

# Innovative Solutions through Innovated Problems\*

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Designers are accustomed to solving problems that are provided to them; in fact, common practice in engineering is to present the problem with carefully delineated and detailed constraints required for a promising solution. As a consequence, engineers focus on creating feasible solutions rather than exploring novel perspectives on the presented problems. However, the Engineer of 2020 needs to respond with innovations for multiple and dynamic user needs, diverse users and cultures, and rapidly changing technologies. These complex demands require engineering students to learn that problems are not “fixed” as presented, and to build the habit of exploring alternative perspectives on the stated problem. Creative innovations in problem understanding may lead directly to more innovative solutions. While previous research has documented the “co-evolution” of problem and solution during the design process, the present work aims to understand how designers intentionally explore variants of problems on the way to solutions. Summaries of two empirical studies provide initial evidence about how stated problems are altered within successful solutions in open design challenges, along with evidence of problem think aloud protocols. Analysis of qualitative changes in problem perspectives reveals systematic patterns, or cognitive “heuristics,” and these same patterns are evident as student engineers solve problems. By exploring diverse perspectives on a stated problem, engineers can incorporate innovations into *both* problems and solutions during the design process.

**Keywords:** engineering design; problem exploration; innovation; co-evolution

## 1. Introduction: Problem exploration

Training on innovation in engineering design has been focused on developing solutions [1–4], with little attention towards facilitating the development of problems. However, problem exploration has been identified as a key process in design thinking [5–8]. We define *problem exploration* as intentionally developing varied perspectives on a problem in order to generate alternative solutions. Problem exploration is not simple elaboration of more detail; rather, it connotes a search for deeper meaning in order to arrive at a novel problem perspective. It relates to a designer’s ability to “move about” in design solution spaces; with broader explorations of the problem, consideration of a more diverse set of possible solutions may result [9]. The process of problem exploration allows the designer to “see”, “think”, and “act” towards creating a novel standpoint from which a problem can be tackled [10]. Karl Duncker [11] first defined the process of problem exploration as a continual restructuring

of the problem; by changing one’s view of the problem, discovery of its essential properties is facilitated, along with the creation of an appropriate solution.

The process of discovering the “real” design problem has also been described as “problem finding” [12]. Related approaches emphasize “problem framing,” or the effects of variations in how the initial problem is stated [13, 14] on how the designer interprets the problem to be solved. A focus on “problem defining” in design [8, 15] reflects a designer’s personal perception and construction of his/her design task, and its impact on the creativity of the resulting design [14]. There is evidence that more rich and varied descriptions of problems occur among designers with greater levels of expertise [16], including superior depth and detail, more interconnections, and more actions than in novices’ representations.

Despite its importance, the identification, development, and pursuit of alternative problem definitions are skills that are rarely taught but are

essential to engineering excellence [17]. Paton and Dorst [8] describe the ability to “frame a problematic situation in new and interesting ways” as one of the key characteristics of design thinking (p. 573). A comparative study of nine designers found those who pursued a “problem-driven” design strategy produced the best results in terms of the balance of both overall solution quality and creativity [18]. Behavioral studies of artists have shown that problem exploration is predictive of more creative outcomes [12] and even longer-term measures such as reputation and financial success [19, 20].

Further, Paton and Dorst [8] found designers defined their experiences with innovative design projects as determined by whether the client’s stated problem could be reframed. These studies support the notion that the problem exploration process—moving from a “presented” to a “discovered” problem – is an important step leading to innovation in the design process [21]. Empirical studies have documented that problem statements do change through the design process, termed the *co-evolution* of problem and solution [14, 22–24]. Cross and Dorst [14] observed oscillation between solution and problem during the design process. In their study, expert designers were asked to create a “litter disposal system” for a new train, and all nine designers restructured the problem to include a newspaper reuse system [14]. This co-evolution of problems and solutions suggests a process where a stated problem is subject to restructuring as solutions are considered, so that designers simultaneously and iteratively explore the problem while searching for possible solutions. However, fewer studies have examined how designers explore stated problems to create alternative perspectives.

A focus on understanding and defining the stated problem has been defined as “problem-driven design” [18]. This approach describes gathering information “only when absolutely necessary,” leading to a more narrow or circumscribed problem statement [25]. In the design thinking process [26, 27], problem exploration is defined by methods aimed at information gathering and building empathy, such as researching the market, competitor analysis, trend prediction, and design ethnography. A recent study with student engineering teams found these exploration methods actually hindered participants’ creativity, with less original concepts compared to a control group [28]. The reason may lie in the details; specifically, detailed information (such as knowledge of previous models or competing products) has been found to reduce the creativity of designs [29], while unstructured (free form) time for problem exploration led to increased originality in final designs [28].

## 2. How do designers explore problems?

The aim of this paper is to introduce a new approach to identifying the cognitive strategies used by designers in the problem exploration process. We propose that problem exploration is a vital contributor to the creation of innovative solutions. Problem exploration involves intentionally introducing variation in problem perspectives in order to produce more varied solutions. By increasing the range of possible solutions considered, more innovative solutions may be uncovered. To examine this hypothesis, we first review proposed strategies for problem exploration in engineering design. Then, we present evidence of problem exploration in two empirical studies, one in open design competitions [9, 30] and one in protocols of engineering students [31]. We document a high degree of variation in the problem perspectives evident in solutions both within a single designer’s work and between designers working on the same problem. We then illustrate some specific strategies for problem exploration, and how they may be useful in exploring new problems.

