Call the Plumber: Improvable Models as Priming Artifacts in Student Engineering Design Activities

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SUMMARY

Within the last decade, there has been an increased emphasis on making engineering education accessible to K-12 students in order to create the “engineering pipeline.” Researchers have focused on high school students and valued engineering design mainly as a medium for teaching science and mathematics and for preparing students to become engineers or taking up science or mathematics as career options. However, there have been recent calls to reorient engineering education and focus more on making students engineering enabled, where students can engage productively with the core disciplinary ideas of making tradeoffs and design optimization. Research in this area is in its early stages and further work is needed to advance our understanding of what it means to productively engage with the engineering design process and how we can support students to achieve that. Through my research work with the sixth grade students, I hope to advance our understanding about these open issues. Specifically, I explore the use of a class of models that I call Improvable Models – models that can be iteratively redesigned and optimized by students, as priming artifacts for supporting productive engagement with engineering design process. I investigate how students use Improvable Models as resources for solving an engineering design challenge, how the use of these models influence students’ design of engineering solutions, and what type of scaffolds support the use of these models. For this research, I use two types of Improvable Models – Suboptimal System model and Optimal Component model. Suboptimal System model presents a complete solution but is suboptimal at the system level. Optimal Component model presents an incomplete solution but is optimal at the component level. Students use these as seed models for solving their engineering design challenge. I use the context of designing a plumbing system where small groups of students serve as "plumbing companies" competing to win the bid for building the plumbing system of a house,

with the winner being the company that met the pressure requirements (10 psi at every tap) for the least cost. The following questions guide this research study - (a) How do students use Improvable Models? How does the use of Improvable Models as priming artifacts influence students' design of engineering solutions? (b) What type of scaffolds and instructions support students' appropriation of the Improvable Models?

Data analysis indicated that students used the Improvable Models as resources for engaging with five different disciplinary practices – (a) attending to either the input or the outcome parameters, (b) making explicit or implicit connection between an input and a single outcome parameter, (c) reasoning with multiple interconnected input and outcome parameters and making tradeoff decisions, (d) weighing outcome parameters and making tradeoffs, and (e) forming design heuristics informed by implicit or explicit rationale. The visual representation of counterexample scaffolded the formation of design heuristics. Three out of five teams using the Suboptimal System seed model generated and used design heuristics to optimize their solution for the design challenge. These heuristics guided their construction of the final solutions that were the three cheapest solutions across both the treatment conditions. Three out of four teams using the Optimal Component seed model displayed three types of design fixation – (a) delayed fixation, (b) immediate fixation, and (c) implicit fixation. Teams that evidenced design fixation were also the ones that evidenced productive disciplinary engagement. This indicates that fixating on optimal features of the Improvable Models may not be a negative characteristic in this context and could help students engage productively with disciplinary practices. Improvable Models help decompose a complex problem into parts and make the problem accessible. All five teams using the Suboptimal System seed model and three teams (out of four) using the Optimal Component seed model productively engaged with the disciplinary practices. Three kinds of verbal and written prompts—procedural, reflection, and disciplinary prompts—along with resources like a software simulator scaffolded engagement with the disciplinary practices by problematizing the quality of a system, problematizing design decisions, giving students authority, maintaining accountability, and providing resources (Engle & Conant, 2002).

1. INTRODUCTION

Over the last ten years, K-12 engineering education has received growing attention from the teachers, researchers, and policy makers. Most of the research into STEM education has focused primarily on science and math education, with only a slight emphasis on technology education and almost none on engineering education. This scenario is summed well by the National Academy of Engineering (NAE) report (2009)—"[i]f technology education is a small blip on the STEM radar screen, engineering education is almost invisible" (p. 20). The interest in introducing engineering in schools has started developing only recently. Developers of engineering curricula believe that engineering education offers K–12 students benefits like stimulating interest and improving achievement in mathematics and science, improving engineering design skills, improving the understanding of engineering and attracting young people to careers in engineering (National Research Council, 2010; Cunningham, 2009). Engineering education contexts using real-time data for engaging students in various problem-solving tasks (e.g., McKay & McGrath, 2007; Project Lead The Way- Bottoms & Uhn, 2007) as well as fictional problem scenarios (e.g., Adventure Engineering- Mooney & Laubach, 2002; Engineering is Elementary- Cunningham, 2009) indicate the value of engineering as a means of improving student performance in and attitude towards science and math. These are certainly desirable goals and help high school students prepare for the "engineering pipeline" (e.g., National Academy of Engineering, 2008; Reynolds, Mehalik, Lovell, & Schunn, 2009; Schunn, 2009). Research focusing on engaging younger students in elementary and middle school with engineering practices is in its early stages (e.g., Cunningham, 2009; Benenson, 2002; Mooney & Laubach, 2002). Most of these endeavors have focused on engaging students with engineering science and thus has treated engineering primarily as a medium for teaching science and mathematics and pushed design in the background (Svihla & Petrosino, 2008). While math and science knowledge is required for solving engineering problems, “it is this design process and the practical nature of the problems tackled that best distinguish engineering” (National Academy of Engineering, 2009). Thus, engineering education should not only be about “making engineers” or making students proficient in mathematics and science disciplines. Providing opportunity for students to become “engineering enabled” (Svihla & Petrosino, 2008) by learning core disciplinary skills and practices used in the design process is equally valuable.

In order to understand what engineering design means and why it might be beneficial to engage students with the process, I draw on the definition suggested by Dym and colleagues – “Engineering design is a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients’ objectives or users’ needs while satisfying a specified set of constraints” (Dym, Agogino, Eris, Frey, & Leifer, 2005, p. 104). This process of engineering design thus offers many interesting dimensions that could be of immense value in K-12 grades.

First, it allows students to deeply engage with tradeoffs. While making tradeoffs, students essentially have to evaluate how well different solutions meet the needs defined for the design as well as the constraints of the problem. They have to weigh competing design parameters and solve the problem in the most efficient way (Dym et al., 2005).

Second, students learn how to negotiate with their peers while interacting in groups during the design process. The process is inherently social in nature (Dym et al., 2005). Engineers collaborate with each other and often work in small teams, settling conflicts by means of negotiation. Similarly, when students work on a design challenge in small groups, it is quite natural to have conflicts due to different viewpoints within the team about what design decisions to take in order to solve the design challenge. These conflicts provide space for the students to negotiate ideas with their peers and learn how to accommodate multiple design perspectives. The process of negotiation has been found to help the students perform better as compared to when they are working on a problem by themselves (Solomon and Hall, 1996).

Third, students experience the iterative decision making process where they have to take into consideration the design goal, design constraints, available resources, and multiple perspectives. Engineering design process makes these decisions and underlying assumptions inspectable (Roth, 2001) thereby encouraging proper articulation and justification of the design ideas.

Fourth, students get to experience the uncertainty that is inherent in the design process (Dym et al., 2005). A design goal can be solved in many different ways following different solution paths i.e. its design space. This creates room for students to ask questions, generate design rationale for selecting a particular solution path, evaluate their work, and redesign with a better understanding of the design space. The availability of multiple solution paths and associated uncertainty is something that students are usually not comfortable with (Svihla & Petrosino, 2008). Thus, an engineering design task creates opportunities for students to experience this uncertainty and learn to tackle it.

Finally, engineering design process requires students to “maintain sight of the big picture” (Dym et al., 2005). Components within an engineering system are very likely to be interconnected, either directly or indirectly. The connections could be physically visible (e.g., students can see that the pedals in a bike are connected to the wheel with the help of different sizes of gears and thus affect the bike’s speed) or hidden (e.g., students cannot see the parts of a sewing machine that affect the sewing process) (Lehrer & Schauble, 1998). Maintaining sight of the entire system would thus need students to take into consideration all these connections, how they are connected (not just which components are connected), and also "grasping the meaning of that interconnection for [their] own action" (Rose, 2004). Understanding these connections help form design rationales in an engineering design task. Developing this perspective of a connection between system and components can help facilitate better understanding amongst students of how things work around them in their everyday lives.

Given these benefits that engineering education has to offer and the early stages of the research at the elementary and middle school level related to providing opportunities for students to become "engineering enabled" (Svihla & Petrosino, 2008), I focus on this space for my research. The early stages of research focus on engineering design in the context of middle school students has lead researchers to pay only fleeting attention to the practices associated with engineering design and how students engage with them. Thus, we have preliminary understanding of what resources might help the students productively engage with the engineering design process and how they might use those resources. Through this research, I attempt to advance our understanding about these issues and add to the early research in this area. In particular, I am interested in investigating how a class of models that students can iteratively redesign and optimize, can be used as resources to help students productively engage with the process of engineering design. I call these Improvable Models. Specifically, the following questions guide my research study:

1. How do students use Improvable Models? How does the use of Improvable Models as priming artifacts influence students' design of engineering solutions?
2. What type of scaffolds and instructions support students' appropriation of the Improvable Models?

This dissertation has eight chapters. In this chapter, I have introduced the research context and provided a rationale for this research study. I have also presented the research questions that guide this study. In Chapter 2, I provide the theoretical background and framework, highlighting existing research that informs this study. I introduce the productive disciplinary engagement framework for understanding student interaction in the context of engineering design. I present the challenges involved in engaging young students with engineering design, use of models and worked examples as enablers for solving design problem in a classroom environment, and introduce the idea of using Improvable Models as resources for solving engineering design problems. In Chapter 3, I describe the research design and methods used in this study. In Chapter 4, 5, 6, and 7, I present the results of this study. Chapter 4 focuses on different disciplinary practices that emerged while students used Improvable Models. Chapter 5 focuses on the inter-play between the Suboptimal System model (SS seed model) and design heuristics to show how the SS seed model scaffolded the process of heuristics generation, refinement and use in the classroom context and helped the teams work productively. Chapter 6 focuses on the phenomenon of design fixation observed while using the Optimal Component model (OC seed model) and highlights the three different types of fixation that supported productive work. Chapter 7 focuses on the prompts and resources provided to the students during the entire unit that prepared and sustained the students' productive engagement with the disciplinary practices. Finally, in Chapter 8, I discuss the findings and present conclusions from this research, highlighting implications of this study on research and teaching engineering design in the classroom context, and present avenues for future research.

2. THEORETICAL FRAMEWORK

2.1 Productive Disciplinary Engagement in Engineering Design

Productive disciplinary engagement is a framework for understanding how to foster development of "new ideas and disciplinary understandings in real-life settings" (Engle and Conant, 2002, p. 403). Engaged participation means absence of unrelated off-task student activities and presence of verbal or non-verbal (using hand movements) indications of students contributing to or attending to each other's ideas (Engle & Conant, 2002). Disciplinary engagement means, "there is some contact between what students are doing and the issues and practices of a discipline's discourse" (Engle & Conant, 2002, p. 402). Students' engagement with the disciplinary work is considered productive when they make progress in a given task (Engle & Conant, 2002). The notion of productivity is domain specific and is defined by the disciplinary practices and specific problems (Engle & Conant, 2002). So in order to understand productive work in the context of engineering design, I will first unpack the disciplinary practices by looking at what engineers do and how they think.

2.1.1 Engineering Design Practices: What Do Engineers Do?

Dym and colleagues have suggested that the systematic process of generating, evaluating, and specifying solutions that satisfy a given set of constraints and meet users' needs is critical to engineering design (Dym et al., 2005). This characterization emphasizes a process of creating, assessing, and refining ideas guided by constraints and design goal or in Sheppard's words, "scope, generate, evaluate, and realize ideas" (Sheppard, 2003). Engineers investigate the solution space to determine the extent of the goal (scope), develop ideas for possible solutions (generate), assess the ideas and check their fit in the solution space (evaluate), and implement their ideas to achieve the intended goal (realize). This is done iteratively to optimize the solution, a process that involves maximizing the “functionality of a design with respect to the design requirements and the resources available” (Silk & Schunn, 2008, p. 5). Thus, design optimization represents progress or productive engagement in engineering design. The optimization process brings together an understanding of the available resources, consideration of the effect of multiple design parameters on the performance of the system, and understanding the tradeoffs associated with various design decisions (Silk & Schunn, 2008). Design optimization is a continuous process that requires engineers to deal with uncertainty due to multiple solution paths or “design trajectory” (Vattam, Helms, & Goel, 2008) that are resolved by making tradeoffs (Dym et al., 2005; Kroll, Condoor, & Jansson, 2001). To aid this process, engineers use design heuristics or rules in order to “narrow the search of a solution space” while solving an engineering design challenge (Dym, 1985; Finke, Ward, & Smith, 1992; Yilmaz & Seifert, 2010).

The process of coming up with solutions to engineering design challenges is tightly coupled with the design goal and thus is inherently driven by inquiry, one that “occurs for the sake of settlement of some issue of use” (Dewey, 1938, p. 61). Dewey calls this “common sense inquiry” and suggests that it requires teleological reasoning, linking design decisions with their consequences or design goal (Dewey, 1938). During this teleological reasoning process, while engineers link design decisions with their consequences, they frequently make tradeoffs in service of design optimization. Silk and Schunn suggest that “tradeoffs occur both when considering the input variables of a system, those that can be manipulated in the system design, and the outcome variables, those that are used to judge the quality of the design… when a choice to modify the level of one variable impacts the effect of another variable on the outcome… also occur when weighing the different outcomes of a design, such as when considering the cost of a design compared to its effectiveness" (Silk & Schunn, 2008, p. 20). Thus, being able to reason with multiple interacting variables in an engineering system and understand their effect on the design goal is essential for making tradeoff decisions.

Thus, the engineering practices that engineers engage with while solving a design problem includes reasoning with inter-connected design parameters, making tradeoff decisions, and forming design heuristics for optimizing the design solutions. These practices require consideration of multiple variables at the same time (Silk & Schunn, 2008), something that students have been found to be lacking in (Zohar, 1995). The problem is further magnified due to the uncertainty arising out of multiple solution paths, which students rarely have to deal with (Svihla & Petrosino, 2008).

2.1.2 Engineering Design for Young Students

Proponents of engineering design education have suggested that the core engineering design concepts of optimization, tradeoffs and constraints should be introduced early on in the school curriculum (National Research Council, 2010; Cunningham, 2009). For example, the "Engineering is Elementary (EiE)" program engages elementary school students with engineering problems like construction of sturdy bridges, where students are expected to design solutions for overcoming an engineering challenge faced by a storybook character (Cunningham, 2009). An EiE unit comprises of the following stages (Hester & Cunningham, 2007) – (a) prepare students (if they do not have prior experience with engineering design) by making them examine everyday technologies like a stapler and describe the problem they were designed to solve, (b) set the context with an illustrated story and have students reflect on the engineering components and reinforce literacy skills, (c) inform students about what engineers do in general and technology they make, (d) help students make connection between science, mathematics, and engineering related to the story presented to them and (e) allow students to design, create, and improve solutions to the engineering problem highlighted by the story. During the final design process (point e), the EiE students go through a cyclical design process consisting of asking questions about the problem, imagining solutions, resources required, creating the solution, and improving the solution (Hester & Cunningham, 2007). This design process aligns with the four actions performed by engineers—scope, generate, evaluate, and realize ideas (explained in previous section). This curriculum has been well received by the teachers as well as students and highlights the readiness of elementary grade students to engage with engineering practices. This is illustrated by Cunningham's (2009) comment:

> "Children, even young children, are capable of much more complex engineering thinking than we originally anticipated. They can balance multiple constraints and criteria, compare the merits of designs, and represent their designs from different points of view." (p. 15)

In another example, Johnsey (1995a, 1995b, 1997) described how children (aged 3 to 11) engaged with "design and make" tasks. For example, a sample design challenge given by Johnsey (1997) to the students asked—"[d]esign and make a game which can be played on a table top. Your game should be built in the lid of a card box and involve a marble. Make your game suitable for a friend in your class" (p. 206). He reported that the skills used by his students as they engaged with the design and make tasks were—(a) investigate, (b) identify needs, (c) clarify implications of the task, (d) specify evaluation criteria, (e) research the problem, (f) generate ideas for solutions, (g) model ideas, (h) plan, (i) make the product, (j) evaluate process and the product while making, and (k) evaluate the final product and processes used. Also, students followed a non-linear design process (Johnsey, 1997; Anning, 1994; Fleer & Sukroo, 1995; Ritchie & Hampton, 1996; and Roth, 1995), an approach typically followed by experts (Cross & Cross, 1998; Medway, 1994; Roth, 1995).

These accounts of young students' engagement with design challenges shows their preparedness for navigating the engineering design process, often using advanced approaches and design thinking.

2.1.3 Challenges of Engineering Design

One of the challenges of engineering education and engineering design process is the issue of fixation on a particular way of solving the design goal. Recent investigations in the field of engineering have highlighted this issue of "design fixation" – a situation where "designers limit their creative output because of an overreliance on features of preexisting designs, or more generally, an overreliance on a specific body of knowledge directly associated with a problem" (Youmans & Arciszewski, 2014, p. 115). Investigations in the field of Mechanical Design highlight the nature of design fixation that can occur when example solutions are given to participants (Jansson & Smith, 1991; Linsey et al., 2010; Purcell & Gero, 1996; Smith & Blankenship, 1991). Jansson and Smith (1991) found that designers reproduced aspects of the example solutions in their final solution, including aspects that were shown to violate the goals of the problem statement, and reduced the range of solutions generated. These studies demonstrate that example solutions can result in generation of fewer and restricted ideas (Linsey et al., 2010). This is likely to lead to a situation where engineers fail to explore the entire solution space (bounded by the design constraints) and thus affect the quality of the solutions generated to solve the engineering design challenge.

One line of research into overcoming design fixation suggests using example solutions that belong to a different material space or domain as compared to the problem scenario. Designers adapt the example solution to fit their domain or material space and this could prevent 'copying' of design elements from the worked example to the design space. Along these lines, researchers have created tools that support designers' idea generation process by providing analogous examples, either using examples from the nature or using other devices (Kurtoglu & Campbell, 2008; Chui & Shu, 2007; Chakrabarti et al., 2005). These types of examples encourage designers to abstract functional principles and customize them for use in their problem scenario, thereby reducing chances of fixation.

A different take on this issue can be found in the Case Based Reasoning framework in a Learning-By-Design environment (Kolodner, 1993; Kolodner 1997) where cases were used to support students' designing process. Cases represented expert solutions to the design problem given to the students but used different scales of construction. For example, if the goal for the students was to build an optimal hovercraft using simple construction materials, the expert cases contained videos of experts making real-size hovercrafts using industry grade equipment and materials. Students reflected on these expert cases, recalled them and adapted them while constructing their designs (Kolodner, 1992). Differences in the scales made it hard for students to replicate the expert designs. Instead, students abstracted design ideas from the cases shown and customized them as per their design goal effectively (Dasgupta & Kolodner, 2009). Thus, using analogous examples and shifting to different scales for generation of multiple examples can help counter the design fixation. But creating such examples usually requires an exhaustive search of the possible design solutions in order to select examples having a sufficiently different scale and material space. It may also require a lot of expertise for selecting or creating analogous examples that have enough connections to the design problem presented to the students. Another challenge that could potentially arise is that of translating expert terminologies or complex concepts in the analogous examples into simplified ideas that could be used by the students meaningfully (Kurtoglu & Campbell, 2008; Chui & Shu, 2007; Chakrabarti et al., 2005).

Another way of overcoming design fixation, that can be potentially useful, is by showing 'negative' examples that are essentially incorrect ways of solving the given problem. This provides an interesting alternative, one that I hope to develop further through this research. Limited research in the past about the use of such examples suggest that negative examples discourage snap judgments about design and thus increase accuracy as they slow down the learners and prevent them from coming to one or more erroneous design decisions while still in the learning phase (Smoke, 1933). Others have suggested that negative examples help students identify limits of the design and help define the requirements for the desired system more effectively (Haack, 1972). Some researchers have even created opportunities for students to create their negative examples since they reasoned that these enable critical self-evaluation of their design decisions and promote efficient work towards an improved solution (Bohle, 1986; Davis et al., 1974). These prior works highlight the potential benefits of using worked examples that are not 'correct' solutions to be emulated by students. The issue of design fixation has been of great interest to the engineering design research community but has predominantly focused on college students or professional designers. While design fixation certainly poses a challenge in the case of young students, not much is known about the process by which fixation might unfold in the case of young students, how it influences them, and the effect on the products they design.

Another challenge is the issue of dealing with uncertainty that is inherent to the design process (Dym et. al., 2005). Uncertainty refers to the presence of multiple solutions at every stage of the design process, creating a dilemma for the students regarding which path to select for solving the design challenge. Students are usually not comfortable with this uncertainty (Svihla & Petrosino, 2008). They are accustomed to the idea of one "right" way of solving a problem (Harrison & Treagust, 2000, Furió et al., 2000). Vattam and colleagues suggested the notion of “design trajectory” (Vattam, Helms, & Goel, 2008) to describe how college level student designers dealt with this uncertainty in the context of biologically inspired design. Students were found to employ two strategies for solving a design challenge – (a) problem-driven approach i.e., formulating the problem in functional terms and starting with a solution-neutral design space and (b) solution-driven approach i.e., formulating the problem using a specific solution and constraining the design process. Both these strategies suggest ways of reducing the design space while solving a design challenge. While prior research shows that young students can work their way through a design problem (Johnsey, 1997; Anning, 1994; Fleer & Sukroo, 1995; Ritchie & Hampton, 1996; and Roth, 1995) and solve a design challenge, the issue of uncertainty and how young students might tackle this is not well understood.

