from a boiler into an outer pot. Concept 6 was a synthesis of previous concepts: the design combined a double boiler with a Fresnel lens. The seventh concept was a blanket with reflectors and a drying rack. The reflective blankets are lightweight, allowing them to be transported easily, while serving as a windbreak. The eighth concept proposed a smoking chamber. It also included a Fresnel lens, and had two box-like structures on top of the other. The final concept was a three-stage boiler, comprised of a solar heater to warm up water to be utilized for steaming or boiling food.

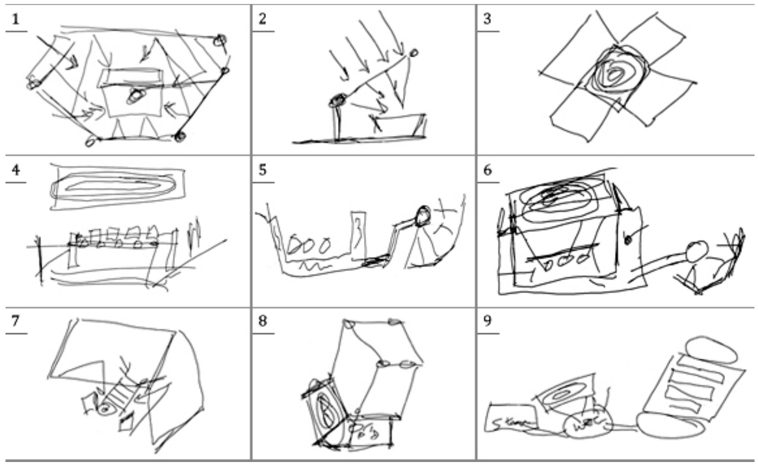

Figure 6. Sequential concepts generated by an engineer

To generate these diverse concepts, the engineer used multiple design heuristics. For example, in concept 3, he applied *Adjust functions by moving the product's parts*, as the angles of the lenses on all four sides could be altered to change the amount of sunlight directed onto the food. He also applied *Repeat*, as he added multiple lenses to direct the sunlight. Another one was *Cover* where he covered the container with a Fresnel lens.

He also frequently used *Contextualizing*. For most of his concepts, he first suggested a type of food, and then generated a concept that could cook that food. For example, he said "Other things to eat. We've got shish-kabobs, jerked meat, the dried herbs, the soups and things; um, let's see." He also emphasized different constraints from the problem as he worked; in concept 3, he focused on "maximizing the intensity of the sunlight", while in concept 7, he emphasized the constraints of being "inexpensive and portable".

In another example, one of the industrial designers worked through seven iterations of a single concept (see Figure 7). The designer began by attaching two existing components to each other -- a magnifying glass and a griddle -- to create a surface with focused sunlight. In her second concept, she transformed the magnifying glass to a square magnifying glass attached to the tray. In the following concept, she made the lens height adjustable, and, in the fourth concept, she added sides to it to maintain the heat more effectively. She then considered portability by adding a rigid handle, which was changed to a flexible handle in concept 6. In addition to all of the features included in the previous versions of the concept, the final concept also included an attachment that held utensils and a spout for draining fluids from the cooking surface.

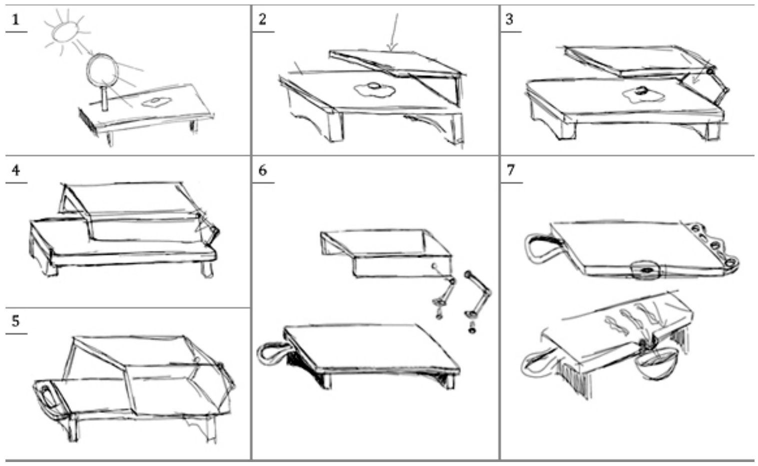

Figure 7. Sequential concepts generated by an industrial designer

The designer was successful in using heuristics to move about and explore within this concept's range. For example, from concept 2 to concept 3, she used *Adjust functions by moving the product's parts*, and *Fold*, and then from concept 5 to concept 6, *Replace solid material with flexible*, as she changed the material of the handle. Table 3 displays the design heuristics within each concept. The total number of Design Heuristics she used increased in each concept while maintaining the changes that were already introduced. The designer did not leave the heuristics she used in the previous concepts, but instead carried them along, iterating on the concept and adding more to further the design.