While the importance of problem exploration has been evident in the literature, there is a lack of empirical evidence on problem exploration [32] in design. Fogler and LeBlanc’s [33] engineering textbook suggests some specific techniques drawn from studies of human decision making. First, the authors suggest critical thinking using Socratic questions [34] to get at the root of the stated problem. The use of “Duncker [11] diagrams,” to describe the present state (where you are), and desired state (where you want to go) may help to identify what needs to change. Parnes’ [35] “restatement” method varies how the problem is stated (using “trigger” prompts, such as “vary the stress pattern by placing emphasis on different words and phrases in the problem”) to identify its most accurate representation. Finally, the Kepner-Tregoe [36] problem analysis technique is proposed to identify what the problem “is” and what it “is not,” sharpening the distinction and helping to define its most probable cause. These strategies are all based on theories of human decision making rather than the design process.

However, a few suggested strategies for exploring problems specifically in a design context arisen in professional engineering settings. The “5 Whys” technique was identified within the Toyota Motor Corporation design groups [37]. This strategy calls for repeatedly asking, “Why?” in order to explore the causal relationships underlying a problem. Spradlin’s [38] *Problem-Definition Process* was proposed to help companies improve their efforts towards innovation based on the challenge-driven

process at *InnoCentive*, a crowdsourcing site. The “problem definition process” includes defining the problem, establishing the need for a solution (e.g., basic need, desired outcome, and benefits), justifying the need, contextualizing the problem, and writing the problem statement.

An interview study of visual communication designers focused on their interactions with clients to negotiate the problem brief [8]. The study found that designers described approaches such as metaphor and analogy, contextual engagement, and conjectures to discuss alternative briefs during client interactions. These qualitative findings provide a first step in characterizing the strategies used by designers to explore varying perspectives on the stated problem, and to identify an appropriate problem description that will further define the goals of the design task. But Paton and Dorst [8] asked designers to recall their past experiences when they had negotiated with clients. Ideally, we would assess the problem exploration process using contemporaneous measures. To address this gap in the evidence about *how* engineers successfully explore problems, we conducted two empirical studies. The first examined changes in problems during design competitions, where a single stated problem is presented to a large group of designers. Differences in proposed solutions reveal changes in problem perspectives taken by each designer. Second, we asked engineering students to think aloud while they solved novel problems, and then asked them to report on the changes in their problem perspective with each solution. These empirical studies provide evidence about how designers intentionally altered the stated problem in the course of generating novel solutions.

### 3. Patterns of problem exploration in design competition solutions

The value of diversity in problem perspectives is readily evident in crowdsourced design competitions such as OpenIdeo [39] and InnoCentive [40]. These sites allow stakeholders to post design challenges online, and designers to post their concepts for comments and critiques, followed by a selection of top candidate concepts by an internal team of experts. For example, the problem, “. . . making agriculture and water systems more resilient in the face of climate threats,” resulted in over 100 different ideas entered onto the site (<https://challenges.openideo.com/challenge/water-resilience/top-ideas?>). The broad set of problem perspectives included concepts focusing on water quality monitors, waste water protection, storm water decision aids, low-power water use monitors in farming, digital

water allocation systems, watershed management, establishing water markets, and AI-based irrigation systems (see Fig. 1). The diversity of the proposed solutions suggests that different designers viewed the stated problem quite differently, and that those differing perspectives lead to variation in the created designs.

For example, one challenge on Unbranded Designs [41] resulted in 55 different problem interpretations, leading to a varied set of potential solutions [30]. The challenge asked the designers to “define a concept to facilitate individual work in a shared work environment.” The top three designs selected in the competition represented very different interpretations of the stated problem. The winner created a carrying case focusing on mobility, a finalist designed a cubicle focusing on privacy, and a semi-finalist came up with a concept for a scroll-top lock box focusing on protecting belongings. While challenge problems are intentionally broad in their definition, changes in problem perspectives may also occur when more specified engineering problems are posed. By exploring the problem perspectives generated by designers, it may be possible to identify strategies used to understand a stated problem from differing perspectives.

In a recent study [9], we created a database of innovative design problems including 238 problems from six different sources. This included problems from *InnoCentive* ([www.innocentive.com/ar/challenge](http://www.innocentive.com/ar/challenge)), an online crowdsourcing platform; *UnbrandedDesigns* ([www.unbrandeddesigns.com](http://www.unbrandeddesigns.com)), an online community for design challenges; *Idea-Connection* ([www.ideaconnection.com/contest](http://www.ideaconnection.com/contest)), a platform for crowdsourcing innovative solutions; and the *Design Secrets* books [42, 43]. Major elements, including user criteria, environmental context, and primary stakeholders, were identified for each stated problem. We analyzed the differences between the stated problem and either the restated problem or the apparent problem solved by the proposed solutions to identify information about the reframing of the problem.