2.2 Physical Models as Resources

Engineers commonly use external models to solve design problems and it has been suggested that these be made available for students so that they can inspect the requirement and constraints and develop a better understanding of the design problem (Penner, 2001; Resnick and Wilensky, 1998; Schunn, 2009). An external or physical model is a simplified representation of a complex system highlighting its important features, thereby making it possible for students to investigate the system by manipulating the model and using it as a thinking tool (Harrison & Treagust, 2000). Models offer the ability to make “student reasoning public and inspectable – not only among the community of modelers, but also to teachers” (Lehrer & Schauble, 2000). Models have been used in classrooms to various extents. An expert-generated model was used to evaluate student-constructed models (Bravo, van Joolingen, & de Jong, 2009) in the Co-Lab environment. At various stages of the modeling task, a software program compared the features of the first year university students’ models with an expert’s model (the reference solution) and generated recommendations about further revisions to the student's models based on what was missing in them. Students revised their model based on these recommendations and improved their model with each iteration. Expert-generated models have also been revised iteratively to present students with an increasingly complex model (de Jong, 2006). High school students were given increasingly complex models of an electrical circuit. They performed experiments using these models by changing variables (such as resistance in the circuit) and observing the effects (e.g. change in current). Students who were presented with the increasing complex model outperformed the students who were given the complex model at the very beginning by evidencing better understanding of the interconnections of the different variables in the electrical circuits. In another instance, students compared multiple canonical models developed by experts (Stewart, Cartier, & Passmore, 2005). During a course on evolution, high school students began by examining three historical models that accounted for species' adaptation and diversity. Students studied each model and the inferences drawn from them. They compared the assumptions of the three models and engaged in class discussions about the relative merits and shortcomings of every model. The students then proposed their own models and the authors reported that these models were similar to those proposed by expert geneticists. Models with different functional qualities have also been used. First and second grade learners compared and rated functional qualities of four types of elbow models based on their accurateness of how the elbow actually worked – picture of an arm highlighting the elbow, a model with popsicle sticks joined by clay, a flexible straw model, and a string pulley model (Penner et al., 1997). They then constructed their own model. The authors found that in comparison to the students who were not given these models, students in the treatment condition demonstrated attention to the functional qualities of the model instead of the perceptual qualities. They also showed an advanced understanding of the modeling process that was similar to the students who were three to four years older. Cartier (1999) studied high school students in an elective genetics class where students started with a simple model and slowly increased its complexity as their knowledge about the subject increased. Students modified the explanatory model developed by an expert as they accounted for various inheritance phenomena observed in fruit flies, reflecting their understanding about advanced genetic concepts.

For this research, I focus on the use of examples represented using physical models as resources for enabling students to engage with a domain specific problem. Worked examples "provide an expert solution for the student to study and emulate" (Atkinson et al., 2000). Such examples are important when engaging with a practice and learning new skills, especially in the initial stages when students solve problems by analogy and develop abstract rules and strategies that guide their problem solving (Anderson, Fincham, & Douglass, 1997; Atkinson et al., 2000). Further, it is known that once students become proficient at using the strategies, they can solve new but similar problems quickly by recalling these strategies and rules formed while solving worked examples and practice problems (Anderson, Fincham, & Douglass, 1997; Atkinson et al., 2000). Worked examples presented to students before giving them an unsolved problem have been known to help students employ efficient problem-solving strategies (Chi et al., 1989; Chi & Bassok, 1989; Chi & VanLehn, 1991; Pirolli & Recker, 1994; Renkl, 1997; VanLehn & Jones, 1993a, 1993b; Ward & Sweller, 1990). Students have also performed well on problem-solving tasks after using "incomplete examples" i.e., worked examples where part of the solution was replaced by 'question marks' (Stark, 1999). These examples were also found to improve the quality of self-explanations, although these explanations were not optimal (Stark, 1999). Thus, models serve as scaffolds during problem-solving tasks and can lend themselves as valuable resources for solving engineering design challenges. Based on the prior literature with models and different types of examples, in this research, I explore the use of a particular class of models – *Improvable Models*, to understand how students use them as resources for solving an engineering design challenge.

2.3 Improvable Models

Improvable Models are a class of models that are simplified representations of visible or hidden engineering systems that can be iteratively redesigned and optimized by students for solving an engineering design challenge. These models present sample solutions that visually represent all the design parameters – both input and outcome parameters, required for solving the challenge. These models also highlight all the design constraints underlying the design space, priming students to focus on the design parameters and constraints in the engineering system and helping in "anchoring of new, incoming ideas" (Ausubel, 1960 cited in Reder, 1980, p. 42) for solving the challenge. So Improvable Models can be considered as seed models that students use to start solving an engineering design challenge. In this way, these models draw on the concept of "primary generators" (Lawson, 2006; Darke, 1979). During the design process, primary generators serve as initiators that drive the design's structure from an abstract level to a detailed level, highlighting the important aspects of the problem (Lawson, 2006). Darke (1979) suggested that primary generators could be a concept, objective or group of related concepts rather than a single idea that "form a starting point for the architect, a *way in* to the problem…" (p. 38). Similarly, the Improvable Models represent a group of related concepts about design optimization and provide a "way in" to the design challenge.

For this research, I used two types of Improvable Models – Suboptimal System model and Optimal Component model. These models draw upon prior research with complete and incomplete worked examples. Suboptimal System (SS) model presents a complete solution but suboptimal at the system level. The solution presented by this model does not satisfy the design constraints. Optimal Component (OC) model presents an incomplete solution but optimal at the component level. The solution presented by this model is optimal and satisfies the design constraints but only represents a partial system. The visual representation of all the design parameters and constraints through these models will likely allow students to inspect these elements and use them for making tradeoff decisions, scaffolding students' engagement with the deeper concepts and disciplinary practices while they are solving the engineering design challenge (Quintana et al., 2004). Improvable Models are likely to be useful in the following ways – (a) as reference solutions, (b) as baseline examples, (c) as tools for inspecting design parameters, and (d) as tools for identifying design limitations. I will follow the process of "progressive refinement of hypothesis" (Engle, Conant, & Greeno, 2007) to iteratively refine my hypotheses about Improvable Model use and collect empirical records so that "analysis of these records informs more specific hypotheses that then may be addressed in other aspects of the data" (p. 2) and help generate more specific questions and explanatory hypotheses (Engle, Conant, & Greeno, 2007).

3. METHOD

This study focused on investigating how students used Improvable Models as resources for solving an engineering design challenge, how the use of these models influenced students' design of engineering solutions, and what type of scaffolds supported the use of these models. For this research, I used two types of Improvable Models – Suboptimal System (SS) and Optimal Component (OC), as seed models. The Improvable Models, instructional prompts and technology scaffolds used in this study were developed iteratively through multiple classroom enactments over a span of two years (Appendix 1).

3.1 Engineering Design Challenge

For this research, I chose the context of designing a plumbing system. There were a couple of reasons for selecting this context. First, plumbing system offered an opportunity for students to engage with and reason about interconnections of system components of an engineering system that is not directly observable, inspired by a class of engineering systems that are hidden from students (Lehrer & Schauble, 1998). Research about how children reason about such systems is in its early stages (Lehrer & Schauble, 1998), thus highlighting the scope for research using hidden systems. Also, the science teachers who participated in this study were interested in providing their students with an opportunity to engage with such hidden systems. Second, prior research showed that young students (elementary and early middle grade) understood better the different components of an engineering system and reason about how they might be interconnected when they are familiar with the context (Lehrer & Schauble, 1998; Silk & Schunn, 2008). Students were familiar with plumbing system to the extent that they used the system in their daily lives. In this way, this engineering system was not a completely new context for the students. However, the challenging part about using plumbing system as the context is that it is very complex with many components (e.g., water pipes in the city, water pipes coming into the house from the city, cold and hot water pipes within the house, water heater, valves, different diameters of pipes, drainage pipes, etc.). In my previous two design iterations of the study (Appendix 1), I had learned that students found it hard to deal with the complexity of the entire plumbing system. They spent more time building a complete system in order to include all the components and less time discussing design rationale. Thus, there was a need to simplify the context. Brophy and colleagues have also suggested the need to provide engineering contexts that are accessible to the students, sufficiently complex and give them opportunity to engage with various disciplinary practices (Brophy, Klein, Portsmore, & Rogers, 2008). Thus, in order to make the design context accessible to the students and yet keep it sufficiently complex, I focused on plumbing system within the house and also limited the system to have a few components – one source point at which the city supply water entered the plumbing system, three taps at different distances and relative location to this source point, and pipes of three different diameters connecting the source point with the three taps. Drainage and all other components were left out. Also, the design space was restricted to one floor only. The three taps and their relative locations along with the three different types of pipes offered sufficient exploration space for the students. The following design parameters were part of the plumbing system used in this study – (a) input parameters i.e., system variables which were to be manipulated by the students (pipe bend, pipe length, and pipe diameter), and (b) outcome parameters i.e., system variables used to determine the quality of the system (output water pressure at the taps and total cost of the system). Specific relationships or system properties connected the input parameters with the outcome parameters (see Table I).

3.2 Material Base

Prior design iterations (Appendix 1) had highlighted the challenges of using a wide variety of construction materials. Thus, the set of construction materials available for every group in this study included a 20 inches wide X 15 inches tall foam board (design board), plastic straws of three different diameters (serving as water pipes of three distinct diameters), and post-its (for recording calculations). Extra pipe segments of all three diameters were given to all the groups in addition to the pipe segments in the seed models. The source point and the three taps were highlighted with the help of board pins and labels. A grid-like arrangement of channels (or runs) was already drawn on these design boards using a black marker. Students could only lay pipes (different sized straws) along these channels. Double-sided tape was pasted on top of these channels to help the pipes stick along the channels (as opposed to being randomly placed on the design board). The double-sided tape also allowed easy removal of the pipes whenever required in order to change the design. The three different types of straws represented three different diameters of PVC pipes (1-inch, ¾-inch and ½-inch diameter wide). Small segments of these different types of straws were provided to the students for making the model of the plumbing system. Each segment of straw or pipe had two corresponding and competing costs – cost in terms of dollars and cost in terms of water pressure. These costs were informed by the actual cost of materials at Home Depot™ and the actual drop in pressure across 1-foot long PVC pipe.

TABLE I
COST AND PRESSURE DROP FOR A PIPE SEGMENT

Pipe Diameter (inches)	Cost (dollars)	Pressure-drop (pounds per square inch - psi)
1-inch	$45	1 psi
¾-inch	$33	4 psi
½-inch	$28	12 psi

Thus, adding a 1-inch diameter pipe to the plumbing system increased the cost of the model by $45 and decreased the output pressure by 1 psi. Similarly, adding other types of pipes affected the pressure and cost as well. Every bend or turn (i.e., pipes arranged at 90 degrees to one another) in the plumbing system had an additional cost of $100 (in addition to the cost of the pipes forming the bend). For simplicity purposes, a T-joint was considered to have the same cost as an L-joint and there was no additional drop in pressure across the bends. Post-its were also provided to help students record the cost and output pressure for their design revisions. A net budget of $3000 and minimum water pressure of 10 psi served as design constraints that bounded the exploration space. The budget amount of $3000 was decided based on a range of design alternatives that I had created in the lab to mimic potential student models. I wanted to leave enough room for exploration and design variation. The minimum tap water pressure of 10 psi was based on the suggested range (20 psi to 90 psi) in the US households as per the Uniform Plumbing Code (2012) and modified according to the cost of the parameters defined for this engineering challenge.

3.3 Design of Plumbing System Improvable Models

Horizontal foam board: A 20 inches x 15 inches white foam board was used as the design board. This served as the floor of the house. The decision to use the board as a horizontal surface was influenced by the need to facilitate collaboration and encourage group work where students standing on any side of the board could see the changes being made on the board as well as contribute actively to the changes by reaching out and accessing any part of the board anytime. The use of a foam board made the design board very lightweight thereby making it easy to carry around or move as required (e.g., carrying the board to another team's table to compare designs). This freedom of motion was designed to facilitate the use of the design board by the students as an effective tool for communicating ideas and expressing/sharing design decisions.

Discontinuous channels: The design board had channels that marked out a grid like intersection of horizontal and vertical paths along which pipes could be placed. However, the channels did not always run all the way across from one end of the board to the other (along both x and y axis). There were breaks in between. The intention behind such discontinuous channels was to avoid providing an easily identifiable shortest path for placing the pipes from source to the taps. Continuous channels would have made the design task very straightforward, possibly boring and reduced chances of design variations. The design of the channels in this way opened up the possibility of connecting the source to the taps using multiple routes, thus increasing the chances of negotiations amongst students regarding which route to follow for placing pipes and why.

Combination of pipe diameters: The use of three different diameters of pipe (1-inch, ¾-inch, and ½-inch) created a design space that was rich enough for encouraging negotiations about different permutations and combinations of pipes. This afforded discussions about tradeoffs related to using a pipe or combination of pipes in the design. It was important to represent all the three types of pipes in the seed model i.e., construct the Improvable Model using all the three pipe diameters in order to provide a visual reminder to the students about all the three pipe diameters in their design decisions.

Written constraints on the board: Another critical representation that was geared towards facilitating design discussion and decision-making process was the design constraints that were written on the design board. The maximum budget ($3000) and the minimum water pressure acceptable at all the three taps (10 psi) were clearly written out on the design board itself to serve as visual reminders.

Additional design features of the seed models varied according to the specific type of the Improvable Model – Suboptimal System (SS) model or Optimal Component (OC) model.

3.3.1 <u>Suboptimal System Model (SS Seed Model)</u>

The design of the Suboptimal System model (Shown in Figure 1) was driven by the goal of providing a complete but suboptimal solution at a system level. Thus, all the three taps in the plumbing system were connected with the source point. The suboptimal solution resulted in a model that had excessive number of bends (12 pipe bends in the entire system with 7 bends near tap A), long winding route of pipes from source to the taps (pipes going above tap A and then coming down to connect tap B and tap C), and lots of expensive 1-inch diameter pipes (35 pipe segments) with a few ¾-inch (6 pipe segments) and ½-inch diameter pipes (3 pipe segments). This suboptimal solution had the following output water pressures at the three taps– a) 42 psi at tap A, b) 5 psi at tap B, and c) 0 psi at tap C. Thus, tap A had very high water pressure while tap B and tap C had inadequate water pressure relative to the 10 psi minimum set for each tap. The total cost of the suboptimal model was $3057, exceeding the $3000 budget.

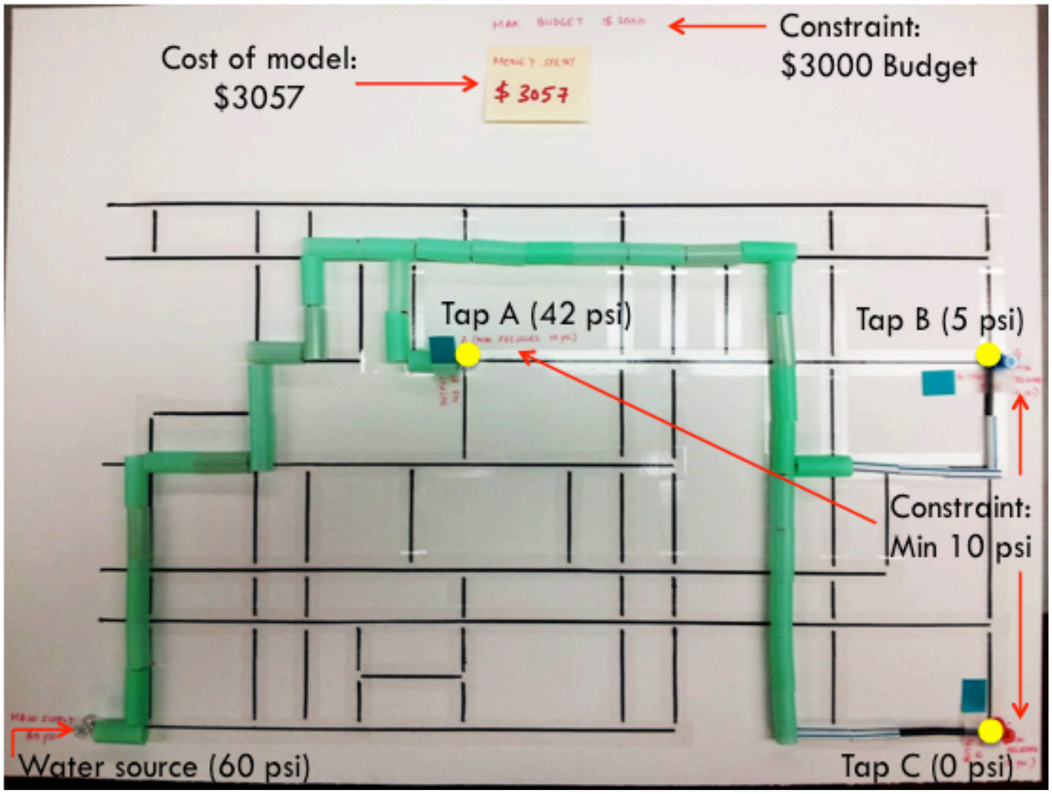

Figure 1. Suboptimal System model (SS seed model)

3.3.2 <u>Optimal Component model (OC seed model)</u>

The design of the Optimal Component model (Shown in Figure 2) was driven by the goal of providing an optimal solution at a component level that was incomplete at the system level. The source point was connected to only tap B using 2 pipe bends (optimal because just tap B is being connected with the source point), shortest pipe length between these two points and optimal combination of different diameter pipes (18 pipes having 1-inch diameter, 5 pipes having ¾-inch diameter, and 1 pipe having ½-inch diameter). Tap B had an output water pressure of 10 psi (meeting the minimum pressure requirement). The source point was not connected to tap A and tap C. The cost of this partial model was $1203.

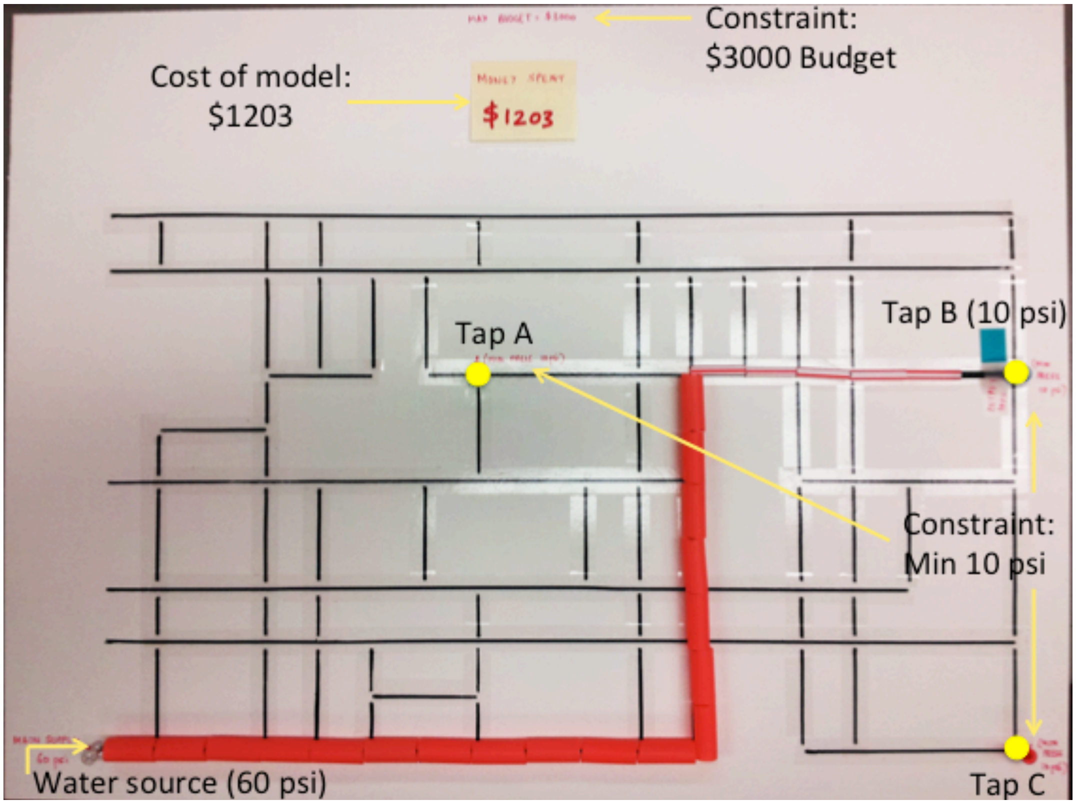

Figure 2. Optimal Component model (OC seed model)

3.4 Instruction unit

Table II below summarizes the sequence of activities in the instruction unit.

TABLE II
SEQUENCE OF INSTRUCTIONAL ACTIVITIES

Day	Instructional Activity
Day 1	Introduce the design challenge (whole class); Elicit prior knowledge about good and bad plumbing system (whole class)
Day 2	Compare schematic representations of suboptimal system and optimal component designs *(small groups)*
Days 3 – 4	Discuss design parameters *(small groups followed by whole class)*; Introduce underlying science *(whole class)*; Use simulator to extract system properties and explore relationship between design parameters *(small groups followed by whole class)*
Days 5 – 7	Discuss system properties and make table having cost and pressure drop for each pipe diameter *(whole class)*; Revisit design challenge, show design board with the Suboptimal System and Optimal Component models (to respective classes); Begin design optimization *(small groups)*: Step 1: Analyze and improve the seed model (Suboptimal System or Optimal Component model); Step 2: Record the modified model after calculating value of outcome parameters (take photo with iPad™); Step 3: Compare and contrast design revision with seed model and prior design revisions; Step 4: Redesign and iterate from step 2
Day 8	Present optimized model *(small groups present to whole class)*; Respond to peer critique and questions

The design challenge given to the students was – "Design an optimal plumbing system using the given resources. Build it as cheaply as you can below $3000, yet meet the minimum pressure requirement of 10 psi at each tap set by the building engineer. This (seed model) represents one way of connecting the tap(s) but it can be improved. First talk within your group about how this model can be improved. You have to improve this and make a better model. Talk about why you built the design and how is it better from this model that you are starting with.