Table 3. Design Heuristics observed in an industrial designer's concepts

	C 1	C 2	C 3	C 4	C 5	C 6	C 7
Attach components that have different functions	●	●	●	●	●	●	●
Elevate	●	●	●	●	●	●	●
Compartmentalize		●	●	●	●	●	●
Adjust functions by moving the products' parts			●	●	●	●	●
Fold			●	●	●	●	●
Rotate around a pivot point			●	●	●	●	●
Cover				●	●	●	●
Detach or Attach					●	●	●
Replace solid material with flexible						●	●
Offering optional components							●
Repeating							●

We believe that the nature of the design problem may impact which Design Heuristics are observed most frequently. For example, participants noted that a key to cooking with solar energy is to retain heat, and therefore, they often covered or enclosed a cooking chamber. Since the design problems called for a compact and portable product, many components (such as reflectors, mirrors, cooking surfaces, etc.) were often attached. Lastly, since the participants were generally aware that natural sunlight is not intense enough to cook food, they often repeated elements to collect more and intensify the light on the food. Some of the Design Heuristics observed in other studies were used less frequently by participants in this study, reiterating that heuristic use likely depends upon the problem context.

Discussion

Design Heuristics extracted from these three empirical studies, resulting in the accumulation of evidence for 77 distinct heuristics. The frequency of their use differed based on the design problem, the context defined in the problem definition, and the designers' preferences. As implied by the use of "heuristic," there is no determinate result from an application; rather, a "best guess" concept is generated for further consideration. Table 4 shows the list of this complete set of Design Heuristics[44].

Table 4. Compiled list of Design Heuristics

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

36	Fold	75	Utilize inner space
37	Hollow out	76	Utilize opposite surface
38	Impose hierarchy on functions	77	Visually distinguish functions
39	Incorporate environment		

Since these studies, we have begun to explore ways to effectively teach Design Heuristics to both student and professional designers. We have created a set of cards representing each of the Design Heuristics, including a description of the heuristic, an abstract graphic image depicting the application of the heuristic, and two product examples that show how the heuristic is evident in existing consumer products. An example of one heuristic card is shown in Figure 8.

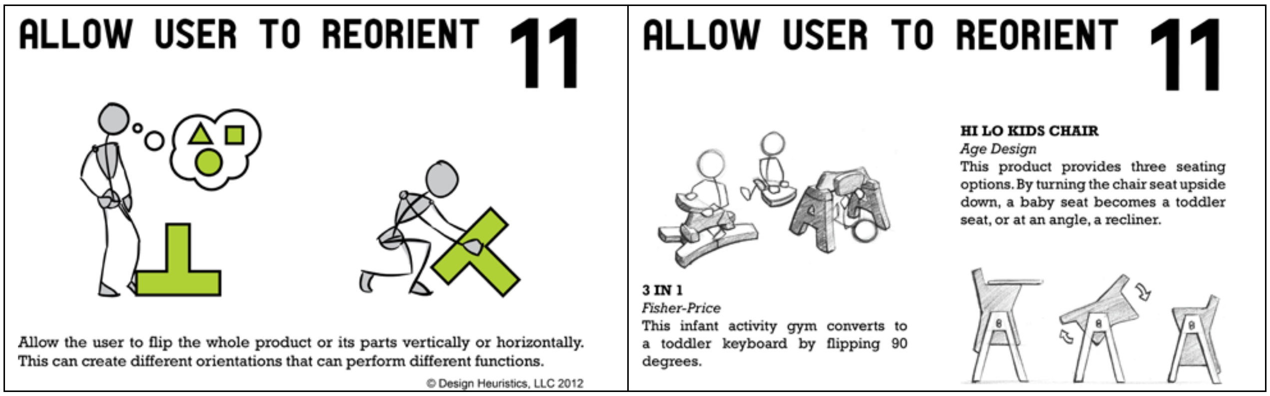

Figure 8. Example Design Heuristic Card

Our preliminary work shows that Design Heuristics can be taught to engineering students in design courses, from freshman to capstone project-based courses, in a relatively short amount of instructional time. The instruction includes an introduction to the Design Heuristics and how they were developed, example cards, and practice using a few cards with guidance by the instructor on a new design task[44]. The students then work with the full set or subset of the cards to generate their own ideas. Response from designers has been positive, and use of the Design Heuristics has been shown to result in creating more designs, and increasing the variety of designs generated, as well as their innovative quality[36].

Conclusions

The outcomes of the studies presented here provide a collection of Design Heuristics observed in over 400 award-winning products, in an expert designer's two-year long ideation process, and in 48 protocol studies with industrial designers and engineers. The Design Heuristics offer a new tool for students and practitioners to explore new design spaces. Rather than getting stuck in one idea, one can choose a Design Heuristic, apply it to the current problem, and see where the resulting transformation leads[60]. These Design Heuristics are empirically derived, and validated in their utility. Design Heuristics appear to add to one's ability to generate multiple, creative ideas to consider, increasing the likelihood of innovative solutions.

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