Identifying a change in problem perspective based on a proposed solution requires interpretation. The goal in the analysis was to describe the *apparent* change in problem description. The test of the results is whether the exploration pattern identified is observed in other design problems, and whether it appears to offer a transformation that can be successfully applied to new problems. The resulting list of strategies was then applied to the data by a second coder, with highly consistent results. Each problem exploration pattern includes a description, and an example with a stated problem and an innovated problem.

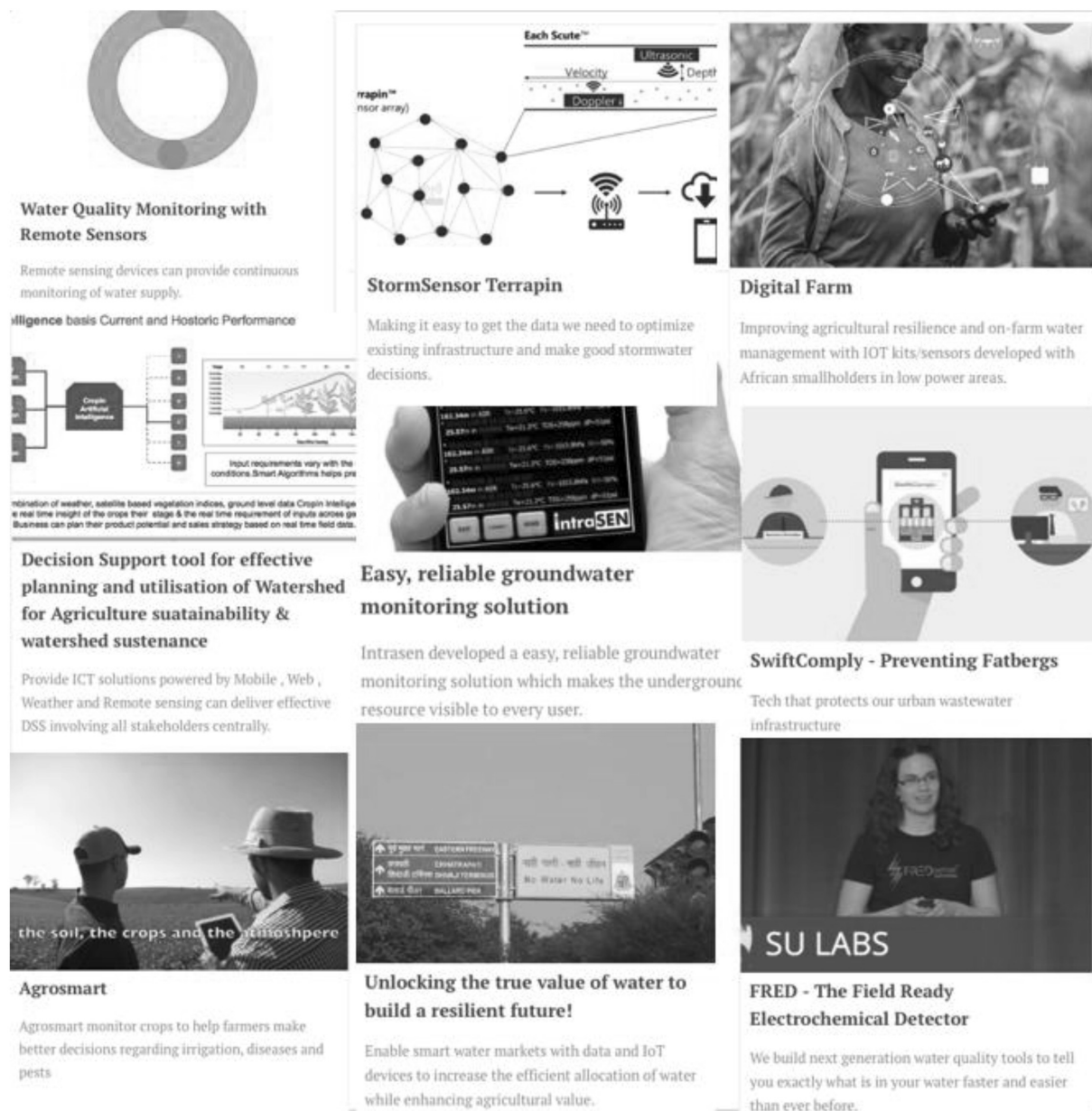
Exploration Pattern 1: *Goal Decomposition*. Analyze the goal for its subcomponents and select a single subgoal as the new primary goal.

**Stated Problem:** Consider the mobile worker and define a concept to *facilitate individual work in a shared work environment*. Develop an innovative solution to a clearly defined problem, optimized for today's mobile worker that is both technically and visually appropriate for the workplace.

**Innovated Problem:** Working in open spaces fosters creativity and collaboration, yet this communal atmosphere possesses security issues. Mobile

workers who utilize this type of space express concern about having their belongings stolen or losing their spot at the table when stepping away temporarily. Design a solution that allows office workers, students, coffee shop goers, and anyone else that works in a communal space to quickly *secure their belongings without having to pack up multiple items and lug them around*.

In this solution, the stated goal was broken into subgoals—security, privacy, and storage, and the designers chose to focus on security as a primary goal (see Fig. 2). Narrowing the goal to focus on



**Fig. 1.** Nine example solutions posted to the “make agriculture and water systems resilient to climate change” challenge on OpenIdeo (<https://challenges.openideo.com/challenge/water-resilience/top-ideas?>). The proposed solutions indicate that the stated problem was altered to create differing versions, such as “water markets” to manage use and methods to avoid “fatbergs” in sewers.