The best design would be the one that meets the minimum pressure requirement and is also the cheapest."

A whole class discussion was first conducted to make students comfortable with the idea that designs had flaws and engineers constantly thought about ways of improving their designs. Students were introduced to the concept of Improvable Models by means of a simple schematic representation of a smaller plumbing system (Appendix 2 and Appendix 3) with the same set of design parameters as the Improvable Models on the design board (pipe bend, pipe length, pipe diameter, cost, and pressure). Basic science underlying how pipe diameter and length influenced the output water pressure was discussed. Students worked in groups and used the simulator (running on their school laptops) to extract the system properties and the relationship between the design parameters. I had developed the simulator using Processing, an open source programming language. Every group used the simulator to first explore the system properties associated with one particular diameter of pipe and then expanded their exploration to the other two pipe diameters if they had time. The teacher then conducted a whole class discussion, collating everyone's findings into one table that was then used as a reference sheet during the design activity. During the design activity, every group received an image of the seed model, which was always kept next to their design board for reference. Unique iPads™ were allocated to every group and they were asked to take a photo of their model after every iteration. Prior design revisions created by a group were only visible to that group on their iPad™. For the design activity, every group received one design board containing a seed model – either the Suboptimal System or Optimal Component model. They also received additional pipe straws of all the three diameters for designing their solution to the challenge. For the final presentation, the students had to present their optimized model to the class and answer questions posed by their peers. The following section delves into the rationale behind various instructions and activities in this unit.

3.4.1 Rationale Behind Various Instructions and Activities in this Unit

Selection of any design iteration as their optimal design: Students were allowed to make as many iterations as they wanted and then select any one design revision as their optimal model. Being able to select any revision as their optimal model, whether it was the last one or not, provided opportunity for the students to explore the design space without being constrained by the need to finish with the optimal model. This also closely mimicked the design process where engineers iterated through different ideas before settling for the most optimal design out of all their iterations.

Using simple schematic representation of a smaller plumbing system to introduce Improvable Models: The simpler plumbing system (having one source, two taps, and just two possible paths from source to the taps) was intended to help focus students' attention on the design parameters of the system and highlight the features of the suboptimal features of the Improvable Models (e.g., long winding pipes, excessive use of broader diameter pipes, lack of adequate pressure, etc.). The seed model provided to the students later on for the design optimization task replicated the same set of features but included further layers of complexity like numerous paths from source to the taps, more design materials, higher design cost, and more taps at various distance from the source. The schematic representations were thus intended to help students practice making design decisions and focus on effective ways of communicating design ideas.

Providing simulation software to understand system properties: The simulation software hid complex mathematical calculations and scientific basis that might have otherwise confused the students and distracted them from the primary design optimization task. Even engineers take aid of automatic algorithms that does the complex calculations for them. The simulation software provided to the students used the Hagen–Poiseuille's equation for calculating water pressure (Appendix 6).

Recollection of prior knowledge about optimal plumbing systems: These prompts were intended to invoke students' personal experiences with plumbing systems and what they understood by good and bad plumbing systems.

Prescribed set of questions after every design iteration: Questions (Appendix 5) were designed to prompt students to reflect on the design ideas, critique them, and form design rationale.

Encourage model comparison and critique: The groups were prompted to compare their current models with both the initial seeding model as well as the previous model (from which they iterated to the current one). This was done with an intention to establish a sense of continuity and promote the notion of design optimization as a methodical and iterative process where the optimal model incorporated the best design decisions.

Making plumbing simulator unavailable during the design process: Students used a plumbing simulator to extract system properties before they began the design optimization process. However, they did not have access to this simulator once they started optimizing their model and were given the table of system properties that they had created during the whole class discussion. Students had to add, subtract or multiply numbers (for finding water pressure and total cost) manually or with a calculator using the system property table, instead of using the simulator. The intention behind this decision was to prevent a potential scenario where the design optimization task transformed into a plug and chug activity due to the presence of the simulator. In such a scenario, students could have simply read-off values of design cost and output pressure by placing the pipes in the simulator and copied the simulated model onto the physical design board. The removal of the simulator also slowed down the students and likely increased the effort that went into making the models iteratively. This was done in order to encourage students to be thoughtful about what they wanted to achieve with a particular iteration.

Provide iPads™ for capturing and reflecting on prior design iterations: Unique iPads™ were allocated to every group and they were asked to take a photo of their model after every iteration. This provided students greater agency and control of their design and documentation process as they had to decide when they felt their iteration was complete and ready to be documented. Every group's set of design revision was only visible to them in the library of images on the iPad™.

Set competitive project-based design goal: A competitive design challenge centered around a project imparts a sense of goal in the students' minds and acts as a motivating factor for prompting multiple design iterations with a continuous focus on working towards that goal. Engineering design activities usually revolve around projects having disciplinary focus and varying in terms of time scales and complexity (Mills & Treagust, 2003). A project-based design goal is authentic, directed to the application of knowledge, and provides students with the agency to manage their own time on task and resources (Mills & Treagust, 2003; Perrenet, Bouhuijs, & Smits, 2000). The engineering design challenge centered on the project of designing an optimal plumbing system was meant to leverage these benefits.

Guided discussions about understanding the science: Students were introduced to the concept of drop in water pressure across a given length and diameter of pipe. The influence of the pipe diameter and length on the output water pressure was discussed in a whole class setting with the help of a demo video created by an engineer around this concept. This was followed by a hands-on activity where students observed differences in output water pressure by pouring water through straws of different diameters. Students were introduced to Bernoulli's principle in the context of the plumbing system. These instructions and activities were intended to introduce the students to the basics of the underlying science without expecting that they would gain in-depth understanding about it.

Documentation of relationship between design parameters (system properties): Students created a table of values that highlighted the changes in the output parameters (pressure and cost) based on changing values of input parameters (pipe diameter, pipe length, and pipe bend). This table served the purpose of a reference sheet for recognizing patterns in the table of values and understanding the relationship between design parameters.

Final presentation: All the groups were instructed to include in their final presentations design decisions and rationale behind their optimal model. Instruction prompts were provided to help students organize their ideas, promote reflection on the entire design process, and enable the groups to filter out and select information that they wished to share with their peers in order to make a strong presentation for their group.

3.5 <u>Design of Simulation Software</u>

The simulation software, as shown in Figure 3, was designed to help the students explore system properties. Students could observe the effect of one design parameter on another and document their observations in a table (Appendix 7). The simulator uses Hagen–Poiseuille's equation (Appendix 6). Engineers use similar calculators based on this equation to calculate drop in pressure across a given cross-section of pipe. In addition, my simulator also calculated the cost of the model based on the market price of actual PVC pipes. The simulator performed the complex calculations (see Appendix 6 for Hagen–Poiseuille's equation) required to find out the output water pressure. The primary intent of black boxing these complex calculations using this simulator was to help the students focus on the design of the plumbing system and not get distracted by the complex calculations.

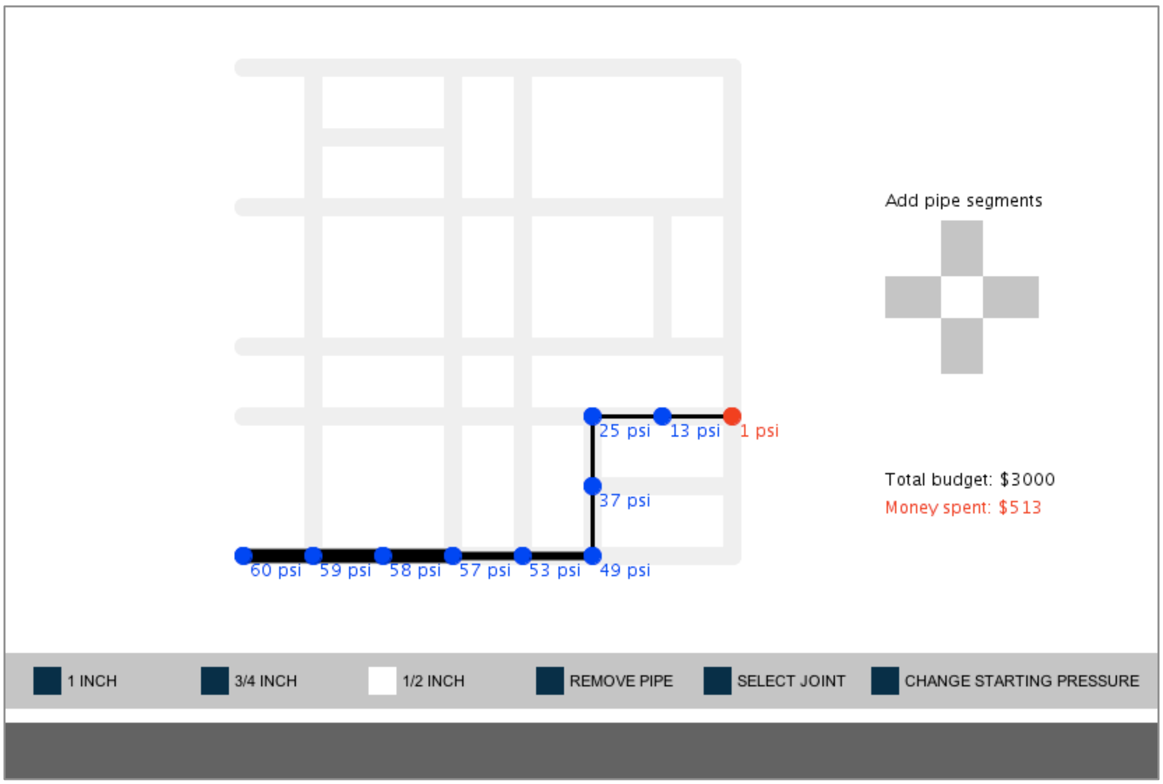

Figure 3. Simulation software screenshot

Click and add fixed length pipe segments: Initial versions of this simulator allowed the user to add pipe segments of variable length. However, preliminary user testing in the lab revealed that this interaction freedom made it challenging to track the relationship between the pipe length and its effects on water pressure and cost since incremental changes were not apparent. Noticing these incremental changes was important in order to extract the system properties. Thus, the simulator enabled students to add pipes of fixed length using direction buttons and observe the changes in cost and pressure for every unit of pipe added or removed.

Automatic calculation of values of cost and pressure: When students were using the simulator, they were guided to notice how the cost of the design and water pressure were affected by pipe length, pipe diameter and pipe bend. Automatically calculating the design cost and water pressure for the students enabled greater focus on the way these two parameters changed when pipe length, pipe diameter and pipe bend were changed. It encouraged identification of patterns.

Display pressure at the ends of each pipe segment: The simulator displayed the value of water pressure in psi at the end of each pipe segment. This was intended to reinforce the idea of pressure-drop across the length of the pipe segment and assert that every pipe segment affected the plumbing system.

Clear indication of start/end point of each pipe segment: The pipe segments were clearly demarcated in the simulator. This was intended to help students get familiar with the idea that the plumbing system was composed of segments of pipes (something that they encountered again while designing their system using the design board).

Ability to connect pipes segments of different diameters: This feature replicated the range of operations allowed with the design board by allowing the students to join together pipes of different diameters and observe the effect on pressure and cost.

Channel runs clearly displayed: The simulator displayed the set of black lines that represented the channels along which pipes had to be placed. This was intended to help students become familiar with the purpose of the channels in the design activity.

Total budget and net cost of the design: The total budget of $3000 and the current net cost of the design were clearly highlighted alongside the direction buttons used to lay pipes. This positioning was intended to make it easier for students to notice the variation in the total cost while they were adding pipes using the buttons.

3.6 <u>Research Setting</u>

This research study was conducted in an urban school in the Midwest. Three sixth grade classrooms participated in the study spanning 10 lessons, 45-minute long, totaling 8 days of instructional activity for each class spread across a month. Two types of Improvable Models (Suboptimal System model and Optimal Component model) were used as treatment conditions for the study and classes were assigned to these conditions randomly. One class (Class A) was assigned to the Optimal Component treatment condition and two classes (Class B and Class C) were assigned to the Suboptimal System treatment condition. Ms. E taught Class A. She had 5 years of experience as a science teacher and 9 years of total teaching experience at the time of data collection. Class A had 12 students (divided into 4 teams, each having 3 students) who consented to have their data recorded and used for this research. All teams in Class A started with the Optimal Component model as their seed model. Mr. K taught Class B. He had 2 years of total teaching experience as a science teacher at the time of data collection. Class B had 13 students, divided into 3 groups of 3 students and 2 groups of 2 students. All teams in Class B started with the Suboptimal System model as their seed model. Ms. C taught Class C. She had 10 years of total teaching experience as a science teacher at the time of data collection. Class C had 12 students (divided into 4 groups, each having 3 students) who consented to have their data recorded and used for this research. All teams in Class C started with the Suboptimal System model as their seed model. The respective class teachers divided the students into small groups.

The small groups of students in all the classes served as "plumbing companies" competing to win the bid for building the plumbing system of a house, with the winner being the company that met the pressure requirements (10 psi at every tap) for the least cost. The competition was within-class. Before the study, I had met all the three teachers and went over the entire instruction unit with detailed lesson plan to help them get familiar with it and prepare for the class.

The findings presented in this dissertation are from Class A (using Optimal Component model) and Class B (using Suboptimal System model). I did not use the data from Class C for this dissertation because of differences in the instruction sequence followed in this class as compared to the other two classes. Class C completed and reviewed their system properties worksheet one week before they had started designing their models. So on Day 5 of the instruction unit (Table II above), Class C directly started their design session. On the other hand, both Class A and Class B completed and reviewed their system properties worksheet on the same day and then started their design session. Also, the design session for all teams in Class C lasted only about 80 minutes due to an unplanned change in their schedule. The design session for all teams in both Class A and Class B lasted about 120 minutes. Given that both these factors have bearing on the design of optimal model and engagement with the activity, I decided to focus only on Class A and Class B for my analysis in order to ensure consistency across both the treatment conditions. Thus, the dataset used for analysis comprises of (a) Class A, 12 students divided into 4 teams, each having 3 students – Team OC-A (S3, S13, S14), Team OC-B (S2, S6, S10), Team OC-C (S1, S4, S9), and Team OC-D (S5, S11, S12) and (b) Class B, 13 students divided into 3 groups of 3 students and 2 groups of 2 students – Team SS-A (S26, S27, S28), Team SS-B (S21, S22), Team SS-C (S32, S33), Team SS-D (S29, S30, S31), and Team SS-E (S23, S24, S25). The shorthand notation OC and SS in each team name highlight the treatment conditions Suboptimal

System (SS) and Optimal Component (OC) models used by the teams. Also, I assigned numbers to students for ease of mapping to the treatment condition. Student numbers below 20 belong to Class A (Optimal Component treatment) while student numbers above 20 belong to Class B (Suboptimal System treatment).

3.7 Data Collection

Data sources for this research included student conversations (both small group and whole class discussions), student written work, models created by the teams, and final presentations. I recorded student conversations using video and audio recorders. Every group (except those who had not given consent to be audio/video recorded) had a dedicated audio recorder and a video camera to capture small group conversations. The audio recorders captured the same conversation as the video cameras and thus served as a backup source in case the video cameras ran out of battery or student conversations were not audible because of the location of the camera. Dedicated cameras for every group enabled me to decipher students' interaction and understand the content of conversation where students used pointing gesture and indirect references to design elements (e.g. "let's move this", "that", etc.). I also collected observational field notes when the students were working in their small groups to highlight when and where interesting conversations might be happening in the video data.

3.8 Data Analysis

I treated small groups of students, or plumbing companies (teams), as my unit of analysis. The analysis process unfolded as follows. After the data collection was completed, I analyzed the characteristics of the final optimized models designed by every team to identify differences or similarities between the models. I compared the models along the dimensions of layout and surface similarities, cost, and number of pipes of different diameters used. The aim of this initial analysis was to identify whether there were any differences between the models created by teams in the two treatment conditions. I noticed differences between the final models that were consistent across the treatments (e.g., the average number of ¾-inch diameter pipes in the final models in the Suboptimal System treatment conditions was higher than the Optimal Component treatment condition). Next, I identified Days 5-7 as my focus days (video duration of approximately 120 minutes) to analyze the design process using the Improvable Models that may have led to the differences noticed in the final models. I sampled the videos based on the teams who had designed the cheapest model in each class. I focused on cost because differences in the other two dimensions (different types of pipes and different layout) would get reflected in the cost dimension. Watching these videos helped me get familiar with the data and verify that the sound quality and angle of video capture was fit for transcribing. While I had taken care that all cameras and audio recorders were working and pointing at the right direction during the videotaping process in the classroom, there were a few occasions when I had found, after data collection for that day, that some of the cameras had not captured audio because of microphone issues. In such cases, I used the data from the corresponding audio recorders from the particular days/team and marked them as my audio source. I transcribed the 120 minutes long video of the two teams (one from each class) who had built the cheapest model. I used Inqscribe™, capturing classroom conversations and also adding gestures (pointing and holding gesture in parenthesis) wherever they were needed to understand the meaning of the conversations. The transcripts thus included all conversations between student and student, between student and teacher, and between student and facilitator that happened in the 120 minutes long design session.

Next, I analyzed the transcripts and grouped consecutive set of utterances (with gestures), which referred to the same plan of action, into “design ideas.” The plan of action was identified based on student actions or conversations and did not involve any additional interpretation from my side. For example –

S28: let's try to not have as many right angle turns (pipe bends)
S27: we have… (waving hands down the middle where they had placed pipes), we'll have lines (tracing the bends)
S28: I know, but we should try and think of direct path that should take less angled turns (running hands along a horizontal straight line across the board in between tap B and tap C)

This represents one logical unit grouped as a "design idea" about the plan of action to "not have as many right angle turns." Each design idea is bounded by student utterance that introduces a new plan of action identifiable by shift in attention to a different parameter not connected to the parameter that was previously in focus or shift in attention to a different section of the system or taking up a new task like doing calculations. Dividing the transcript into such design ideas helped me analyze the transcript as a collection of many ideas generated by the team in order to solve the engineering design challenge.

Next, I identified the design parameters (pipe length, pipe diameter, pipe bend, cost or pressure) that constituted each design idea, and use of the seed model in that design idea (if any). Seed model use was identified when students mentioned the model in their conversation or pointed at the seed model (either physical model or image of the model) during the design session. Next, I analyzed the design ideas to identify different types of disciplinary engagement that may be happening during the design activity. The types of disciplinary engagement were informed by the different engineering practices identified in the theoretical framework along with emergent practices that were seen in the data. I looked for themes and patterns across the design ideas in both the treatments using an iterative constant comparative method (Glaser & Strauss, 1967). Multiple rounds of coding reduced the types of disciplinary engagement to six codes. A subset of the transcript was then coded by another researcher using the refined codes and compared to identify any differences. When differences were noted, I discussed my rationale for using the codes in a certain way and refined the definitions further in order to reach an agreement about them that was best aligned with the research focus. I analyzed the transcripts using these refined codes. Table III below presents these six types of disciplinary engagement. Next, I transcribed the 120 minutes design session for all other teams in Class A (total 4 teams) and Class B (total 5 teams). I analyzed these transcripts by repeating the process of identifying design ideas, design parameters, type of disciplinary engagement (using the codes in Table III), and use of seed model.

TABLE III
TYPES OF DISCIPLINARY ENGAGEMENT

D_C	Students doing mathematical calculations S21: But could we do the calculations of this first? S21: So S2, you ready? S22: yeah S21: 45 times 27... S21: plus 33 times 5... S21: plus... 28 times 4? S21: plus 500
D_P	Students attending to either the input parameters (pipe bend, pipe length, pipe diameter) or the outcome parameters (water pressure, cost) but making no connection between the input and outcome parameters S27: we can't take any more off here S28: that's what I'm saying... what if we put one of these here (putting 1-inch diameter pipe after the branch before tap B) and take out some there (1-inch diameter pipe before the branch) S27: ok S28: you want to try it?
D_S	Students make an explicit or implicit connection between one or more input parameters and one outcome parameter. S26: we should make this a ½-inch (pointing at the ¾-inch immediately before

tap A)
S27: no
S26: yes
S27: no
S26: we don't need 21 psi
S27: trust me S6
S27: because then we will go down to 9 psi

D_T Students make an explicit or implicit connection between one or more input parameter and multiple outcome parameters and make a tradeoff

S26: let's change this one (pointing at the ¾-inch diameter pipe connecting tap C) to this (pointing at the ½-inch diameter pipe)
S27: no
S26: yesss…
S26: we have 21 psi (at tap C) it's good it'll save us some money!

D_W Students refine the constraints by weighing outcome parameters and make a tradeoff

S27: hey S28, why did we even change it from ½-inches? (replacing ¾-inch with ½-inch diameter pipes)
S28: no we are not… no because ½-inches are a drop of 12(psi)
S26: so what!
S28: no we are not using ½-inches
S28: they don't save you that much money
S26: yeah they do
S28: they save you like 5 dollars
S28: we are not losing that much

D_H Students articulate an overarching design principle or a heuristic informed by a rationale (may be stated explicitly or implicitly evident) to optimize their design.