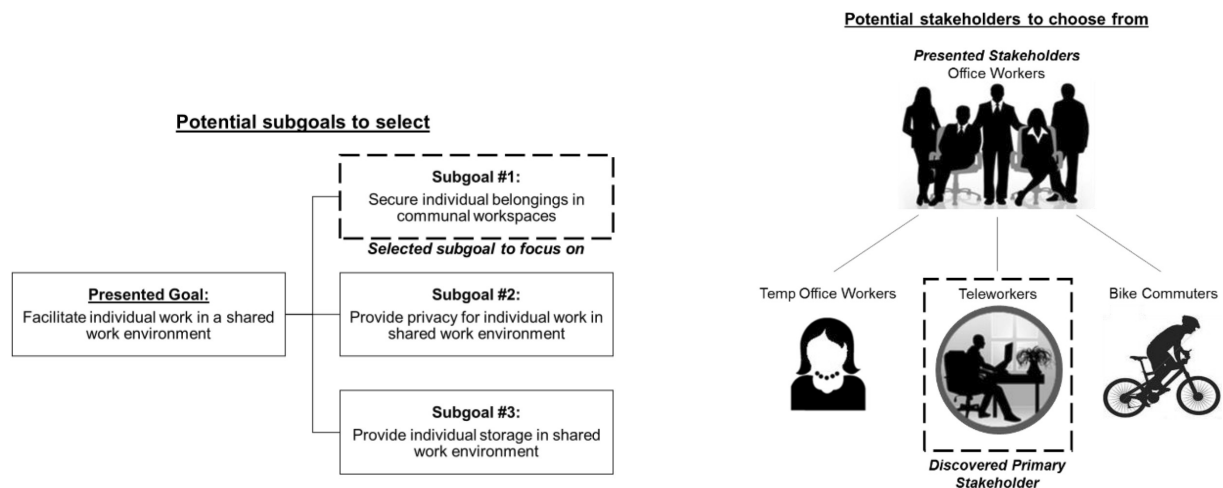


Fig. 2. Example designs where the stated problem is altered to focus on a subgoal (left) and a stakeholder subgroup (right).

criteria and functionality leads to a more specific design.

**Exploration Pattern 2: Stakeholder Group Decomposition.** Select a subgroup as the primary stakeholder. Narrowing the stakeholder group allows a more specific focus during idea generation.

**Stated Problem:** Design a personal storage component that responds to what *people in the workplace* need to store today, and what they will store in the future.

**Innovated Problem:** Design a sophisticated, mobile workstation for *teleworkers* to hold all the necessary components as more and more Americans are working from home.

In the stated problem, the stakeholder group was broadly defined as “people in the workplace.” After decomposing the population of workers into subcategories, such as temporary office workers, individuals who work from home, and individuals who bike to work, the designer identified “telecommuters” as the new primary stakeholder. Such an exploration is usually highlighted by stakeholder mapping techniques, where the designers document the stakeholders involved in the problem as either ones with interest in the solution or ones with power to change the solution [44, 45] and where they describe the relationships among the stakeholders to identify influences, processes and interactions. In this problem, this approach allowed the designer to focus on the needs of a teleworker, and led to the idea for storage. Fig. 2 illustrates how this strategy may be used in the problem context. The discovered problem is highlighted with dashed lines.

**Exploration Pattern 3: Change use scenarios.** Analyze scenarios in which the desired solution could be

useful and could determine how the users might interact with the design. Define the positive and negative characteristics of the scenarios, such as individual or group, or stationary or mobile, etc. This helps to determine the criteria for meeting the needs of users in these scenarios.

**Stated Problem:** Create a system that would *allow wheelchair-bound individuals mobility* and the ability to see the world at standing eye level using the idea of balance.

**Innovated Problem:** Develop a system that can be *used to move people and products short distances*, with minimal energy, in urban areas. This includes food delivery and manufacturing operations.

This pattern is illustrated here with the design of the Segway Human Transporter. The pattern works to expand use scenarios to include food delivery, manufacturing operations, mail delivery, and individual transportation. This changes the focus of the design to incorporate features needed in each scenario (Fig. 3).

**Exploration Pattern 4. Identify environmental constraints:** Evaluate the environmental setting for the desired solution for potential constraints, such as climate and the resources available (labor, tools, natural resources, etc.). Also, identify the existing products or materials that may be in use in that environment. Determine the environmental constraints for the solution.

**Stated Problem:** Design a new solution to medical waste management in Sub-Saharan Africa. Currently temporary burners and small-scale incinerators are used to deal with the rapidly growing medical waste. These are not always feasible and are not as efficient as desired.