S28: let's try to not have as many right angle turns (pipe bends)
S27: we have… (waving hands down the middle where they had placed pipes), we'll have lines (tracing the bends)
S28: I know, but we should try and think of direct path that should take less angled turns (running hands along a horizontal straight line across the board in between tap B and tap C)

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4. DISCIPLINARY ENGAGEMENT SUPPORTED BY USE OF IMPROVABLE MODELS

Engineers engage with practices of forming design heuristics, making tradeoffs, and reasoning with inter-connected design parameters while solving engineering design problems (discussed in detail in Chapter 2). Data from this study revealed that students engaged with these practices, performed calculations, and paid attention to design parameters in order to solve the design challenge given to them. The engagement with these disciplinary practices happened to various extents throughout the design session. While a majority of the design ideas reflected attention to individual design parameters (D_P, 48%) and performing calculations (D_C, 24%), students also engaged with the core practices of connecting input and outcome parameters (D_S, 18%), formation of design heuristics (D_H, 1%), weighing the outcome parameters and making tradeoff decisions (D_W, 5%), and reasoning with multiple interacting variables and making tradeoff decisions (D_T, 4%). Figure 4 shows the frequency distribution of engagement with the different types of disciplinary practices across the entire design session, for all the teams and both the treatment conditions.

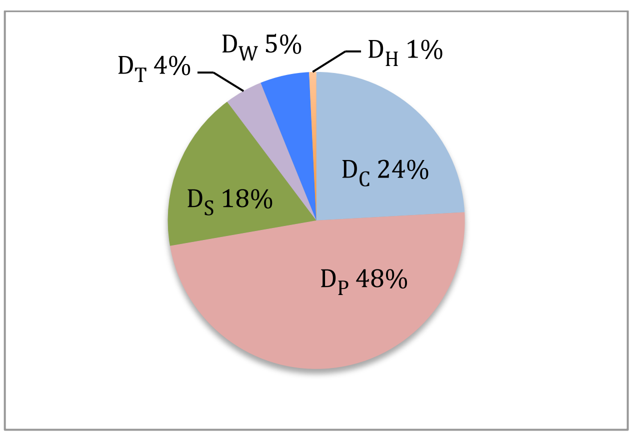


Figure 4. Overall distribution of types of disciplinary engagement (entire dataset, all treatments and teams combined)

Thus, core practices formed a small percentage across the entire design session. However, the distribution is different when I only analyzed the design ideas that were generated when students used the Improvable Models (Shown in Figure 5) during the design session. The percentage share of the core practices increased considerably.

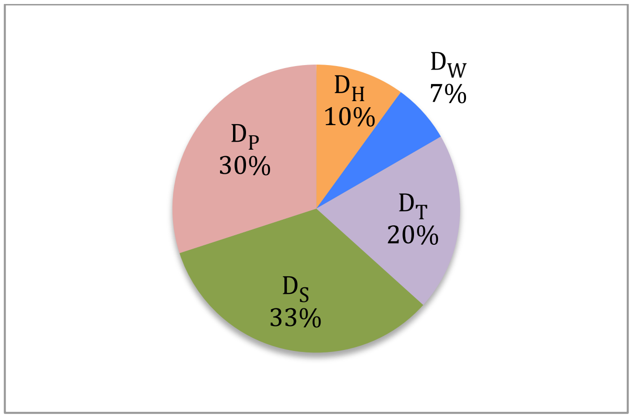


Figure 5. Distribution of types of disciplinary engagement when Improvable Models were used (entire dataset, all treatments and teams combined)

In other words, the share of the design ideas reflecting student engagement with the core practices of connecting input and outcome parameters (D_S, 33%), formation of design heuristics (D_H, 10%), weighing the outcome parameters and making tradeoff decisions (D_W, 7%), and reasoning with multiple interacting variables and making tradeoff decisions (D_T, 20%) increased considerably when students used the Improvable Models. The data revealed that students engaged with the core disciplinary practices while using the Improvable Models either spontaneously or when the teacher scaffolded their design process by giving different kinds of prompts. Episodes of student engagement with the core disciplinary practices while using the Improvable Models, either spontaneously or when scaffolded by the prompts, are presented in the section below. I also highlight the features of the Improvable Models that scaffolded the ebb and flow of the design ideas during these episodes.

4.1 Using the Improvable Models as Resources for Making an Explicit or Implicit Connection Between One or More Input Parameters and Single Outcome Parameter (D_S):

Teams formed design ideas about manipulating the input parameters by considering the effect on a single outcome parameter. One third of the design ideas (33%) generated by the teams while using the Improvable Models comprised of this disciplinary practice.

Decomposing challenge to focus on input parameter (pipe bend) and connecting with outcome parameter (cost). Students decomposed the design challenge and isolated the effect of the input parameter (pipe bend) on the outcome parameter cost while analyzing the Improvable Models. For example, immediately after the teams were given the design challenge, Team SS-B (Excerpt 1) analyzed the SS seed model and noticed the extra pipe bends near tap A. S21 counted the number of extra pipe bends near tap A in the SS seed model. The team generated the idea of placing pipes along a different path in order to reduce the number of pipe bends and optimize their model.

Excerpt 1 (Team SS-B)

1	S21:	Right now they (pointing at the SS seed model) are using 1...2...3...4, 5, 6, 7, 8 turns (pointing at the extra bends near tap A while counting them). Right? But if we go right there (pointing to an alternative path below tap A), that's 1, all the way up 2…3… 4 so that's why it's better instead of going turn, turn, turn, turn, turn, there up (tracing alternative path) and then down (towards tap C)
2	S22:	I have a better idea
3	S21:	do you agree?
4	S22:	I have… a better idea
5	S22:	I like your idea of going here (pointing at the same area that S21 was pointing)
6	S21:	it'll also save us a lot of pipe
7	S22:	it also saves you pipe too...
8	S21:	what's your idea? just...

S21 shared the idea of reducing the extra pipe bends near tap A with S22 by pointing at the areas of the design board near tap A and traced the alternative path that he was suggesting

(Excerpt 1, line 1). He spontaneously added the rationale that this idea would lead to a reduction in the number of pipes (pipe length) as well as number of pipe bends (line 1), making an implicit connection between the input parameters pipe bend and pipe length with outcome parameter of cost (line 6). The extra pipe bends in the SS seed model supported the formation of the idea of reducing the pipe bends and pipe length in order to optimize the model. However, the team moved on to another idea (Excerpt 9) without refining this idea further.

In another example (Excerpt 2), Team SS-D was modifying the SS seed model when the teacher (Mr. K) asked the team to articulate their design decision by asking "why are we thinking of going this way." Mr. K then waited for the students to provide their rationale.

Excerpt 2 (Team SS-D)

83	Mr. K:	why are we thinking of going this way?
84	S31:	because it's less, this is what I think, because it's less intersection so it's cheaper (waving hands over the bottom part of the design board)
85	Mr. K:	what do you mean by less intersection
86	S31:	or not intersections, it doesn't have as many turns (bends)
87	Mr. K:	ok
88	S31:	so it's cheaper
89	Mr. K:	ok

S31 presented the design rationale that his team had decided to place pipes horizontally along the bottom part of the design board since it didn't "have as many turns" (line 86), referring to the extra pipe bends in the SS seed model above tap A, resulting in reduction in the cost (line 88). Thus, the team made a connection between the input parameter (pipe bend) and outcome parameter (cost of the model). The teacher's disciplinary prompt asking why the students had built their design a certain way followed by waiting for and acceptance of students' response along with further clarification questions encouraged the students to present their design rationale using the SS seed model. Mr. K's prompt created space for the articulation of the connection between pipe bend parameter and cost of the model, using the SS seed model as reference.

Decomposing challenge to focus on input parameter (pipe diameter) and connecting it with outcome parameter (water pressure). Students formed design ideas by focusing on the input parameter (pipe diameter) in order to reduce the pressure while analyzing the Improvable Models. For example, in the case of OC seed model during the first iteration while Team OC-B was modifying the OC seed model (Excerpt 3), the facilitator gave a disciplinary prompt and reminded Team OC-B to discuss their design rationale (F: "ok, so when you guys make these changes, just say why you are making them"). The team responded to this prompt and explained their design decisions by comparing their design changes with the OC seed model.

Excerpt 3 (Team OC-B)

49	S10:	ok, so far we have made it go a different way (looking at the seed model's image)
50	S2:	we made it one straight line... not one straight line, we made it one line... branch a little (waving hand over the middle of the design board)
51	S10:	but I think ...
52	S10:	but I think the pressure might run out so we can change to ¾-inch eventually
53	S2:	yeah

The team used the layout of pipes in the OC seed model to articulate that they had placed the pipes differently, along a straight line (Excerpt 3, line 49—50). They also mentioned that their modification might cause the output pressure at the taps to fall below the constraint ("pressure might run out", line 52) in which case they would have to use ¾-inch diameter pipes. The team made a connection between the input parameter pipe diameter and outcome parameter water pressure. They also made a prediction based on the current design changes. The facilitator's initial disciplinary prompt asking students to provide a design rationale encouraged students to articulate their design rationale, forming a connection between the input and outcome parameters. After responding to the prompt, the team moved on to another design idea and started calculating the cost of the model and pressure drop across the pipe segments that they had placed.

Decomposing challenge to focus on area of interest as well as input parameter (pipe length) and connecting it with outcome parameter (cost). Students used the existing pipes in the Improvable Models to reason about which area of the model to use for placing pipes and also focus on reducing the length of pipes to reduce the cost of the model. For example, in the case of OC seed model during the first iteration, Team OC-B analyzed the OC seed model (Excerpt 4) and then started discussion ideas about modifying the model by reusing a section of the pipes near tap B (Excerpt 4).

Excerpt 4 (Team OC-B)

16	S2:	if we go this way (continues tracing the pipes vertically and then draws a horizontal path using existing the seed model pipes near tap B) and form a straight line..
17	S2:	then it's less money not…
18	S10:	(cuts S2) no it's
19	S10:	(tracing path from source towards tap A) <unclear>
20	S2:	here go here this way that one that one (using the same path as he had suggested earlier in line 16 but now branching to connect tap C).. simple

The team discussed their design rationale supporting differing views and made a connection between the pipe length parameter and the cost of the model (line 17 – 19). Further (Excerpt 5), S10 used the OC seed model to figure out which area of the design board should be used in order to branch out effectively. He selected the vertical section of the OC seed model as the area of interest and suggested branching off from that section towards the three taps.

Excerpt 5 (Team OC-B)

21	S10:	I know, go here (traces horizontal path along seed model's pipes), branch out here (to tap A) and then branch out two ways (making a fork towards tap B and tap C from the seed model's vertical section)
22	S2:	yeah but it costs... costs a lot more than if we just did a one straight line

23	S10:	ok, so… let's try..

S10 focused on the vertical section of the seed model and shared his idea of branching out to tap B and C (Excerpt 5, line 21). He used a hand gesture (making a fork out sign above the OC seed model's vertical section) for indicating the branch. S2 followed S10's idea but suggested that it would cost more if they did it like that instead of going in a straight line (line 22). The team spontaneously made a connection between the pipe length parameter and cost parameter. The OC seed model helped the team determine an appropriate area for branching and also articulate their design ideas, leading to negotiation about placing pipes one way or the other based on how it would affect the outcome parameter. After this discussion, the team decided to remove the pipes given in the OC seed model and put them along a different path according to their plan.

4.2 Using the Improvable Models as Resources for Making an Explicit or Implicit Connection Between an Input parameter and Multiple Outcome Parameters and Making Tradeoffs (D_T):

Teams formed design ideas about manipulating the input parameters by considering the effect on both the outcome parameters, making tradeoff decisions. 20% of the design ideas generated by the teams while using the Improvable Models comprised of this disciplinary practice.

Decomposing challenge to focus on input parameter (pipe diameter) and connecting it with outcome parameters (water pressure and cost). Students broke down the challenge by isolating the pipe diameter parameter and discussed design ideas about manipulating this parameter based on potential impact on the water pressure and cost of the model. They weighed the outcomes of using different pipe diameters along these two dimensions (pressure and cost) and made tradeoff decisions while determining how to balance these two outcome parameters. For example, Team SS-A analyzed the SS seed model and determined that they wanted to place pipes along the middle of the design board. They refined this idea further (Excerpt 6) by combining it with the idea of using ¾-inch diameter pipes instead of 1-inch diameter pipes in order to reduce pressure and cost.

Excerpt 6 (Team SS-A)

21	S26:	that tap (C) is 26 (psi), we don't need all these ones here (running hand over the 1-inch pipes)
22	S27:	how much money do we have left?
23	S28:	<unclear>
24	S27:	ok, how much pressure do we have left?
25	S28:	let's take out some of the 1-inches and put ¾-inches

While the team was placing pipes along the middle of the design board, S26 pointed towards the SS seed model's 1-inch pipes that they had decided to reuse. S26 generated the idea that they should replace them since they did not need 26 psi at tap C (Excerpt 6, line 21). The team combined this idea with their earlier idea of placing pipes through the middle and agreed to replace some of the 1-inch diameter pipes that they had been placing with ¾-inch diameter pipes, making a tradeoff between cost and pressure (lines 22 – 25). The ¾-inch diameter pipe, which cost $33 and resulted in a pressure drop of 4 psi, reduced the pressure as well as the cost when compared to 1-inch diameter pipes, which cost $45 and resulted in a pressure drop of 1 psi. The team reasoned that they would still satisfy the minimum pressure constraint of 10 psi by using ¾-inch diameter pipes but potentially saved more money by using ¾-inch diameter pipes, thus spontaneously making the tradeoff that using ¾-inch diameter pipes instead of 1-inch diameter pipes that came with the SS seed model would help them optimize the model.

In the case of OC seed model (Excerpt 7), Team OC-C used the OC seed model's existing pipes to spontaneously focus on the pipe diameter while extending the OC seed model to connect all the taps. S9 decided to add 1-inch diameter pipes to the existing seed model's design (line 33) in order to get a higher pressure at tap A and tap C, the taps that had not been connected in the OC seed model, making a tradeoff between pressure and cost.

Excerpt 7 (Team OC-C)

33	S9:	(placing 1 inch pipes and extending the seed model to connect tap A and C) let me put it here so that the psi is strong.
34	S4:	<unclear> (pointing at the pipe segments being laid by S9) so if it doesn't reach then...
35	S4:	it won't fit (pointing to the uneven length of some pipe pieces)
36	S4:	guys, we went wayyy over budget

After S9 placed the 1-inch diameter pipes, S4 calculated their cost and determined that the 1-inch diameter pipes were making their cost exceed the budget (Excerpt 7, line 36). They rechecked their calculations and found that they were not exceeding the budget and so moved on with implementing their design idea. A little later, the team used the existing pipes in the seed model again (Excerpt 8) to focus on the ¾-inch diameter pipes near tap B (part of the OC seed model's design) while replacing pipes near tap A and tap C to get higher pressure.

Excerpt 8 (Team OC-C)

86	S1	we should make these bigger (putting hand on the ¾-inch pipes from the seed model's design leading to tap B)
87	S9	no we'll be fine still

They wanted to "make these bigger" (line 86) i.e., replace the ¾-inch diameter pipes that were part of the seed model near tap B with 1-inch diameter pipes in order to increase the pressure at tap B. But S9 commented that they did not need 1-inch diameter pipes since the pressure at tap B still satisfied the constraint of 10 psi (line 87). The team spontaneously made a connection between pipe diameter parameter and water pressure, making tradeoff decisions regarding what pipe diameter to use and validating their design change using the design constraint.

4.3 Using the Improvable Models as Resources for Weighing Outcome Parameters and Attempting to Reach Equilibrium Between Outcome Parameters by Making Tradeoffs (D_W):

Teams formed design ideas centered around refining the constraints given to the students and determining ways of maintaining a balance between the cost and pressure design parameters by taking into consideration the tradeoffs associated with attaching more design value to pressure or cost. 7% of the design ideas generated by the teams while using the Improvable Models comprised of this disciplinary practice.

Decomposing the challenge to focus on the input parameter (pipe diameter) and connecting it with outcome parameter (water pressure) while refining the constraint. Students broke down the design challenge to focus on the input parameter pipe diameter in the context of refining and weighing the outcome parameter water pressure. For example, in the first iteration while analyzing the SS seed model, Team SS-B (Excerpt 9) used the SS seed model to determine what diameter of pipes to use after they identified the upper bound for the pressure constraint. S21 read out the seed model's pressure at tap A and determined that it was "a LOT" (line 18).

Excerpt 9 (Team SS-B)

18	S21	42 is a LOT. So what we could do is like put these two as… really thin ones (pointing to the ½-inch pipes)
19	S22	and that's <pipe?>, no you will get more pressure from here
20	S21	no you wouldn't
21	S22	yeah, we are going down (towards tap C), if you go there then go... you go here and here (tracing on the design board but occluded).
22	S21	yeah but, look S22, so when you turn this one on (referring to tap C)
23	S22	you don't even get water here (tap C)
24	S21	what do you mean? let me see
25	S22	Zero psi

S21 pointed out that tap A had a very high pressure and they should use ½-inch diameter pipes to reduce it (line 18). The team used the value of 42 psi as an upper limit for the output pressure, refining the pressure constraint, which had the lower limit of 10 psi (specified as part of the design challenge). In this process, the team made a spontaneous tradeoff between cost and pressure, deciding to reduce the pressure. S22's response that tap C had zero psi (referring to the SS seed model's pressure at tap C), made S21 take notice of the range of pressure (Excerpt 9, lines 23 – 25) that they were working with. After this discussion, the team started thinking about ways of increasing pressure at tap C while decreasing pressure at tap A.

Decomposing the challenge to focus on the outcome parameters (water pressure and cost). Students broke down the design challenge to just focus on the outcome parameters and balance them to determine the scope of manipulations possible in the given design context. For example, Team OC-B (Excerpt 10) analyzed the OC seed model in the first iteration and S2 generated the idea of placing pipes along a vertical path near the source going towards tap A, which then connected with tap B using the OC seed model's existing pipes (line 9). The idea of reusing the seed model's pipes near tap B led the team to negotiate the idea of branching and then have a discussion about the tradeoff between pressure and cost.

Excerpt 10 (Team OC-B)

9	S2:	So I think for ours we should probably do... (starts tracing out pipes splitting from the seed model's pipe)
10	S10:	branching out
11	S2:	nope
12	S2:	you don't want to branch out, it's more
13	S10:	you know branching out is less, so we should branch out 3 times (brings both palms together over the seed model's vertical segment and then opens them to make a fork shape) because then it keeps the pressure
14	S2:	yeah, but it costs more

When S2 shared his idea for connecting the source with tap A and tap B by reusing part of the seed model's pipes, S10 objected to the idea and pointed out an alternative route. He suggested branching out from a place along the vertical section of the seed model (Shown in Figure 6) in order to connect the three taps (Excerpt 10, line 13).

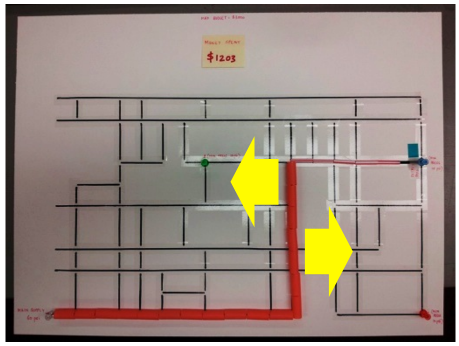


Figure 6. Team OC-C's proposed modification to the OC seed model

He reasoned that this would ensure adequate output pressure at the taps (line 13). However, S2 challenged S10 by suggesting that branching would increase the cost, since every pipe bend adds an extra $100 to the model's cost (line 14). After this negotiation process, the team finally agreed to try out branching to understand how the pressure and cost were being affected by their design modification. The team found branching useful for maintaining the equilibrium between cost and pressure and used that repeatedly throughout all their design iteration.

4.4 Using the Improvable Models as Resources for Articulating an Overarching Design Principle or a Heuristic Informed by an Implicit or Explicit Rationale (D_H):

Teams formed design ideas that were accepted by all the team members as rules driving their design decisions. These ideas were applicable throughout the design session. 10% of the design ideas generated by the teams while using the Improvable Models comprised of this disciplinary practice.

Decomposing challenge to focus on area of interest and generating a rule for guiding the design process. Students divided the challenge into smaller chunks by focusing on specific physical areas of the Improvable Models to form design ideas. For example, while the teams were analyzing the Improvable Models in the first iteration, Team SS-A (Excerpt 11) analyzed the extra pipe bends and long-winding pipes above tap A in the SS seed model—suboptimal features in the SS seed model—to first identify that there was "obviously no point" in using the area above tap A, eliminating this area with extra pipe bend and long winding pipes from their design focus. The team then focused on the remaining areas on the design board and determined that the middle area of the seed model, below tap A, should be used instead.

Excerpt 11 (Team SS-A)

5	S26:	there's obviously no point in doing it here (sliding hand across the section with extra bends and 1-inch pipes going above tap A in seed model) when you can go here (making a straight horizontal line right through the middle of the model)
6	S27:	yeah, so I think exactly
7	S28:	we need to get to a position...
8	S27:	we sort of go here (along the path that S26 just suggested) and go across here (right all the way near tap C) and then branch it off this way (making branching sign with hand towards tap C and tap B) and you can branch it off here (branching off towards tap A from an earlier point)
9	S26:	exactly, let's do it

S26 first analyzed the SS seed model and shared the idea that the extra pipe bends and pipe segments above tap A were not required. He then spontaneously generated the heuristic of placing pipe segments along a horizontal straight line through the middle portion of the seed model (in between all the three taps) (line 5). S27 then refined this idea by reusing part of the seed model, adding details about where to branch in order to connect all the taps with S26's pipe segment along the middle (line 8). This helped the team reduce cost as well as ensure adequate pressure at the taps. Team SS-A scoped out the part of the SS seed model for modification that had been made salient due to the extra bends and pipe length (Shown in Figure 7).

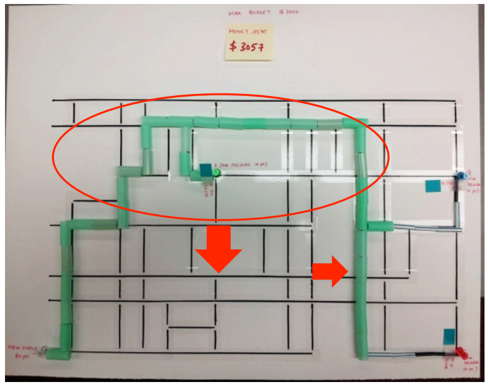


Figure 7. Team SS-A's proposed modification to the SS seed model

They kept the portion of SS seed model (where the pipes branched near tap B and tap C) same and connected the modified part with this preserved part. S26 agreed with this refinement (line 9) and the team started implementing the idea after this discussion. The SS seed model, thus, formed a basis for generating the heuristic of placing pipes along the middle of all the three taps and branching out to connect the taps. The existing branching available for tap B and tap C potentially helped anchor the refinement discussion centered around modifying the section around tap A.

Decomposing challenge to focus on an input parameter and generating a rule for guiding the design process. Students divided the challenge into smaller chunks by isolating an input parameter while using the Improvable Models to form design ideas and generating a rule that was tied to that parameter. For example (Excerpt 12), while Team SS-E was making their design changes, S24 used the SS seed model to focus on pipe bend and generate the heuristic that they needed to have the least number of bends (line 67).

Excerpt 12 (Team SS-E)

67	S24:	we want to have the least amount of bends (pointing at the seed model)
68	S23:	now we need to figure out the pressure
69	S25:	no hold on…
70	S25:	1 2 3 4 5 6 7 8 (bends)
71	S24:	no wait, you have to do 800 and then the pipe
72	S25:	yeah I know I did that

73	S24:	every bend is 100
74	S25:	yeah I know

After S24 shared this heuristic, his team's focus turned towards the pipe bend parameter. Everyone accepted the idea as a rule. S25 jumped in to calculate the number of bends due to their design changes (Excerpt 12, line 69). They determined the effect of having eight bends on the cost of the model (line 71 – 74). This rule then informed all their future iterations and was visible in the form of the team trying to reduce the number of bends whenever possible.

The nature of the design activity allowed the teams to engage with different practices as and when required during the design session. The episodes of student interaction presented in this chapter highlight how the Improvable Models scaffolded student engagement with various disciplinary practices. The SS seed model's extra pipe bends, long winding 1-inch diameter pipes, and high pressure (42 psi) at tap A scaffolded students' engagement with the disciplinary practices. In the OC treatment condition, teams used the OC seed model's layout comprising of the vertical section of the pipes between source and tap B and the pipes connected to tap B to inform their design decisions and engage with the disciplinary practices. The features of the models served as initiators or primary generators for engaging with the disciplinary practices. The prompts provided by the teachers and facilitator also scaffolded the process by creating space for the students to articulate their design rationales underlying various design decisions.

In the next two chapters, I will present the findings specific to each treatment condition, highlighting the key differences between the disciplinary engagements in the two classes with additional focus on productivity. These chapters highlight the ebb and flow of student interaction using various affordances of both the types of Improvable Models along with prompts given for scaffolding productive disciplinary engagement.

5. SUBOPTIMAL SYSTEM MODEL AND DESIGN HEURISTICS

In Chapter 2, I had highlighted that engineers engage with the practice of forming design heuristics in order to determine effective ways of optimizing design solutions. Data from this study revealed that only the students who started with the SS seed model engaged with the practice of heuristics formation. The figures below (Shown in Figure 8 and Figure 9) illustrate the distribution of different disciplinary practices when students used the Improvable Models in both the treatment conditions. The distribution highlights the presence of heuristics formation as a practice that students engaged with in the SS seed model treatment.

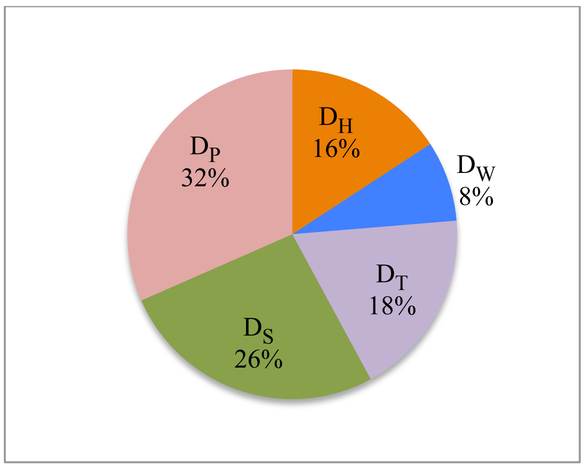


Figure 8. Distribution of types of disciplinary engagement when SS model used (Class B)

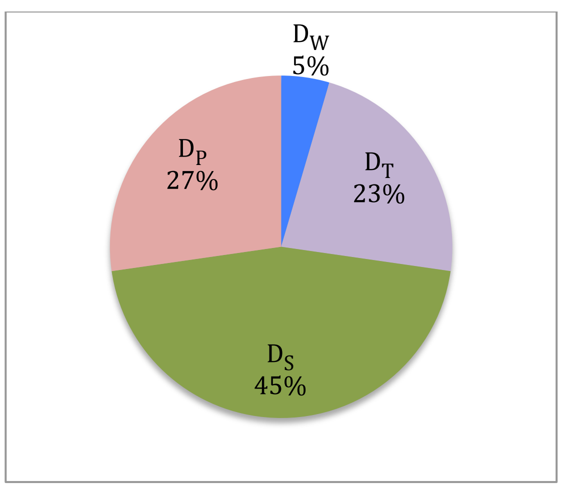


Figure 9. Distribution of types of disciplinary engagement when OC model used (Class A)

16% of the design ideas generated by the teams while using the SS seed model comprised of heuristics formation and use. Three out of five teams using the Suboptimal System seed model generated and used design heuristics over multiple iterations to optimize their solution for the engineering design challenge. These heuristics guided the design optimization process and construction of the final solutions for these three teams that were the three cheapest solutions across both the treatment conditions. None of the design ideas generated by the teams using the OC seed model were about heuristics generation and use. In this chapter, I focus on the inter-play between the Suboptimal System model (SS seed model) and design heuristics to show how the SS seed model scaffolded the process of heuristics generation, refinement and use. The SS seed model served as a baseline example that the students used to determine how their optimal model should not be designed, thus using it as a counterexample. I use the case of Team SS-A to illustrate the ebb and flow of student interaction around design heuristics during the entire design session. Team SS-A consisted of three students – S26, S27, and S28. Mr. K taught this class (Class B).

5.1 Generating a Heuristic: Placing Pipes Along the Middle

In the first iteration, immediately after analyzing the SS seed model, Team SS-A formed the heuristic of placing pipes along the middle of the design board (in-between all the three taps) and connecting the taps with the source point by branching out from this central section of pipes (Chapter 4, Excerpt 11). I showed in the previous chapter how the suboptimal features of the SS seed model—extra pipe bends and long winding pipes near tap A—scaffolded this heuristic generation process. The team used the SS seed model as a counterexample and decided that they did not need the extra bends and long-winding pipes. The team followed up this discussion by modifying the SS seed model according to their heuristic. They moved the pipes that were originally going above tap A and arranged them along the middle of the design board, branching out near tap A to connect that tap, and connecting their central pipe section to the SS seed model's existing section of pipes for connecting tap B and C. The team calculated the cost of the model as well as the pressure at the three taps after making these changes. By the end of the first iteration, the team had worked productively and successfully optimized the model by reducing the cost and improving the pressure at the taps by making design modifications based on their heuristic.

5.2 Refining the Heuristic: Direct Path

During the third iteration (on the first day), the team analyzed their design revision to figure out how they could improve the model further. The revised model, at this moment, had been designed as per their heuristic of placing pipes along the middle of the design board in order to reduce the bends and length of pipe but the team wanted to reduce the cost further. S28 suggested (Excerpt 13) that they should try to reduce the number of bends further (line 157), pointing at the pipe bends and branching near tap B and tap C where the pipes along the middle branched off towards the two taps. This was the branching of the SS seed model that they had reused in the previous iterations. The team used the SS seed model's layout as a counterexample ("let's try to not have as many right angle turns," line 157) to determine how to improve their model further by reducing the number of bends between tap B and tap C.

Excerpt 13

157	S28:	let's try to not have as many right angle turns (pipe bends)
158	S27:	we have… (waving hands down the middle where they had placed pipes), we'll have lines (tracing the bends)
159	S28:	I know, but we should try and think of direct path that should take less angled turns (running hands along a horizontal straight line across the board in between tap B and tap C)

S27 tried to understand what S28 meant and said that they will always have pipe bends (Excerpt 13, line 158). He referred to the pipes that they had placed along the middle of the design board as per their heuristic formed in the first iteration. S28 responded by suggesting that they should try to "think of direct path" (line 159). He made a horizontal line between tap B and tap C suggesting that he wanted the team to think about reducing bends in that area of the design board now (in the first iteration they had focused on the area around tap A). This idea of a "direct path" was a refinement of their earlier heuristic of placing pipes along the middle of the design board that they had generated using the SS seed model. Thus, the team recalled the heuristic that they had generated using the SS seed model and refined it. They used this refined heuristic for their future design revisions.

5.3 <u>Generating a Heuristic: ¾-inch Diameter Pipes Have More Worth Than Other Pipe Diameters</u>

While the team was working on implementing the direct path heuristic, S28 realized that there was a flaw in their design (Excerpt 14). The teacher, Mr. K, gave a disciplinary prompt by encouraging S28 to talk about his observation and share his design strategy with the team. He also gave a procedural prompt, asking S28 to record his explanation while sharing it with the team.

Excerpt 14

163	S28:	(talking to himself) - I know what is the fault in our design
164	Mr. K:	so do you want to talk about your strategy and what you see is the fault in your design?
165	S28:	yeah
166	Mr. K:	talk about it into the microphone
167	S28:	the flaw that we saw is that <unclear> ½-inch pipes are actually not worth so we can save more money using ¾-inch pipes instead
168	S27:	we have 18 psi right here (tap C)
169	S28:	yeah, but what I'm saying is that you could take three (pointing at ½-inch pipes) and then take away some of these (1-inch before tap C) and use 3/4 here and actually gain psi (pointing to tap C)

170	S28:	think about this, this is ...
171	S27:	if you take away these 2 (removing two 1-inch pipes before tap C) then it will go down to 10 psi
172	S28:	but why can't you take away these (pointing at ½-inch pipes)
173	S28:	these are dropping 12 psi and you are only saving 5 dollars
174	S27:	(removes ½-inch pipe before tap C)
175	S28:	why don't you take away ... and you can get 3/4
176	S28:	and you take away some of these (removing one more 1-inch pipe)
177	S28:	and now you save bunch of money ... (replacing with ¾-inch pipes)
178	S28:	and we probably just gained psi
179	S28:	the black.. ½-inch pipes are not worth it
180	S28:	so think about this... so
181	S28:	you got to keep that there (not clear from video what is being referred to)
182	S28:	just take away this (removes ½-inch before tap B and puts in ¾-inch pipes)
183	S28:	and now we are at 22
184	S28:	take away this (removes 1 inch after the branch towards tap B)
185	S28:	you are at 18
186	S28:	take away this (replaces the next 1 inch with 3/4)
187	S28:	that's 12.. 14
188	S28:	you just gained pressure and saved money
189	S27:	let's do that math

S28 articulated the heuristic that "½-inch pipes are actually not worth so we can save more money using ¾-inch pipes instead" (Excerpt 14, line 167). Mr. K created space for this articulation to happen by encouraging S28 to share his design strategy. He posed a question and then waited for the students to respond. He also asked the students to record the explanation in the microphone, removing himself from the interaction and transferring authority back to all the students in the team and making them accountable for their design decisions. S28 now spoke into the microphone as well as addressed his teammates, presenting his design strategy and inviting critiques from them. In response to S28's comment about using more ¾-inch diameter pipes, S27 pointed that they had 18 psi at tap C, presumably suggesting that they were satisfying the pressure constraint (line 168). S28 then elaborated the rationale underlying his heuristic. He suggested that they could optimize their model further by using more ¾-inch diameter pipes since these pipes helped reduce the cost similar to the ½-inch diameter pipes but did not reduce the pressure as much (lines 169 – 173). The team discussed the tradeoff of using more ¾-inch diameter pipes. S28 suggested replacing a combination of ½-inch and 1-inch diameter pipes with ¾-inch diameter pipes to improve their model. He then demonstrated what he was suggesting by incrementally replacing the 1-inch and ½-inch diameter pipes with ¾-inch pipes (lines 175 – 188). He finished off by revisiting the tradeoff associated with using the ¾-inch diameter pipes when he said "you just gained pressure and saved money" (line 188).

The idea of using ¾-inch pipes had first originated in the first iteration (Chapter 4, Excerpt 6) while using the SS seed model. At that time, in the first iteration, it was S28 who had suggested replacing the 1-inch pipes of the seed model with ¾-inch pipes ("let's take out some of the 1-inches and put ¾-inches," Chapter 4, Excerpt 6, line 25), evidencing the use of the SS seed model as a counterexample. The team had eventually replaced 1-inch diameter pipes that were part of the SS seed model's design with ¾-inch diameter pipes. Now, in this third iteration, while looking for ways of optimizing their model further, it appears that S28 continued his initial line of thought of using ¾-inch diameter pipes that had originated due to the SS seed model. At the same time, it could be possible that there might be no connection between these two episodes of conversation. The reason why there might be a connection is because both the first and third iterations occurred on the same day and the team had only replaced two more 1-inch diameter pipes near tap B and one more 1-inch diameter pipe near tap C with ¾-inch diameter pipes in the second iteration, thus continuing the implementation of the idea of using more ¾-inch diameter pipes that S28 had initially suggested in the first iteration. It is likely that the second iteration helped them refine their idea of using more ¾-inch diameter pipes in order to optimize the model by observing the effect on cost and pressure. Thus, it is likely that the heuristic of using ¾-inch diameter pipes in the third iteration was scaffolded by the use of the SS seed model as a counterexample. The second iteration where the team varied only the pipe diameter must have helped them realize the benefit of using ¾-inch diameter pipes, which likely influenced the generation of the heuristic of using ¾-inch pipes in the next (third) iteration. The team made tradeoff decisions while determining the worth of using ¾-inch pipes.

5.4 Recollecting Use of Heuristics: Direct Path and Use of ¾-inch Diameter Pipes

On the second day of the design activity, Mr. K began the class with a reflective task that all the teams had to do before they could continue with their design revisions. Mr. K asked the teams to reflect on all their models – SS seed model, all design revisions, and current model. He encouraged students to think if any of their models was a "step backward" and if so, why. He combined disciplinary and reflection prompts, encouraging students to critically evaluate their own prior work and provide explanations. He gave them prompts that scaffolded the critique and reflection process (e.g., "how your design is different than…from the original design. So what I mean is, what changes did you make… How is my design improving? What did I do? So you are taking a look at the original and thinking about how you are able to improve it"). In response, Team SS-A started comparing the images of SS seed model and their previous design revisions (Excerpt 15).

Excerpt 15

275	S26:	what's the best one?
276	S26:	2229 (cost of the fourth design revision)
277	S26:	what's that, how much is that?
278	S27:	it's not in this picture
279	S27:	but here it's 2229
280	S27:	here (pointing at the seed model's image) it's 3021 (actual cost of seed model is 3057 but it is not clearly visible in the image)

During this comparison process, the team used the cost of the seed model ($3057, which they misread as $3021) for their comparison process (Excerpt 15, line 280). A little later, the facilitator gave a reflection prompt, asking the team "how is this (current model) better than the original model (SS seed model)?" In response (Excerpt 16), S27 picked up the image of the SS seed model and assessed the changes that his team had made.

Excerpt 16

343	S27:	so we have enough water pressure and we save money here (pointing at the extra bends and 1-inch pipes above tap A in seed model)
344	S27:	so we changed it and made it like here (pointing at their first design revision where pipes were placed along the middle of the design board)
345	S27:	then we changed 1 inch pipes to 3/4s (pointing at the 1-inch pipes they had replaced with ¾-inch pipes in their second design revision)

S27 used the SS seed model for decomposing the design challenge into area of interest (highlighting the middle of the design board) as well as input parameter. The team articulated their tradeoff decision for balancing pressure and cost (line 343). S27 compared their current model and the SS seed model and pointed that they had placed the pipes along a direct path down the middle of the design board to reduce the extra bends in the SS seed model and save money, and used ¾-inch diameter pipes (line 344) in order to have adequate pressure and also reduce cost (lines 343—344). Both these modifications had been based on the "negative" features that the team had identified in the SS seed model and did not want their optimal model to have i.e., use of the SS seed model as a counterexample.

By revisiting these changes, it is possible that the team implicitly recollected the associated heuristics – direct path and use of more ¾-inch diameter pipes. Explicit references to the heuristics were not made during this comparison process. On the other hand, it is also possible that the team had forgotten about their heuristics and was procedurally comparing their models based on surface level differences only. But the likelihood of comparing surface level differences only without having a strong underlying rationale for the comparison is low because of the following conversation that happened after this comparison process (Excerpt 17). S26 wanted to reduce the cost further by using more ½-inch diameter pipes but S28 did not support the idea.

Excerpt 17

453	S28:	NO we are not using 1/2 inches,
454	S28:	they don't save you that much money
455	S26:	yeah they do
456	S28:	they save you like 5 dollars!
457	S28:	we are not losing that much
458	S26:	well, we can get rid of some of these 1 inches (pointing to the 1 inch pipes before the 2nd branch but S27 removes his hand)
459	S27:	(replaces the 1-inch that S26 was tapping, with ¾-inches, S28 does not object to this change)

S28 strongly opposed S26's idea of replacing ¾-inch diameter pipes with ½-inch diameter pipes by emphasizing the tradeoff that they had made (Excerpt 17, lines 453 – 457). However, S28 did not oppose the replacement of 1-inch pipes with ¾-inch pipes (lines 458 – 459), likely because of their earlier heuristic of using more ¾-inch diameter pipes than the other two types of pipes. This indicates the likelihood that the team was following through with their heuristic of using ¾-inch diameter pipes for optimizing their design while explaining their design changes in Excerpt 16.

After the comparison process in Excerpt 16, when the facilitator gave a procedural prompt, asking the team to make sure they were answering the list of disciplinary and reflection questions, S28 responded by recording their design rationale (Excerpt 18).

Excerpt 18

386	S28:	(Q1) how was your design better then the first one (seed model) that was given to you?
387	S28:	our design is better than the 1st one given to us because it has even psi
388	S28:	it's cheaper and it has less right angles so that saves us a lot of money

S28 compared their current model with the SS seed model along the dimensions of cost and pressure (Excerpt 18, 387 – 388). He used the seed model to decompose the challenge and focus on the input parameter – pipe bend, and highlighted the relationship between pipe bend and cost while forming the design rationale. The team had earlier formulated the heuristic of using a "direct path" with fewer pipe bends during the third iteration. The rationale provided by S28 here indicated the use of that heuristic for design optimization.

5.5 Productive Disciplinary Engagement

Team SS-A worked productively during their design session and optimized the model iteratively. The final model highlighted the productive work done by the team and reflected the incremental changes they had made informed by their heuristics. Team SS-A's first design revision cost $2307 (Shown in Figure 10). Their final design revision cost $1780 (Shown in Figure 11). It consisted of more ¾-inch diameter pipes than 1-inch diameter pipes and no ½-inch diameter pipes, reflecting their heuristic for using ¾-inch diameter pipes. It also used minimal number of pipe bends, a reflection of their "direct path" heuristic.

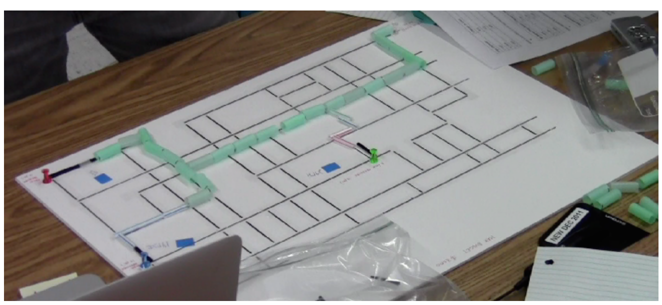


Figure 10. First design revision by Team SS-A: $2307

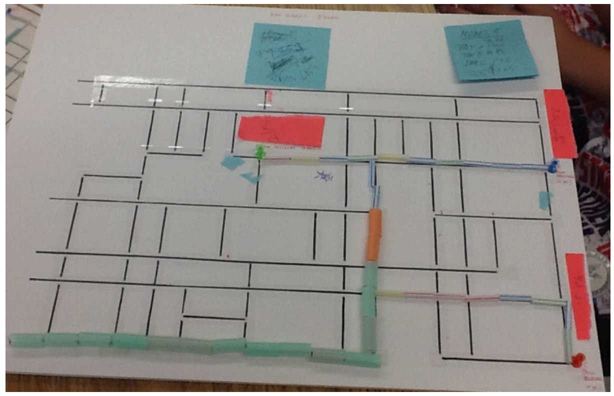


Figure 11. Final model by Team SS-A: $1780

The design trajectory followed by all the teams in the Suboptimal System treatment, represented by tracing the cost of the design revisions for every iteration, indicates productive work across the multiple iterations (Shown in Figure 12). The cost of the model reduced between the first and final iterations for all the teams, including Team SS-A.