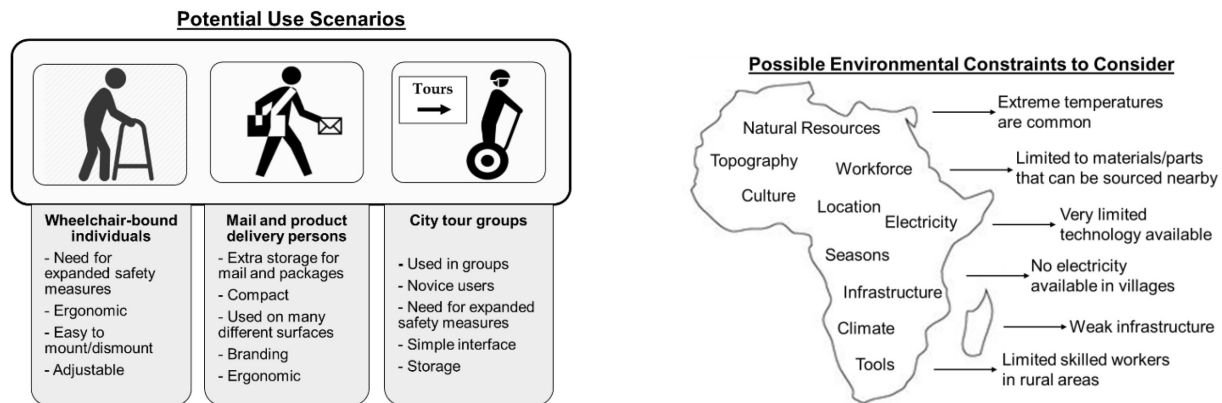


Fig. 3. Two examples of problem exploration patterns involving use scenarios (left) and environmental setting (right).

**Innovated Problem:** Medical waste management is a key concern during emergencies. Current solutions are made from oil drums and other easily accessible materials. Humanitarian workers try to construct more durable incinerators, but these are often limited by the availability of trained staff, and ability to source specific materials/parts such as heat-resistant cement or bricks. A higher performing alternative solution is urgently needed to burn medical waste in humanitarian settings.

In the example, the designer elaborated on the constraints of the environment from the stated problem by recognizing the lack of trained staff and the inability to source specific materials or parts due to the location. The new problem specifies these constraints (Fig. 3).

**Exploration Pattern 5. Identify size and space criteria:** Analyze the context in which the desired solution will be used and the space needed. Specify size or space criteria for the final solution. This includes identifying specific spaces that should be utilized or the required measurements; e.g., fit in a “backpack” or “smaller than 12in. × 16in. × 4in).

**Stated Problem:** Update the 1959 model of the BMW MINI Cooper to meet twenty-first century standards.

**Innovated Problem:** Design a new model of the BMW MINI Cooper with air bags, high-fidelity audio components, plush seating, and air conditioning. It should accommodate consumers who are on average 4 inches larger today than in 1959.

The innovated problem adds specific size and space requirements for the solution. The new model needs air bags, audio components, seats, and air conditioning. It also states the need to expand to accommodate taller individuals. This allows the designer to create solutions specific to the size and space criteria stated in the problem, bringing the “update”

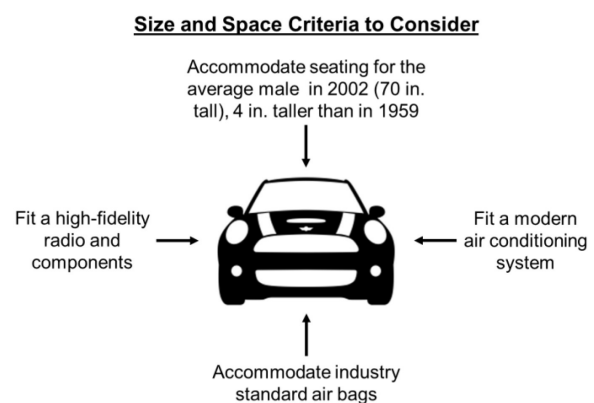


Fig. 4. An exploration pattern where the specification of desirable design criteria improves understanding of potential solutions.

goal to earlier phases of front-end design. Fig. 4 demonstrates how this pattern was applied.

The observed exploration patterns capture just one transformation of the stated problem towards a new, innovated problem. Each pattern helps the designer by providing additional structure and specifies the design goals to promote particular solutions. Problem exploration, or the translation of the stated problem into a new problem formulation, is an identified stage in the design process, but there is little information available about how designers successfully accomplish it. The analyses of design competition results provide a window into successful innovation on problems and illustrates how specified exploration patterns can affect the exploration of the solution space [9].

#### 4. Strategies for problem exploration in design protocols

Design challenges offer naturalistic data for design problems “before” and “after” their solution. From these examples, we can build a systematic, descriptive account of the ways that problems change through the design process [9]. But are these changes

in problems occurring naturally in the design process? To investigate, we conducted a study using a “think-aloud” or verbal protocol, where student engineers worked on novel problems for 25 minutes [31]. The two stated problems were to “. . . design a solar oven for mobile use . . .”, and to “. . . design a deployable device(s) that can be used at the site of a disaster relief effort . . .”.

The students were asked to think aloud about their thinking as they worked on each of two short design problems, and all of their work was recorded. In total, 28 concept solutions were collected from 5 students. Then, in a new task, we asked them to go back and define the problem they had addressed within each of their solutions: “For each of the solutions you generated, write a problem statement that would allow other students to come up with the same solution you developed.” This was challenging for the students but allowed them to identify their own view of the important differences between the stated problem and the innovated problem they had solved.