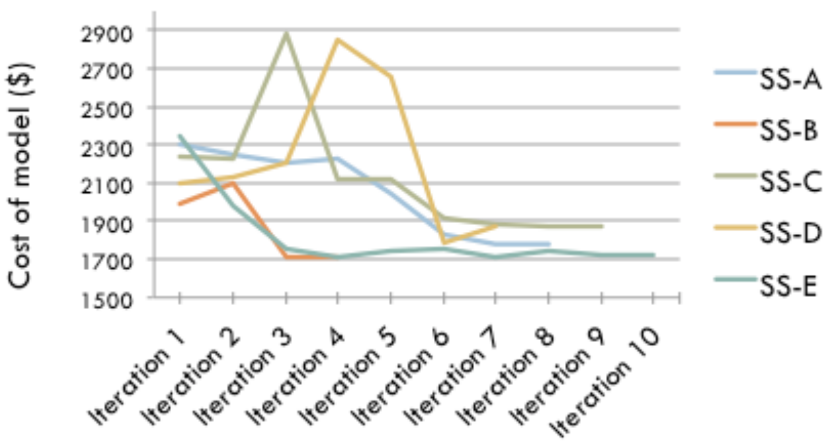


Figure 12. Progress with Design Optimization (Productive)

The design trajectory of Team SS-A consisted of generating, refinement and use of heuristics accompanied by design rationale and tradeoff decisions, evidencing disciplinary engagement. The other four teams in the SS seed model treatment also productively engaged with the disciplinary practices. After the first iteration, prompts by the teacher and facilitator created space for the teams to compare their design revisions with the SS seed model in ways similar to the case of Team SS-A described above. They compared the models along the dimensions of pressure and cost and used the SS seed model to decompose the design challenge and focus on the input parameters as well as area of interest. All the four teams made tradeoff decisions about the types of pipes used in their models, weighing the effect on the outcome parameters.

On the first day, during the first iteration, Team SS-E had spontaneously generated their heuristic for having "least amount of bends" (Chapter 4, Excerpt 12, line 67) while analyzing the SS seed model's excess pipe bends. During the fourth iteration on the first day, Team SS-B focused on the area of interest and generated the heuristic (D_H) "stay low and then branch out and stay low again and branch out there…try to make it lower now" giving the rationale that the SS seed model "goes really high and then comes all the way down." Both these teams indicated use of the SS seed model as a counterexample, gathering from the model features that they did not wish to replicate in their own design revisions. This means that three teams (Teams SS-A and SS-E in the first iteration and Team SS-B in the fourth iteration) out of the total five teams in the SS treatment generated and used heuristics. The two teams (Team SS-C and Team SS-D) who did not generate heuristics had engaged productively with the disciplinary practices as well. However, the cost of the final models for Teams SS-C and SS-D were still higher than the models of the other three teams, indicating the usefulness of heuristics for the process of design optimization. All the teams optimized their model by reducing the cost and meeting the minimum pressure requirement and worked productively. The final models created by the other four teams (Shown in Figure 13, Figure 14, Figure 15, Figure 16) show the path selected by each team and the types of pipes used by them to optimize their designs.

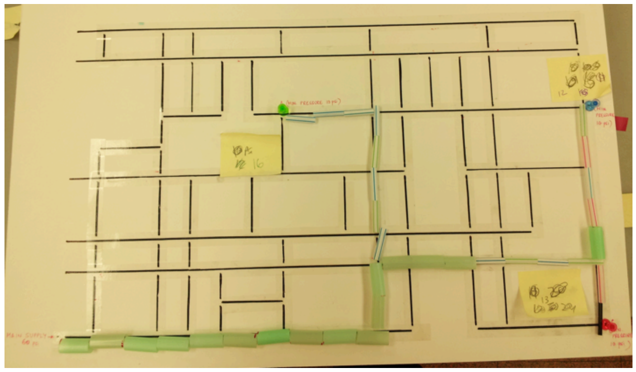


Figure 13. Final model by Team SS-B: $1709

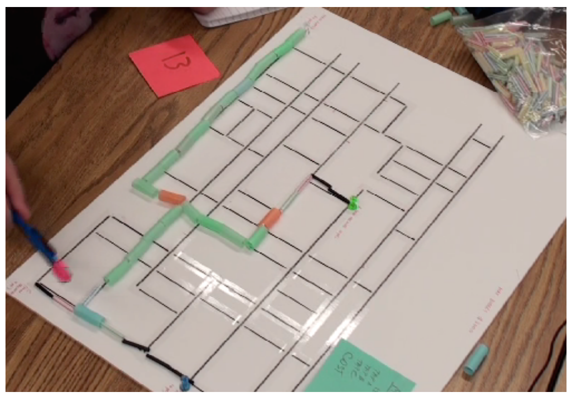


Figure 14. Final model by Team SS-C: $1868

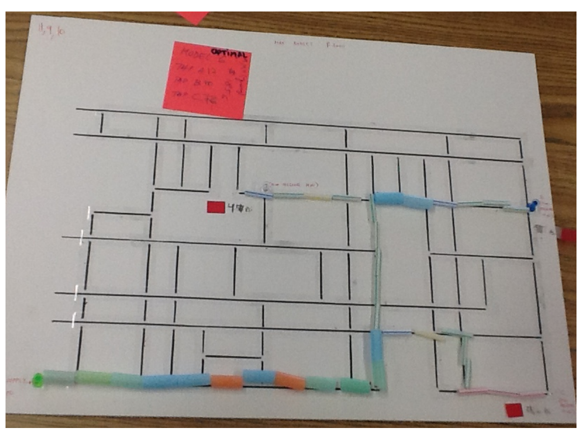


Figure 15. Final model by Team SS-D: $1868

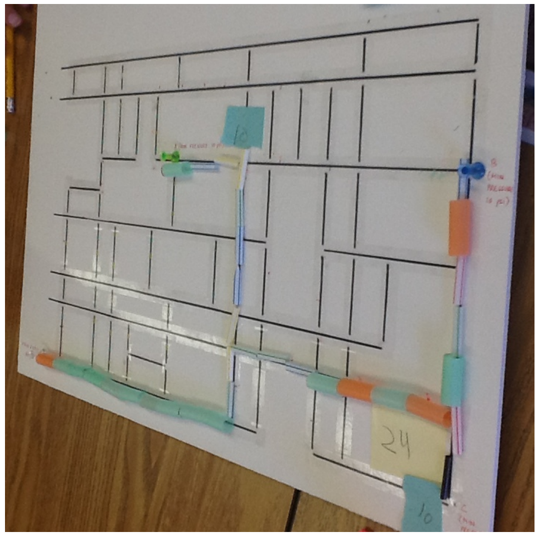


Figure 16. Final model by Team SS-E: $1720

Team SS-B reduced the cost of the model from $1992 (first design revision) to $1709 (Final model shown in Figure 13). Team SS-C reduced the cost of the model from $2242 (first design revision) to $1868 (Final model shown in Figure 14). Team SS-D reduced the cost of the model from $2095 (first design revision) to $1868 (Final model shown in Figure 15). Team SS-E reduced the cost of the model from $2342 (first design revision) to $1720 (Final model shown in Figure 16).

6. OPTIMAL COMPONENT MODEL AND DESIGN FIXATION

All four teams in the Optimal Component treatment condition engaged with the core disciplinary practices of reasoning with multiple design parameters and making tradeoff decisions. However, unlike the teams in the Suboptimal System model treatment, none of the teams in this treatment generated heuristics. Instead the design optimization process revealed evidence of a fixation effect due to the OC seed model. The figure below shows the distribution of different disciplinary levels that emerged across all the teams in this treatment (Figure 17).

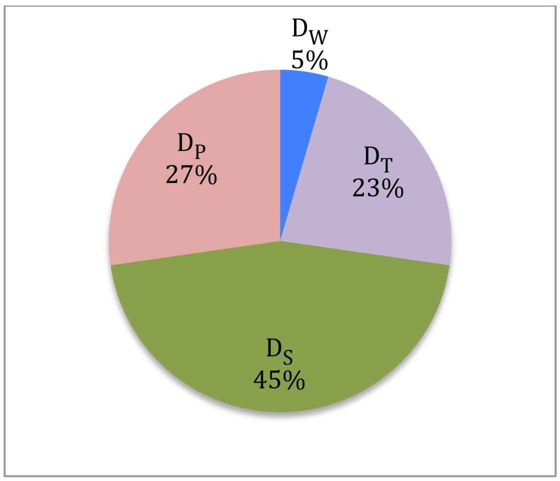


Figure 17. Distribution of types of disciplinary engagement when OC model used (Class A)

Almost half of the design ideas generated using the OC seed model comprised of making connections between input and a single outcome parameter (D_S, 45%). Students also engaged with tradeoff decisions, both reasoning with multiple interacting variables and making tradeoff decisions (D_T, 23%) and weighing the outcome parameters and making tradeoff decisions (D_W, 5%). In the absence of design heuristics, a different optimization strategy emerged during the design session. The teams reused the OC seed model's design and either extended it or emulated the seed model's design. Three out of the four teams in this treatment worked productively and made progress with the design optimization task (Figure 18). These three teams (Team OC-A, OC-B, OC-C) evidenced signs of design fixation, thereby indicating the potential benefits of fixating on optimal design features of the OC seed model in an engineering design context.

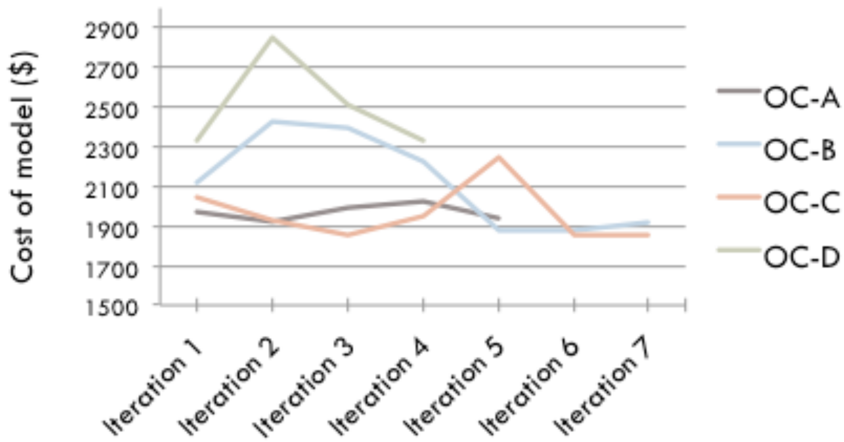


Figure 18. Progress with Design Optimization (Productive)

The above figure illustrates the design trajectories followed by the four teams in this treatment condition. It shows that Teams OC-A, OC-B, and OC-C reduced the cost of their model to a greater extent than Team OC-D, which ended up with a cost that was the same as what they had started with in their first design revision. In this chapter, I will present accounts of design fixation and highlight the ebb and flow of interactions as they happened while using various features of the OC seed model. I will also highlight the prompts given to the students during this model construction process. Ms. E taught this class (Class A).

6.1 <u>Team OC-B: Delayed Design Fixation</u>

In the first iteration, after analyzing the OC seed model, Team OC-B had taken the OC seed model apart and started building from scratch.

6.1.1 <u>Exploring the Design Space</u>

On the first day, the team explored the design space using the ideas they had generated while analyzing the OC seed model. When the facilitator gave a reflection prompt and asked the students to compare their revised model with the OC seed model (Excerpt 19), S2 responded by highlighting that the OC seed model did not connect tap A and tap C, which they had connected in their revised model.

Excerpt 19

201	F:	say what did you guys do to this one (pointing at the seed model)
202	S2:	so we, in the first model it didn't go to tap A or C, so we made it go there
203	S2:	and we probably, if they, umm...
204	S2:	if in model 1, they did go to A & B, the pressure probably would have been a lot less than what we have now since we used more of the bigger pipes
205	S10:	and...
206	S10:	and we also took a different path and we used these (pointing at the pipes)
207	S10:	½-inch pipes to connect to the taps
208	F:	ok so you connected all the taps with ½-inch pipes, why did you guys think that was necessary or good decision
209	S2:	because of the cost, it's a lot anyways but we'd like to lower it a little bit because we have so many of the bigger pipes
210	F:	uhmm
211	S2:	and we stayed within the pressure
212	S2:	it's it's more than 10 psi

S2 used the OC seed model as a resource for decomposing the challenge and focus on the area of interest as well as types of pipes they had used (mostly 1-inch diameter pipes) and predicted that the output pressure at tap A and tap C would have been a "lot less" (Excerpt 19, line 204) even if the seed model had been complete because his team had used more 1-inch diameter pipes than the seed model, connecting the pipe diameter parameter with the water pressure parameter (D_S). S10 shared that they had also used ½-inch diameter pipes near the taps (line 207). When the facilitator gave a disciplinary prompt encouraging the team to share their design rationale for using ½-inch diameter pipes (line 208), S2 responded by articulating a tradeoff decision suggesting that they were trying to reduce the cost while satisfying the constraint of 10 psi (D_T, lines 209 – 212). Thus, the facilitator's initial reflection prompt followed by the disciplinary prompt seeking design rationale and acceptance of the student response created a space for the team to articulate a tradeoff decision of using a certain pipe diameter in order to balance the performance parameters – cost and pressure. After this, the team revised their model iteratively by using different combinations of pipe diameters and also moved the placement of pipes to reduce the cost of the model and ensure adequate pressure at the taps. They did not refer to the OC seed model during these revisions. Instead, they evaluated their progress by comparing the cost and pressure between their design revisions.

On the second day of the design activity, Ms. E began the class with the reflective task that all the teams had to do before they could continue with their design revisions. Ms. E reminded the students to compare their model with the OC seed model and think about how their design was different. She provided reflection prompts (e.g., "…refer back to and compare it to this one…") and disciplinary prompts (e.g., "…how it's different…") to encourage students to critically assess their design decisions. Team OC-B used the image of the OC seed model to discuss what they had done the day before and brainstormed alternative paths that might help them reduce the cost and yet meet the pressure requirement (Excerpt 20). They continued with their fourth iteration that they had started in the previous design session.

Excerpt 20

444	Ms. E:	we just want to remind you to... as you go on to build your next models like refer back to and compare it to this one (pointing at the seed model).
445	Ms. E:	We want you to think about how it's different from this one.
…		
447	S6:	(immediately after receiving the image of the seed model, pointing and tracing path) thinking about how we would go...right over there to that one then you go over that one and down... (tracing imaginary path over the seed model's image connecting source to tap A then tap A to B and then tap B to C)
448	S10:	so we did.. we did like here and then branch this way and branch (tracing path of the most recent iteration)...
449	S2:	yeah but branching... I just thought that branching like <unclear> the cost go up
450	S6:	won't going down work though (tracing horizontal line with finger over the seed model's pipes near the source going towards tap B and tap C)
451	S2:	yeah that'll be easier... the cost would be a lot less
452	S6:	are we allowed to change yet?

453	S2:	yeah
454	S10:	so we go here (overlap with S6 - you want to go straight (tracing a path that goes vertically up towards tap A and then horizontally across through A to B) and then around (to tap C)
455	S2:	yeah
456	S10:	we already tried that one, it didn't work
…		
464	S2:	the problem was this though is 1) it costs more and 2) it's a lot quicker if you just go boom boom boom boom...
465	S6:	ok
466	S10:	the problem was that by the time we had the orange one we had less than 10psi... even with all orange ones… remember?

In response to Ms. E's prompts, S6 began using the OC seed model's layout to suggest different ways in which they could connect the taps (line 447). She used the given layout of the OC seed model as her basis for forming new ideas. S10 reminded his teammates about some of the layouts they had already tried that "didn't work" (lines 448 – 456). The moratorium on making changes created space for the students to dedicate their entire attention towards their previous design revisions and revisit their drawbacks or advantages to inform new design ideas. The team used outcome parameters to form their rationale as they negotiated the tradeoff between cost and pressure due to the use of a specific pipe diameter (D_T, lines 464 – 466). Ms. E's initial prompts followed by dedicated time for reflection scaffolded the process of engaging with these disciplinary practices. Ms. E also transferred the authority back to the students after giving the prompt. She removed herself from the interaction and allowed the students to discuss how their model had changed. This move by Ms. E made the students accountable to each other, rather than to her or the facilitators, and encouraged the students to be critical of their design decisions.

6.1.2 Fixating on the Seed Model's Design: Delayed Effect

A little later (Excerpt 21), while the students were still working on the reflective task assigned by Ms. E, S10 counted the number of 1-inch diameter pipes in the OC seed model's horizontal segment near the source.

Excerpt 21

473	S10:	1 2 3 4...6 7 8 (counting the number of 1 inch pipes in the seed model's image)
474	S2:	do you just want to try… making this (marking out the vertical segment of seed model with thumb and index finger) but branching out like (indicating branching towards tap A from the seed model's bend near tap B)
475	S10:	1 2 3 4
476	S2:	how about if we do this...we do the same thing that they did here (again marking out the vertical section of the seed model with thumb and index finger) but branching out right here (for tap A) and doing that (branching out for tap C)
477	S10:	ok
….		
493	S2:	but the cost would be very high if we just did these (pointing at the 1 inch pipes on the seed model's image)
494	S10:	ok
495	S6:	no we don't have to just do those
496	S2:	but then the psi would go down by a lot
497	S2:	if we ...
498	S6:	no but I would say that we use the big ones (1 inch pipes) all the way until the blue (tap B) and then you can use the small ones there (sliding down hand to tap C)

S2 suggested reusing the seed model's design ("…we do the same thing that they did here," Excerpt 21, line 476), marking out the vertical section of the seed model with his finger and extending it to connect tap A and tap C. He used the OC seed model as a resource for decomposing the challenge into area of interest and focused on where to branch-off. The team explored the idea of revising the model by reusing the vertical section of the OC seed model and connecting tap A and C by adding more pipes (Shown in Figure 19).

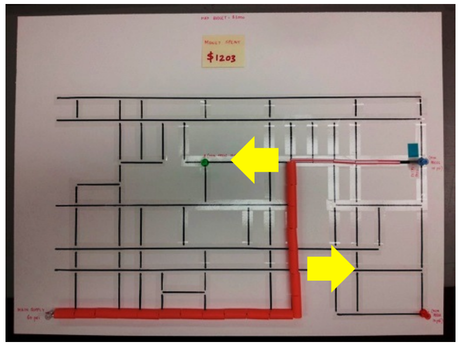


Figure 19. Team OC-B’s proposed modification to the OC seed model

However, discussion about the tradeoffs of using 1-inch diameter pipes (D_T) led them to consider an alternative idea for placing pipes for their fourth iteration (Excerpt 21, line 493 – 498). The team shelved the idea of reusing the vertical section of the OC seed model for now but returned back to it in their sixth iteration (Excerpt 22) when S2 suggested that he had an idea for a better design.

Excerpt 22

783	S2:	oh no no, I actually have a good idea
784	S2:	we go here and watch this (putting down 1 inch pipes using the same path as the seed model)
785	S6:	oh I know what you mean
786	S2:	yeah
787	S2:	so we can just go like this, branch here (near tap C), take all of these off
788	S2:	so we make... so let's make
789	S6:	can we use these 2 small ones (picking up the two 3/4 inch pipes before removing them from the board… these were part of the previous design)
…		
795	S2:	that's a good idea (putting pipes along the same path as the seed model and extending to connect tap A and tap C)

S2 placed pipes along the same path as the OC seed model, reusing the vertical section of the OC seed model that they he had suggested earlier (Excerpt 21, line 476, “we do the same thing that they did here…”). The team decided to try that idea now (Excerpt 22, lines 784 – 788). After constructing their model, they reflected that this design revision (Excerpt 23) had “less turn” than their previous design revisions and thus cost a “lot less money” (line 843), making a spontaneous connection between the pipe bend parameter and cost parameter (D_S).

Excerpt 23

842	S6:	do we need to talk about our design (S2 nodding head)
843	S2:	our design is different, it goes to the middle and then branches out on all sides, so I think since there's less turns it's a lot less money.

Thus, the team revised their model by using the same pipe path for connecting source with tap B and used the same number of 1-inch diameter pipes as the OC seed model between the source till the bend near tap B (18 pipe segments), indicating a delayed but strong influence of the OC seed model. Fixating on the OC seed model’s design scaffolded the team’s efforts of optimizing the model by suggesting a design alternative with fewer pipe bends. The team stopped making further revisions, deciding that this was their optimal model. The team engaged with tradeoffs and discussed design rationale while they revised their model iteratively. Their decision to reuse the seed model’s design was backed by the rationale that it had the least pipe bends and thus was their cheapest model.

The final model highlighted the productive work done by the team and reflected the incremental changes they had made based on the tradeoff decisions. Team OC-B’s first design revision had a cost of $2118. Their final design revision cost had a cost of $1915 (Shown in Figure 20). The highlighted area of the final model (dashed lines in Figure 20) indicates the path for placing pipes and the number of 1-inch diameter pipes of the seed model that the team had emulated from the OC seed model’s design. The fixation effect seems to have been beneficial for Team OC-B by helping them make a cheaper model than their prior design revisions.

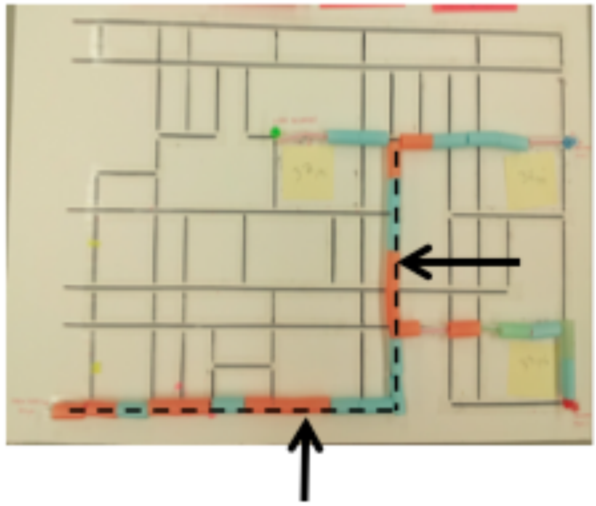


Figure 20. Final model by Team OC-B: $1915 (dotted lines highlight section of OC seed model that the team fixated on)

6.2 Team OC-C: Immediate Design Fixation

The other team whose final model was similar to the OC seed model was Team OC-C who evidenced fixation with the OC seed model's design from the initial stages of the design process when they started out by extending the OC seed model in their first iteration. The team began their design session (Excerpt 24) by analyzing the OC seed model and observing that it was incomplete.

Excerpt 24

1 S9: it doesn't go to all three taps.
2 S9: it's not finished.
…
7 S9: it's really not going to be much hard. Just connect it using more pipes
8 S4: yeah but we have to get it cheap, under budget.
…
11 F: first talk about this model, why you guys think it's not that good and then when you change it talk about ...
12 S9: well there's nothing wrong with this model.
13 S9: oh S4, there's nothing wrong with the model. It's just not finished.

S9 reasoned, "it's really not going to be much hard. Just connect it using more pipes," (line 7) indicating the fixation effect of the OC seed model. They reiterated their focus on incompleteness again when the facilitator gave a reflection prompt and also asked students to provide a rationale for why the seed model was not that good (line 11). The team proceeded to modify the model by adding more pipes to the OC seed model's design (Shown in Figure 21).

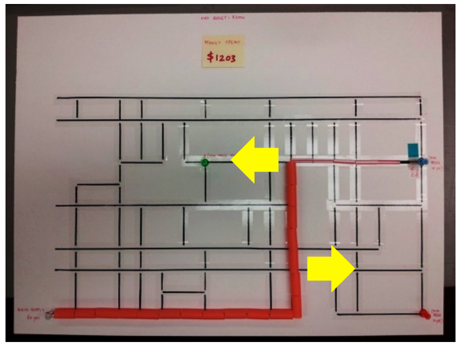


Figure 21. Team OC-C's proposed modification to the OC seed model

They engaged with tradeoff decisions (D_T), determining what diameter of pipes to use for extending the OC seed model (e.g., "let me put it (1-inch diameter pipes) here so that the psi is strong," Chapter 4, Excerpt 7, line 33) and also figuring out whether they needed to replace any pipes in the OC seed model (e.g., "we should make these bigger… no we'll be fine still", Chapter 4, Excerpt 8, lines 86 – 87).

They kept the pressure at tap B same since it satisfied the pressure constraint and went on to make sure that their cost was below the budget (Excerpt 25).

Excerpt 25

91	S9:	the pre-made one, S4... the pre-made one is exactly 10
92	S9:	S4, this premade one is exactly 10. So our psi is good. We just have to make sure our money is good

S9 used the given pressure of 10 psi at tap B (as it was originally designed in the OC seed model), to justify why they did not need to replace the ¾-inch diameter pipes of the OC seed model (line 91). He highlighted that since the "pre-made one" or the OC seed model had 10 psi at tap B, it satisfied the minimum pressure constraint and thus their "psi [was] good."

They also extended the OC seed model's calculation. They took the cost of the extra pipes that they had used to complete the seed model and added that to the partial cost of the OC seed model to compute the cost of their complete system (Excerpt 26).

Excerpt 26

169	S4:	then we'll add it up with this ($1203 cost of partial model), ok
170	S1:	no because that is from here to that (running hand along the pipe section from source till tap B)
171	S4:	so guys why did we add this stuff if we know it's <unclear> dollars
172	S9:	we can just add this (bracketing with fingers the section from 2nd bend till tap C)
173	S4:	yeah
174	S4:	all we had to do was add this (tapping the section leading to tap A) and that (pointing to section connecting tap C)
…		
196	F:	can you go over the calculations again?
197	S9:	yeah, sure
198	S9:	so we basically just found a point here (pointing at their 1st bend), where we agreed it <unclear> us money and then we kept adding up this link (bracketing section leading to tap C) to this link (section between 2nd bend to 2-way split between tap A & B) to this link (section from this 2-way split to tap A) and that link (section from 2-way split to tap B) and then we got our number
199	S9:	so we basically kept yours (pointing to the $1203 cost of the partial model) and ended up adding only about $300...

The team was trying to determine the cost of their complete model. S4 and S9 determined that they could find out the cost of the model by just adding up the cost of the extra pipe pieces that they had placed for extending the OC seed model (lines 169 – 174). S9 articulated this explicitly (lines 197 – 199) after the facilitator gave a procedural prompt asking the team to explain their calculations. This prompt created space for the team to share their design strategy and evidence the fixation effect.

Team OC-C worked productively and reduced the cost of the model from $2043 (first design revision) to $1851 (Final model shown in Figure 22). Team OC-C had designed their final model by extending the seed model to connect tap A and tap C, keeping the pipes connecting source with tap B same as the seed model. They engaged with tradeoff decisions while extending the OC seed model.

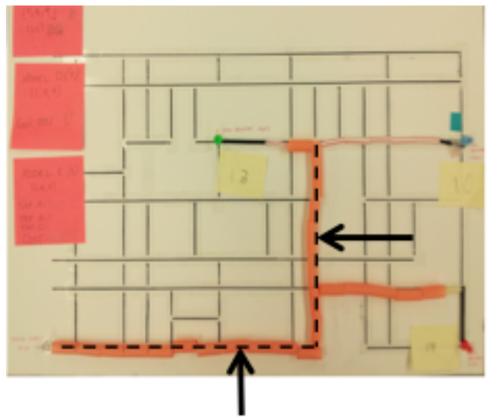


Figure 22. Final model by Team OC-C: $1851 (dotted lines highlight section of OC seed model that the team fixated on)

6.3 Team OC-A: Implicit Design Fixation

While analyzing the OC seed model during the first iteration, Team OC-A highlighted that the OC seed model did not connect all the taps (Excerpt 27, lines 2 – 5). S3 noticed the budget amount of $3000 written at the top of the design board and concluded that the OC seed model was lacking "appropriate use of materials."

Excerpt 27

1	S3:	so what's lacking in this? (OC seed model is kept on the table and all the team members are looking at it)
2	S13:	it's not connecting to this tap and this tap (pointing at tap A and C)
3	S3:	it's not connecting to that tap (pointing at tap A)
4	S3:	not connecting to this tap either (pointing at tap C)
5	S13:	yeah
…		
12	S3:	if the matched budget is $3000 I think this is lacking appropriate use of materials and this model can be better even though at a higher price it'll be better for a greater good

S3 suggested that the model could be improved for the “greater good” (possibly referring to higher pressure) but at a higher price (line 12). This initial critique of the OC seed model indicated a tradeoff between cost and pressure, weighing both the outcome parameters (D_W). After this discussion, the team took apart the model and rebuilt the complete system.

For rebuilding the complete system, the team discussed various ideas and then settled for the one that had similar features as the OC seed model (Excerpt 28). They decided to connect the source point with all the taps by placing pipes from source along the same path as the OC seed model and then branching out to connect the three taps. However, the team did not refer to the OC seed model explicitly in this case.

Excerpt 28

67	S3:	ok, right here is the point where we are going to have to divert into three (S13 was laying pipes. Now S3 touches the point to indicate branching point)
68	S13:	it has to touch S3 (pointing at the pipes that S3 was placing)
69	S3:	actually no change of plans we should go right here (readjusts the central point and moves it up to align it horizontally with tap A)
70	S3:	<unclear> just go side to side (tracing the two branches out this point)
71	S3:	and we branch off right here (pointing at another point closer to tap B) and then we go there (tracing path going down towards tap C)

S3 suggested placing the pipes from the source till the branching point that was between tap A and tap B, very similar to the OC seed model’s placement of pipes (lines 67 – 71). While there is no explicit use of mention of the OC seed model, the suggested design revision indicates an implicit fixation effect. After this discussion, the team determined (Excerpt 29) what pipe diameter to use for rebuilding their model.

Excerpt 29

77	S13:	so now.. should I.. what type of pipe do you want to go here (tracing the path towards tap A from the branch)
78	S3:	these? (picking up ¾-inch pipes)
79	S3:	that would be a lot of <unclear--down/reduction?> we need to replace this with 1-inch (replaces the ¾-inch pipe he had placed with 1-inch pipe)
80	S13:	ok

81	S13:	well I think it fits there (trying to place pipes touching each other)
82	S13:	well I think we can finish
83	S3:	and then branch off (pointing to the location where branching will happen)
84	S13:	it's gonna cost more if we use all 1-inch pipe
85	S3:	I know! I meant to use 1/2 when going down here (tracing path towards tap C from the tap A and B channel)
86	S13:	ok
87	S3:	or maybe I'll.. let's see (placing 1-inch pipes)
88	S3:	I also don't want to hit ... I also don't want to hit 10 psi

S13 and S3 discussed what type of pipe they wanted to use for connecting tap A to the closest point between the three taps. S3 suggested using ¾-inch diameter pipes but realized immediately that it would cause a huge drop in pressure. So he used 1-inch diameter pipes instead of ¾-inch diameter pipes (lines 77 – 79). S13 then cautioned S3 that using only 1-inch pipes would increase their cost, highlighting the tradeoff of using 1-inch diameter pipes (D_T). S3 responded by stating that he was planning on using ½-inch diameter pipe near the taps to keep the cost down (lines 84 – 87). He shared his concern that he did not want to "hit 10 psi" (line 88), highlighting the minimum pressure constraint and his preference for keeping the pressure above the minimum requirement. This strategy was aligned with S3's tradeoff in the first iteration after analyzing the OC seed model, preferring higher pressure and thus higher cost ("…model can be better even though at a higher price it'll be better for a greater good…").

Team OC-A articulated tradeoff decisions while comparing their design revisions with the OC seed model (Excerpt 30). The team used the written prompts and started by answering the reflection and disciplinary prompts ("How was your design better than the very first one given to you").

Excerpt 30

247	S13:	ok let's answer the questions now then
248	S13:	ok S3, you want to answer?
249	S13:	ok, how was your design better than the very first one given to you?

250	S3:	(speaking into the audio recorder) let's start with the fact that [it] actually delivered water to all taps and it also..
251	S3:	it didn't cost any less but it didn't .. ummmm
252	S3:	it did have .. ummm
253	S3:	what was the pressure of the one tap the original design delivered it to ?
254	S13:	it was.. (picking up the image of the OC seed model and looking at it)
255	S13:	10 psi
256	S3:	and it has better... higher psi for each tap it delivers water to

S3 reiterated that their model delivered water to all the taps, highlighting the incompleteness of the OC seed model (line 250). The team also determined that their revised model was better because it had higher pressure at all the taps, highlighting a tradeoff between cost and pressure (D_W). The prompts, thus, created a space for the team to revisit the OC seed model, reflect on their design decisions and articulate their rationale for their revised design; weighing the effect of the decisions on both the outcome parameters. The comparison process with the OC seed model does not appear to be very valuable because the team just reiterated that their model was complete whereas the OC seed model was incomplete. By having the students record their explanation into the audio recorder, the prompts facilitated the creation of a shared understanding of the design process and encouraged everyone to participate in the design process. However, the explanations never highlighted the fixation effect that was visible in the physical models designed by the team, suggesting an implicit design fixation.

Team OC-A worked productively. Team OC-A reduced the cost of the model from $1974 (first design revision) to $1940 (Final model shown in Figure 23). The highlighted section of the model (dotted lines) indicates the section of the OC seed model that the team had implicitly fixated on and emulated in their final model.

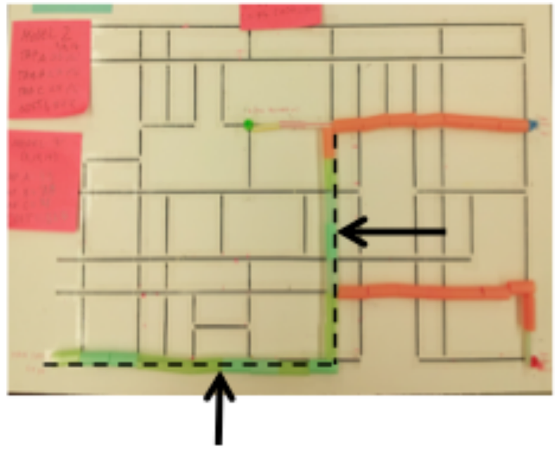


Figure 23. Final model by Team OC-A: $1940 (dotted lines highlight section of OC seed model that the team fixated on)

Team OC-D was the only team in this treatment that did not evidence fixation, neither in their design discussions nor in their final model. After exploring a few design ideas, they reverted back to their first design revision and considered it to be their final model (Shown in Figure 24) since the design revisions after the first revision were more expensive than their first revision. Thus, they ended up with $2330 as the cost of their final model, same as their first revision. This final model was the most expensive model when compared to the other three teams who were fixated by the OC seed model's design, indicating the potential value of fixating on the optimal features of the OC seed model.

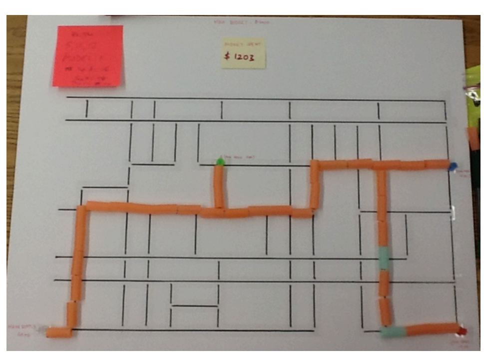


Figure 24. Final model by Team OC-D: $2330 (reverted to first design revision)

7. PROMPTS AND RESOURCES PROVIDED TO STUDENTS

Along with the Improvable Models, students were given various kinds of prompts and resources to scaffold the design process. Three kinds of verbal and written prompts—procedural, reflection, and disciplinary prompts—and additional resources like simulation software, audio recorders, and iPad™ scaffolded productive engagement with the disciplinary practices using the Improvable Models. In the previous three chapters, I had highlighted the use of these prompts that happened while the two seed models were being used. This chapter focuses entirely on the prompts and the resources used by the students before and during the design session. The prompts and resources scaffolded the design process and helped foster productive disciplinary engagement along the four dimensions highlighted by Engle and Conant (2002): problematize, authority, accountability, and resource.

7.1 <u>Problematize Quality of a System</u>

On the very first day of the instruction unit (before the design session), the teachers in both the treatment conditions separately conducted class discussions about plumbing system to elicit prior knowledge about good and bad plumbing system. It encouraged students to talk about various plumbing issues that they might have faced in the past due to bad design. Students discussed issues like pipe bursting due to cold weather or blockage. They also discussed how pipes were arranged ("through the whole house" or "basement") and the use of different types and length of pipes. Teachers captured this discussion on the board for everyone to see (e.g., Ms. E's notes during this discussion, Shown in Figure 25) and reflect on. The discussion problematized the meaning of good and bad plumbing system and encouraged the students to think about what constituted a good plumbing system.

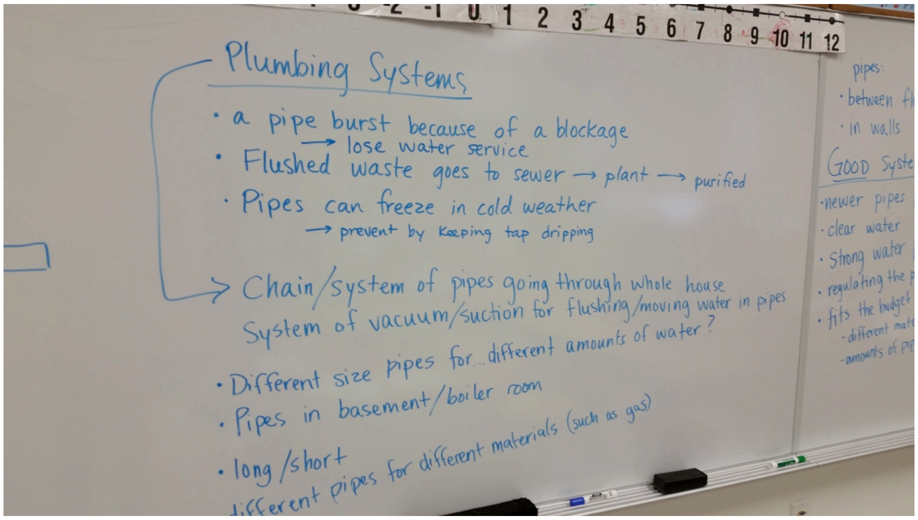


Figure 25. Ms. E's discussion notes on Day 1 of instruction unit

The students discussed that a good system should provide clear water, have regulated pressure and fit the budget. This highlighted the multiple factors that governed the quality of a plumbing system. A similar discussion happened in Mr. K's class as well.

7.2 Problematize Design Decisions

During the design session between days 5-7, the teachers and facilitators gave reflection prompts to the students that encouraged them to compare their models and reflect on their design decisions. While the teams were iteratively constructing their optimal model, Mr. K and Ms. E imposed a moratorium on the construction process in their respective classes and instead asked students to reflect on the design changes that every team had made. For example, Mr. K asked students to work in their teams and reflect on all their models – SS seed model, all prior design revisions that they had constructed, and current model that they were working on. He wanted them to compare and contrast the models with each other and also with the SS seed model to highlight the changes they had made till then – "When I hand you your designs, you are not going to change it… spend the first few minutes of the class discussing with your group how your design is different from the original design... right now I want you to look back." Reflection prompts like these created opportunities for the students to question their design decisions and deeply engage with the design process. He also gave disciplinary prompts to help students think about the design philosophy (e.g., “at one level like you can say that yeah we moved this pipe from here to here but what are some of the bigger levels...”). Students were not allowed to modify their model until they had finished this task. Following this prompt by Mr. K, teams began analyzing all their models and productively engage with the disciplinary practices. For example (Excerpt 31), in Team SS-A, S26 noticed a difference in the types of pipes used in their current model and their most recent design revision.

Excerpt 31 (Team SS-A)

291	S26:	(pointing to the ½-inch pipes in their most recent Improvable Model that were replaced with ¾-inch pipes in the current model) why did we pick these and have 3/4s?
292	S27:	because it'll go to...
293	S27:	it'll go to 11 psi and that's too low
294	S26:	no it's not
295	S27:	it's 1 psi higher than 10 psi
296	S26:	that doesn't matter
297	S27:	yeah it does, because we want all of these (swiping hand over all the taps) to be closer together
298	S26:	how much is that? (pointing at tap A)
299	S27:	that's 21 psi
300	S26:	that's too much (pointing at tap A psi)
301	S27:	no it's not
302	S26:	yes, it is! (exclaiming)
303	S27:	no it's not

S26 went back and forth between their most recent design revision and their current model. He questioned the use of ¾-inch diameter pipes in their current model and challenged S27’s notion of 11 psi being “too low” since he believed that 21 psi was “too much.” He suggested that they should adjust the output pressure and lower it further (lines 291 – 303). However, S27 believed that 11 psi was only “1 psi higher than 10 psi” and thus very low. He wanted the output pressure at all the taps to be higher than the minimum pressure and also be uniform ("because we want all of these to be closer together," line 297), making a tradeoff between pressure and cost because higher pressure would result in higher cost (D_W). The team assigned weights (more or less valuable) to different output pressure values as they negotiated the value for optimal pressure. The design challenge given to all the teams did not specify an exact value for optimal pressure. This created an ambiguity regarding the ideal value of pressure, which possibly allowed Team SS-A to debate whether 11 psi or 21 psi was better. It must be noted that Team SS-A was using the SS model as their seed model that had primed them from the beginning with a range of pressure (0 – 42 psi) at the taps. The team was critiquing the SS seed model as part of the reflective task given by Mr. K here. It is likely that this range of pressure in addition to the 10 psi minimum pressure constraint was influencing their choice of output pressure values. S27 likely determined that it was optimal to have a value of pressure that was above the 10 psi minimum and closer to 42 psi whereas S26 preferred having a lower pressure and determined that their model would be optimal as long as it satisfied the 10 psi minimum.

Mr. K's instructions that had asked all the teams to reflect on their prior design revisions and compare them without making any modifications, created a space for this interaction to happen. Mr. K gave the prompts directing the students to spend time reflecting on their design revisions in their teams and then removed himself from the interaction, thus giving the students authority to challenge each other's design decisions.