The protocols revealed multiple cognitive strategies used to structure the stated problem in alternative ways. Three of the students were observed to follow a process where they addressed problem requirements and boundaries prior to generating ideas, while two proceeded directly to idea generation and problem reframing, simultaneously. This suggests that process models with a separate, initial problem exploration phase will not be sufficient to account for all designers. Instead, at least some students pursued a process as suggested by co-evolution of problem and solution [14].

From the students’ verbal reports, it is evident that their changes to the stated problem were implicit, often not recognized until they were asked to write it down. However, their explanations of their solutions were more directly available to conscious report. Previous studies have also found cognitive strategies could be implicit, such that the person is not consciously aware of their use [46–48]. Cognitive heuristics, or “rules of thumb,” appear to guide the search for solutions, can play a role in organizing problem solving effort [46], and have been found to operate in the process of generating new ideas [49]. The framework of cognitive heuristics appears to capture the generalized patterns of exploration described by the students.

All five protocols showed evidence of exploration strategies. For example, all five students chose to *Break down the primary need* [31], generating sub-goals for design. This approach—narrowing the scope of the stated design problem during exploration—is consistent with findings from expert designers [50, 51]. MacCrimmon and Taylor [51] prescribe a similar exploration heuristic of “factor-

ing into sub-problems.” Two other observed exploration patterns, *Define the characteristics of the setting*, and *Focus on one scenario*, were also frequently observed across students and problems.

The student engineers appeared to broaden the problem using some strategies, which we call “exploration heuristics.” One heuristic, *Incorporate additional scenarios*, was demonstrated when a student redefined the problem as, “providing electricity whenever and wherever electricity is not available.” The solutions generated with this pattern were also more general, such as portable lights for a blackout and its use in places where power is not always accessible. Each student also used one or two unique exploration patterns; for example, one student focused on *Determine the required cost* in three of five innovated problems created. This may reflect individual differences, such as life experiences that influence how a problem is perceived [52]. Differing perceptions of uncertainty, complexity or conflict can lead two individuals, even with similar experiences, to employ different strategies for problem formulation [51].

Figure 5 presents example solutions and innovated problems for the disaster scenario problem. Each of the five students changed the stated problem in a variety of ways on their path to generating solutions, and each student’s problem perspectives differed, at least in part, from those of other students. Further, each innovated problem led to a

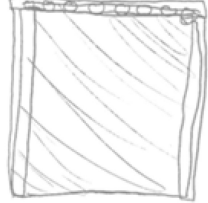
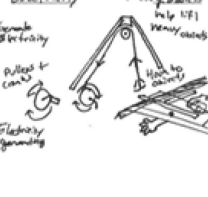

	<p><b>Innovated Problem:</b> “A tornado has torn through a town. Using easily salvageable components, create a single-family shelter. Note that electricity will be scarce and families may be in this shelter for extended periods of time.”</p>
	<p><b>Innovated Problem:</b> “There is a need to generate some form of tools to help lift and move heavy objects such as debris or people. *No electricity or power. *Semi portable/moveable. *Simple for most people to operate.”</p>
 <p>“Solar-panel phone charger that’s water-resistant and hand-held”</p>	<p><b>Innovated Problem:</b> “Charging a handheld device that is portable, water-resistant and uses sunlight.”</p>

Fig. 5. Three examples of students’ concepts and their description of their innovated problems

new type of design solution. For example, one student reframed the disaster relief problem by thinking about the end user of the potential product (victims of a disaster), and determined the important need was to provide them with a comfortable shelter. This innovated problem led to focusing on shelter plans with bathrooms and showers to make victims as comfortable as possible. The same engineer moved on to redescribing the problem as “providing power,” leading to a different set of solutions such as a mobile generator. Each engineer displayed a specific, unique pattern of exploration, and each described one or two patterns for changing the stated problem that were not evident in other students’ protocols.

These cases show how students changed the stated problems as they created new solutions in a co-evolutionary process of design [14]. For instance, after first designing an emergency food delivery drone, one student stated, “. . . *that made me think that maybe shelter would probably be more important than food at first, and it should be simple enough for the victims to build themselves . . .*” This supports prior research that identified concept design as a “co-evolution” of problems and solutions rather than discrete, separable stages in the creative design process [14, 22–24]. The generation of partial solutions enables the problem to be structured and examined differently. As observed in these protocols, design problems are not “fixed” as initially stated but are changed during the design process. The specific changes detailed in the protocols serve as a record of problem exploration patterns that can be observed across problems and across designers. Generating alternative problems may facilitate forming more diverse solutions because each innovated problem may bring new potential solutions to mind.

## 5. Applying exploration heuristics to new design problems

The advantage of problem exploration heuristics is that each pattern brings the designer to a new area of the problem space to identify solutions. With each heuristic applied, new aspects of the problem are explored beyond the original problem definition. For example, in the protocols, engineering students explored the limitations of the current state, and then identified solutions that could remove these limitations. The students also explored a list of stakeholders that stand to benefit from a solution and decided to focus on subgroup. Additional use scenarios were identified, along with environmental constraints such as laws and regulations. Location was identified as the primary environmental constraint, with the intent to eliminate this constraint in

the design. Simple heuristics, such as further specifying the size and space constraints, helped the designers be more targeted about their design solutions. The protocol data suggests that the application of different heuristics could produce a wide variety of alternative problem descriptions, leading to less common and more diverse designs.

Consider these three heuristics identified in the two studies described above:

1. *Determine the end user and detail their needs* [9].
2. *Define the characteristics of the setting* [9].
3. *Find the root cause* [9, 53].

Each of these heuristics promises to draw the designer’s attention to a new area of the problem space, focusing on the setting, or the root cause, or the end user. These alternative perspectives may then lead to the exploration of additional aspects of the problem and its solutions beyond the focus in the stated problem.

We propose that the heuristics uncovered in previous design explorations can be generalized, and then serve as “prompts” to encourage designers to consider alternative perspectives. Fig. 6 illustrates how these three problem exploration heuristics might be applied to a current, real-world design problem:

“In hundreds of refugee settings like Darfur, women and girls are made more vulnerable to sexual violence because of the almost daily need to leave camps in search of firewood” [54].

Multiple, engineered solutions now exist for this problem, each reflecting a differing perspective on the stated problem. Can the prompts based on the problem exploration heuristics be applied to generate new solutions?

The first heuristic, *Determine the end user and detail their needs*, helps the designer recognize the user requirements that must be addressed in a good solution. In design fields, it is common to create stakeholder maps and personas to analyze the targeted user characteristics, needs, motivations, and life styles. However, when it comes to framing design problems for engineers, such an exploration is not common. In this problem, identifying the end user as females away from the safety of camp suggests addressing the safety issues. Solutions for this problem perspective were implemented in Darfur, where security patrols now accompany women seeking firewood [54].

The second heuristic, *Define characteristics of the setting*, assists engineers in understanding the space in which the final solution will be implemented and used. This helps in determining any limitations or constraints that might arise from the context of use. The location of the firewood emerges as the primary



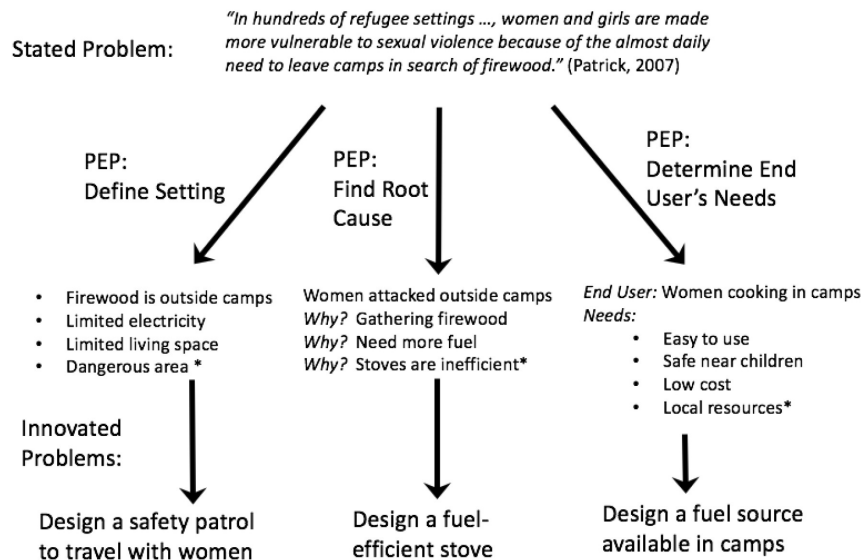


Fig. 6. Example illustrating the application of Problem Exploration Heuristics to create variations in problem perspective.

environmental constraint, suggesting the possibility of eliminating this constraint in a new solution. This restructuring suggests, "Collect fuel from a source close to the cooking." This apparent focus on identifying alternatives to wood as a fuel source is evident in a new invention proposed for this camp problem: An inexpensive screw tool can turn refuse into biofuel pellets [55].

The third problem exploration heuristic is to *identify the root cause* of the stated problem. As shown in Fig. 1, identifying the cause suggests improving the efficiency of firewood use in cooking, which would decrease the number of needed trips outside the camp. This problem perspective is represented in the introduction of a new, inexpensive stove design. A current design is made of mud and ash in just 3–5 days, costs less than \$1 per stove, and allows users to reduce their firewood consumption by 20–80% [54].

The ability to consider each perspective through the use of exploration heuristics would allow the designer to weigh the advantages of each alternative. Rather than stopping with one problem structure, one can choose another heuristic, apply it to the stated problem, and see where the resulting problem transformation leads. As this example demonstrates, each problem exploration heuristic brings additional aspects to be explored beyond the original stated problem.

These three heuristics offer differing perspectives on the goals for design, and lead to different solutions. They may assist designers by pointing out alternative perspectives to consider. While the process is indeterminate, the heuristics may serve to push designers to parts of the problem space where they may not otherwise venture. By considering a

broader spectrum of potential solutions, the designer may select a final design that addresses the problem situation in a more novel and innovative manner. Novice engineering designers, in particular, may benefit from exploring the problem with an arsenal of problem exploration heuristics, leading to innovative solutions.

## 6. Discussion

The two empirical studies discussed here provide varied evidence for the use of cognitive heuristics to explore design problems. Data collected from public, online design competitions suggest that the same stated problem produces solutions addressed to very different problems. The empirical evidence of multiple designs generated for a stated problem revealed systematic patterns of problem revisions resulting in highly competitive design proposals. This open data provides a documentation of the problem finding stage in the design process and suggests that alternative problem perspectives are a common outcome in a design challenge. Because the competitors range from students through experts in design, it appears that changes in problem statements is an important part of the design process. This phenomenon, called problem finding [21, 56], problem framing [13, 57–59], and co-evolution of problem and solution [14, 22, 24, 60], is readily apparent in designs collected for a separate purpose.

Are these consistent patterns of differences between the stated and apparent problems observed in design competition solutions "in the heads" of designers? To address this question, the think-aloud protocol study asked students to solve problems,

and then to describe how their solutions differed from the stated problem. Students noted difficulty in identifying how they moved from the stated problem to the one solved by their proposed design. Other studies have also found that even experts have trouble articulating the cognitive strategies they use on an intuitive basis. For example, Klein and colleagues [61] observed firefighting experts on the job, and noted they speedily identified an appropriate course of action without the ability to articulate a rationale for their choice. Similarly, interviews with a professional designer showed he also could not describe how his designs changed; however, he could readily see the pattern evident in the concepts themselves [47, 62]. Paton & Dorst [8] also found their designers “rarely volunteered an explanation of how this change had been negotiated with the client” (p. 580). The problem reframing process was not at the forefront of designers’ reflections about their projects.

Nevertheless, the patterns of problem exploration observed appear to be systematically used by designers. They are robust, in that they are evident in the design solutions proposed for a set of different stated problems. In addition, they are observed across designers and contexts, such that each is evident in design solutions proposed by different designers. While the design competition results are not based on observing the design process, the protocol study helps to establish that these problem exploration heuristics are used by engineering students working in a single design session as they vary the solutions they generate. More research is needed to identify how these exploration heuristics are learned and developed, how they are represented in memory, and how they are accessed during the design process to guide designers to new problem perspectives. In addition, further research is required to investigate if and how problem exploration processes lead to more innovative outcomes in the form of novel solutions.

The research described here offers new evidence about *how* designers explore problems, and how they are able to create novel problem perspectives. Prior research demonstrated the co-evolution of problems and solutions in a study of designers working on a single problem [14, 24]. Paton and Dorst [8] interviewed designers who described how they altered the design brief through interactions with clients. However, there is little additional information about *how* designers alter their perspective on the stated design problem to generate alternative solutions. To our knowledge, the evidence described here is the first to document co-evolution in multiple design problems and with many designers. By comparing the outcomes of competitions with stated problems, we were able to observe

consistent patterns of changes in problem perspectives leading to different solutions. In the protocol study, we were able to document that the exploration takes place within a single designer’s process as they search for multiple solutions to a state problem. In combination, this work makes a case for the existence of problem exploration heuristics and their use in design.

The stated problem has been shown to cause fixation in design, where the designer may be limited to known solutions [63–65]. The problem exploration heuristics may serve as a means of combating fixation by changing the design goal to focus on alternative problem perspectives. Strategies to aid in examining presented problems for their underlying characteristics may be critical in identifying innovative solutions. Previous accounts of design research on innovation have focused on idea generation processes as a source of innovation solutions [66]. The present work adds to these efforts by documenting how problems change with solutions both across problems and across designers. The systematic observation of variations in problem perspectives suggests this may be a fertile area for developing an understanding of innovation in design.

There are limitations of the evidence described here about problem exploration processes. In particular, the design competition analyses examine only the “before” (the stated problem) and “after” (the apparent problem in the proposed solution). No information about process is available from these competition sources. In the protocol study, only a small number of students participated, and the single design session is unlike the team design environments typically found in the engineering workplace. Further, the analyses of problem exploration patterns produced generalized heuristics that are reliably observed but may not be the same as those generated by participants. More research is required to document the application of these heuristics during the design process, and their role in the generation of more innovative solutions.

Pedagogy for enhancing design creativity is essential because engineering problems increasingly demand innovative approaches in the design of products, equipment, and systems. Many engineering and design students are provided with general instructions about finding, framing, and defining problems [33]; however, it is less common for them to learn about specific cognitive strategies for problem exploration that may lead to defining novel problems, and in turn, to generating more creative solutions. Exposure to a variety of these problem exploration heuristics during training and gaining experience in applying them in many different problems, may facilitate the development of expertise in

problem exploration and innovation. For many engineering students, simply having an arsenal of heuristics to try might lead to increased variety in their proposed solutions. Improvement in problem exploration skills may be assessed by a growing variety of problem statements and proposed solutions. Generating a variety of solutions may also be an indicator of achieving an understanding of problem exploration heuristics and their application as triggering prompts.

## 7. Conclusion

This paper presents evidence that engineering design problems can be restructured to reveal alternative views of a problem, and the varied and innovative solutions that result. A variety of heuristics for problem exploration during design have been identified, along with empirical evidence about their spontaneous use by student engineers within a single design session. These findings suggest it may be helpful to encourage engineering students to adopt problem exploration heuristics to help them discover alternative problem perspectives, including when and how to apply them. Increasing ease of integrating and implementing heuristics in problem exploration may result from the gradual acquisition of knowledge about exploration heuristics and outcomes, perhaps through the implementation of exploration “prompts.” The development of problem exploration skills may move the engineer of 2020 to consider more novel ways of approaching problems, and provide opportunities for designing surprising, uncommon, and innovative solutions.

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