Students also used the minimum pressure constraint (10 psi) to form their rationale while comparing the Improvable Models. The lack of a specific optimal value for the output pressure potentially allowed the students to interpret the values of the parameters shown in the

Improvable Models in very different ways for designing their optimal model – by satisfying the given constraint (e.g., S26 preferring 11 psi) and by maximizing the value of the outcome parameter (e.g., S27 preferring 21 psi).

Written reflection prompts like "how is your design better than the original one that was given to you?" that students had to respond to after every design iteration also facilitated reflection on the design changes that the teams might have made. In response to this prompt, teams articulated their tradeoff decisions that had guided their design changes. For example, in Team SS-A's case, S27 explained that his team had changed the SS seed model in order to get "enough water pressure" and also "save money" (lines 343 – 344), highlighting the tradeoff between water pressure and cost (D_W). The facilitator followed up with further reflection prompts and asked for design rationale – "why is model 3 better?" S27 articulated the tradeoff between pressure and cost by highlighting that their team's goal was to have uniform pressure across all the three taps but also save money – "…because all the psi pressures, I mean all the output pressure is close to the same and we actually saved a lot of money over here (pointing at their third design revision)" (D_W, line 371).

In addition to the reflection prompts, disciplinary prompts that facilitated formation of design rationale helped problematize the design process. For example, during the design session on the second day, Mr. K prompted students to articulate the rationale underlying their decisions – "…try to think about what MADE the price go down. What was kind of my overall philosophy of trying to make... that made the price go down… So you are taking a look at the original (SS model) and thinking about how you are able to improve it." Such prompts also guided students to evaluate whether their model was optimal or not and provide evidence for their claim. For instance, Mr. K guided students to evaluate if the design changes had resulted in the creation of the best model – “Have I made the best model? Is there maybe... if I were to keep working on this, is there maybe a model out there that's cheaper and better? And why and why not?” Also, written disciplinary prompts that the students had to respond to after every iteration like “Is your design optimal, give reasons,” created space for the teams to justify their design decisions. For example, in Team SS-A’s case, S28 responded by suggesting that his team had optimized their model by reducing the number of pipe bends and lowering the cost of the model – “we will say that our design is pretty optimal, it can always get better but… it's good because it has the least amount of right angles and... it's very cheap and very good psi, yeah” (lines 407 – 409).

Thus, the teacher-imposed moratorium on changing the model along with the guiding reflection prompts probably helped create a space for the teams to engage in rich discussions about tradeoffs of different design decisions. These prompts encouraged students to make connections between various design parameters and provided a platform for the students to engage with tradeoff decisions. The disciplinary prompt directed students to recapitulate and articulate their design rationale. This process enabled them to remake the connections between the design parameters and revisit their tradeoffs.

7.3 Provide Authority by Forming Plumbing Companies

Teams of students were identified as “plumbing companies” from the first day of the instruction unit. Every company had the authority to modify the Improvable Models in their own unique ways, backed by proper design rationale. So, every company was publicly recognized in the class as an author of a design idea, which gave a sense of ownership to the students. Every company had the agency to define, address and resolve the problems in the plumbing system in order to make it optimal. The companies were allowed to interact with each other and challenge each other’s point of view with proper justification supporting their challenges. This created the expectation that students should resolve the problems themselves and take ownership of the outcome of the team's design decisions.

The expectation that every company would present and defend their optimal model at the end of the design session promoted the culture of negotiation within the companies where students questioned each other's design decisions and worked towards a mutually agreed solution to the design challenge that they would present at the end of the design session.

7.4 Provide Authority by Giving an Ambiguous Design Challenge

Students were given further authority by means of the ambiguity in the design challenge. The design challenge specified the minimum pressure constraint of 10 psi at every tap and the maximum budget limit of $3000. However, it did not give the exact specifications for the final optimal model—the output pressure and cost of model that would make the model optimal—and teams had to reconcile this ambiguity by means of negotiation. There were episodes during the design session when this ambiguity likely gave rise to and sustained tradeoff discussions. For example (Excerpt 32), Team SS-A was negotiating the optimal value of pressure and cost for their model towards the end of their design session. The team was trying to come up with new ideas for reducing the cost of their model.

Excerpt 32 (Team SS-A)

647	S26:	we should switch this with 3/4 (pointing to the 1-inch pipe branching out towards tap A and C)
648	S27:	no
649	S26:	yeah, that brings it down...
650	S27:	all we save is 5 bucks
651	S26:	it'll be 5 bucks different
652	S26:	this and the 3/4
653	S26:	no they are really different (looking at the property table)
654	S27:	we don't need it
655	S26:	yeah we do, it's good
656	S26:	it'll get down to the 1600s (pointing to the cost at the top)
657	S28:	Nooo!

658	S26:	what's the difference?
659	S28:	actually yeah
660	S27:	yeah but we lose pressure (looking at the tap B and tapping it)
661	S26:	well, we need to make this smaller (tap A)
662	S26:	that's 27, that's crazy, we don't need it that high (pointing to the output pressure)
663	S27:	fine, give me ¾ (replacing pipe segments with ¾-inch pipes)
664	S26:	how much are 3/4?
665	S28:	33 bucks
666	S26:	and how much are 1's (1-inch pipes)
667	S28:	45
668	S28:	so that just saves us 12 bucks

S26 suggested using ¾-inch diameter pipes but was met with resistance from S27 as he felt that reducing the cost by $5 would not help (line 647 – 649). S27 suggested that it was not worthwhile to reduce the cost by just $5 while S26 argued for reducing the cost since it would still be "5 bucks different" than the previous iteration (lines 650 – 656). S27 opposed the idea since replacing 1-inch diameter pipe with ¾-inch diameter pipe would lead to a drop in pressure (lines 657 – 660), making a tradeoff between cost and pressure (D_W). S28 joined the negotiation process by suggesting that reducing the cost was not worth it ("that just saves us 12 bucks", line 668) because of the large drop in water pressure. The negotiation process focused on determining what value of output pressure and cost would make the model optimal. The disagreement regarding these values captured by the above discussion is likely due to the lack of a clear articulation of the exact value of the outcome parameters that would make the model optimal. This ambiguity in the design challenge authorized the students to reinterpret the design challenge and assert what they determined should characterize an optimal model.

Similarly, in the previous excerpt (Excerpt 31), the team negotiated whether they wanted higher pressure after being primed by the range of output pressure (0 – 42 psi) of the SS model and engaged in making tradeoff decisions between different values of output pressure (i.e., S26 preferring 11 psi while S27 preferring 21 psi).

7.5 Making Students Accountable

The teams were accountable for their design ideas. By setting the expectation that each plumbing company would defend their design decisions, students were held accountable for their team's design. For example, Mr. K gave the disciplinary prompt that sought design rationale from the students – "Why is it that you chose a particular way to build your design? Why did you pick this path, why did you make it split here and not somewhere else, why did you go high and not low or low and not high. Tell me WHY?" This encouraged the teams to consider the tradeoffs of various design decisions. For example, in Team SS-A's case in the previous excerpt (Excerpt 32), they considered the effect of using ¾-inch diameter pipes on the outcome parameters (pressure and cost) and discussed the tradeoffs (lines 647 – 668).

Students were accountable to each other – within their team and also to peers outside their team. Students were asked to build as a team after discussing ideas with their team members. Every student was also allowed to visit and inquire about another team's design, thus making them accountable to the entire class. The physicality of the design board on which the models were built prevented it from being 'hidden' away from sight (like one can hide a paper or the screen of a laptop from peers). It afforded easy visual inspection by anyone passing by a team's model, promoting a sense of accountability towards other students as well as accountability for reviewing others' work.

7.6 Providing Resources to Scaffold the Design Process

Teams were provided with the plumbing simulator between days 3 – 4 to extract the system properties and explore relationship between design parameters. The simulator allowed the students to place different lengths and diameters of pipes and calculated the resultant cost and output pressure that the students could analyze. This resource helped the teams focus on designing the system rather than get distracted by the underlying calculations for determining the pressure and cost of the system. This enabled the students to explore the plumbing system and discover patterns in the data collected from the simulator.

The figure below (Shown in Figure 26) shows the simulator being used by Team OC-A. They naturally took turns to work with the simulator and discussed their findings after using the simulator. The worksheet (Shown in Figure 27) helped guide this discussion as it clearly highlighted the variables that the students needed to focus on while using the simulator.

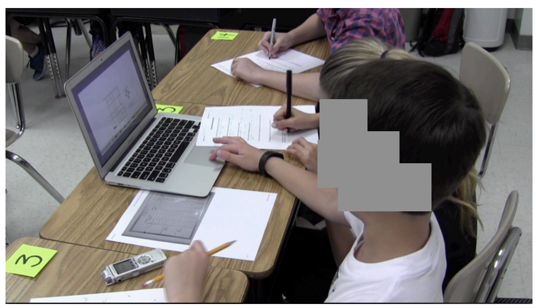
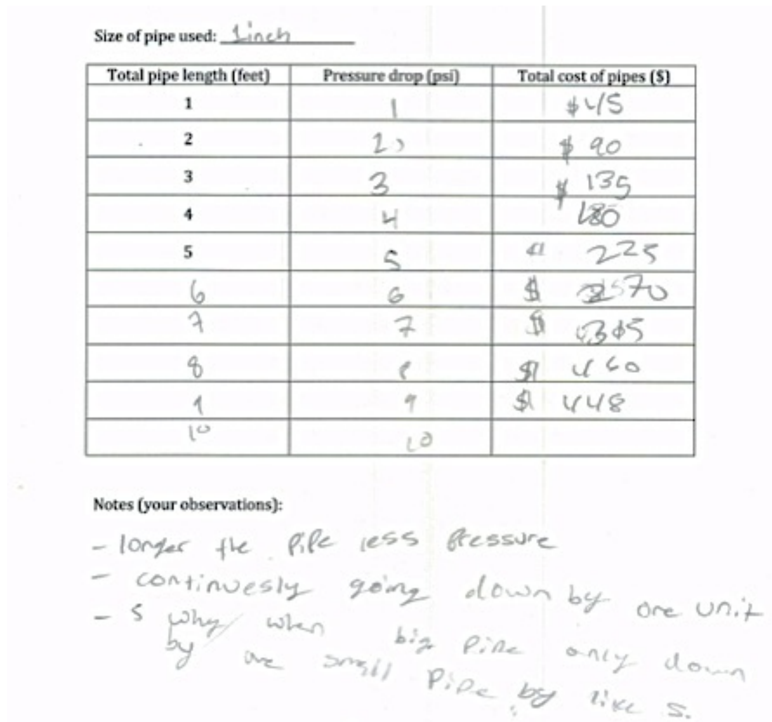


Figure 26. Team OC-A using the simulator



Size of pipe used: 1 inch

Total pipe length (feet)	Pressure drop (psi)	Total cost of pipes ($)
1	1	$45
2	2	$ 90
3	3	$ 135
4	4	180
5	5	$ 225
6	6	$ 270
7	7	$ 315
8	8	$ 460
9	9	$ 448
10	10	

Notes (your observations):

- longer the pipe less pressure
- continuesly going down by one unit
- 5 why when big pipe only down by one small pipe by like 5.

Figure 27. Team OC-A's worksheet filled by the team while using the software simulator

Team OC-A identified that longer pipe resulted in less pressure – "longer the pipe less pressure." They also found the pattern that the pressure was "continuously going down by one unit" by observing that each segment of 1-inch pipe caused a pressure drop of 1 psi. They also explored what happened if they used "small pipe" (¾-inch diameter pipes) and noticed that the pressure drop was different than a 1-inch diameter pipe. This set the stage for the students to become aware of the underlying system properties and use them to form design decisions and productively engage with the design process. This experience early on in the instruction unit likely prepared the students for the design session that followed (days 5 – 7).

During the design session, procedural prompts were periodically provided to ensure that the students were on-task and made progress with the procedural aspects of the design task. Throughout the design session, the teachers and facilitators helped the students with the calculations while they were determining the values for pressure and cost of the model. They highlighted calculation errors (if any) and ensured that the teams could move on to engage with the different disciplinary practices. For example, in the case of Team SS-A, the Mr. K helped them calculate the cost of the model – “so let's say how many 1 inch pipes do I have… how many ¾… how many ½… so write each one out and then how much does each one cost.” Students also used the iPad™ during the design session as a resource to record their progress and organize their work by taking pictures after every iteration. They referred to these records throughout their design session to form design rationale.

7.7 Relation Between Prompts and Disciplinary Practices

Thus, we see that the three types of verbal and written prompt—procedural, reflection, and disciplinary prompts—given to the students created space for different kinds of interactions and disciplinary practices and helped sustain these disciplinary engagement. Further analysis of these three prompts given during the design session revealed that the frequency of different prompts were significantly and positively correlated with each other for both classes at the iteration level (procedural prompt and reflection prompt, $r = .437$, $p < .001$; procedural prompt and disciplinary prompt, $r = .415$, $p = .001$; reflection prompt and disciplinary prompt, $r = .487$, $p < .001$). This means that across all the iterations throughout the design session (N=61, both the treatments), all the three prompts were given to the students while the teams were making multiple design iterations and revising their models. In order to predict the association of the core disciplinary practices of reasoning with multiple design parameters, making tradeoff decisions and heuristics formation with these prompts, I ran a multiple regressions model with all three kinds of prompts included in the same model (Table IV). It was necessary to include all the three prompts in the same model since the three prompts were significantly correlated with each other (as highlighted above). This analysis revealed that the reflection prompts were significantly related to these disciplinary practices, highlighting their importance in the productive disciplinary engagement process.

TABLE IV
REGRESSION ANALYSES EXAMINING THE RELATIONSHIP BETWEEN PROMPTS AND CORE DISCIPLINARY PRACTICES

	B	SE B	β
Procedural Prompt	-0.048	0.025	-0.208
Reflection Prompt	0.357	0.065	0.631***
Disciplinary Prompt	0.108	0.058	0.215
R-squared	0.468		

p <0.001***
N=61, total number of iterations across both treatments and all teams

The procedural prompts helped students with the procedural aspects of the design work like calculations or record keeping, etc. These practices are essential in the engineering design process and do not involve tradeoff decisions or heuristics formation. Thus, although there is a negative association highlighted by the regression model, procedural prompts are important for keeping students on task and helping them make progress. Disciplinary prompts probed the students to help them form their design decisions and articulate their rationale, encouraging students to think about relationships between multiple design parameters and thus supporting tradeoff decisions and heuristics formation. The positive association highlighted by the regression model indicates the usefulness of these prompts in facilitating engagement with the design activity. The reflection prompts helped the students think deeply about their design, reflect on the modifications made to the Improvable Models, and articulate tradeoff decisions and form heuristics while critiquing the Improvable Models. These prompts created space for the students to provide explanations, share their understanding, self-evaluate their comprehension, and construct new knowledge, providing opportunities for students to productively engage with the disciplinary practices and refine their understanding about designing optimal systems.

8. DISCUSSION AND CONCLUSIONS

This study focused on investigating how students used Improvable Models as resources for solving an engineering design challenge. Specifically, I investigated: How do students use Improvable Models, how does the use of these models influence students' design of engineering solutions, and what type of scaffolds support the use of these models. For this research, I used two types of Improvable Models – Suboptimal System (SS) and Optimal Component (OC), as the seed models.

8.1 Improvable Models are Useful as Resources for Engaging Productively with Disciplinary Practices While Solving an Engineering Design Challenge

Teams used the Improvable Models as resources for engaging with five different disciplinary practices – (a) attending to either the input or outcome parameters (D_P), (b) making explicit or implicit connection between an input and single outcome parameter (D_S), (c) reasoning with multiple interconnected input and outcome parameters and making tradeoff decisions (D_T), (d) weighing outcome parameters and making tradeoffs (D_W), and (e) forming design heuristics informed by implicit or explicit rationale (D_H). Three out of five teams using the SS seed model generated and used design heuristics to optimize their solution for the design challenge. These heuristics guided their construction of the final solutions that were the three cheapest solutions across both the treatment conditions. Three out of four teams using the OC seed model displayed three types of design fixation – (a) delayed fixation, (b) immediate fixation, and (c) implicit fixation. Teams that evidenced design fixation were also the ones that evidenced productive disciplinary engagement. This indicates that fixating on optimal features of the Improvable Models may not be a negative characteristic in this context and could help students engage productively with disciplinary practices. All five teams using the SS seed model and three teams (out of four) using the OC seed model productively engaged with the disciplinary practices. They iteratively optimized their model and reasoned about the outcome using the input parameters, formed design rationale, engaged with tradeoffs, and also generated heuristics (in the case of the three teams using SS seed model).

Teams modified the Improvable Models, reusing portions of the existing design, revising and redesigning it by using different pipe diameters, pipe bends, and pipe length. An essential part of modification and redesign involves understanding the "current instantiation of a product" (Wood, Jensen, Bezdek, & Otto, 2001, p. 363). Redesign has been suggested to be better than starting from scratch since it provides opportunities for additional design cycles (Schunn, 2009). So it is likely that the use of the Improvable Models provided more opportunities to the teams for iterative refinement of their solution to the design challenge, essentially providing the students jumping off points into the design task. The models served as baseline examples that provided a worked out solution that students studied and used for forming explanations while developing strategies for problem solving, especially beneficial during the initial stages of a task (Anderson, Fincham, & Douglass, 1997; Atkinson et al., 2000). Hatano and Inagaki (1987) showed that student's comprehension about a particular concept was enhanced when they were asked to explain their views and clarify their position about the concept. They highlight that in the process of explaining to convince, implicit knowledge is represented explicitly. In this process, students examine their own comprehension and become aware of inadequacies (if any) in their conceptual understanding. Brown and Campione (1990) argued that "the burden of explanation is often the push needed to make students evaluate, integrate and elaborate knowledge in new ways" (p. 114).

Teams used the seed models for decomposing the design challenge to focus on areas of interest and input/outcome parameters. Decomposing complex tasks into smaller manageable chunks or "activity spaces" has been identified as a crucial scaffolding strategy in order to make the task more accessible to students (Quintana et. al, 2004). However, what is different in this study is that these spaces were not actively given to the teams as was done in WISE (Linn & Slotta, 2000) or KIE (Bell, Davis, & Linn, 1995). Instead, these emerged during the design activity while students were working on the design challenge. Features of the seed models like long winding pipes above tap A with extra bends in the SS seed model and vertical pipe section in an optimal location in the OC seed model made these activity spaces accessible to the students. Expert designers also use a similar analytical strategy for idea generation by reducing whole into parts (Smith, 1998). The decomposition process likely helped students "convert an undifferentiated stimulus into one rich in detail, offering cues for idea generation" (Smith, 1998, p. 119).

8.2 Visual Representation of Counterexample Scaffolds the Formation of Design Heuristics

Design heuristics are important for solving engineering design challenges as they help "narrow the search of a solution space" (Dym, 1985). Three out of five teams using the SS seed model generated and used design heuristics. These teams used the SS seed model to decompose the design challenge into the activity spaces. The heuristics guided their design optimization process and construction of the three cheapest final solutions across both the treatment conditions. The SS seed model visually presented the teams with a suboptimal solution – cost exceeding the budget amount of $3000, excess pipe bends, and use of unnecessary pipes for connecting the source with the taps. Teams that generated the design heuristics did so by referring to these suboptimal features in the SS seed model and using the SS seed model as a counterexample. These visual representations potentially primed the students, facilitating "anchoring of new, incoming ideas" (Ausubel, 1960 cited in Reder, 1980, p. 42) and use them for forming design decisions, scaffolding their disciplinary design process (Quintana et al., 2004).

The visual representations embodied "opposites" or provided "negation" in the form of how each design parameter should not be in the optimal model, suggesting its use as a counterexample (Thompson, 1992) or a contrasting case which helps students "notice things they otherwise might have missed" (Bransford, Franks, Vye, & Sherwood, 1989; Schwartz & Martin; 2004). Smith (1998) highlights that "negation provides more direction for idea generation and can result in dramatic breakthroughs" (p. 121). Thus, the suboptimal design features in the SS seed model likely provided "more direction for idea generation" and scaffolded the formation of heuristics. None of the teams in the OC seed model treatment generated heuristics. That is likely because such a visual representation of a counterexample was missing in the case of OC seed model, which presented an incomplete but optimal solution instead.

8.3 Fixating on Optimal Design can Help Students Engage Productively with Disciplinary Practices

In the case of OC seed model, three teams displayed fixation effects due to the seed model that were similar to Youmans and Arciszewski's (2014) interpretation of design fixation where a pre-existing design leads to overreliance on its features thereby limiting the solutions created by designers. In this study, the three teams that evidenced design fixation considered the model obtained by fixating on the seed model's design as their best solution and restrained further exploration of the design space. Team OC-C demonstrated immediate design fixation since they started their design session by preserving the design of the OC seed model and modified it by only adding more pipes to this design and engaged in tradeoff discussions during the process. On the other hand, Team OC-B demonstrated delayed design fixation when they reverted back to the seed model's design towards the end of the design activity, reasoning that the layout of the pipes in the seed model would help them build a cheaper model than what they had designed till that point. In Team OC-B's case, the seed model helped them optimize their design by suggesting a possible solution that was cheaper than their previous design revisions. They engaged with tradeoff decisions regarding what diameter of pipes to use in order to balance the pressure and cost during the design revision process. Team OC-A evidenced implicit design fixation and successfully optimized their model as well. All the three teams worked productively by reducing the cost of the final model and engaged with the disciplinary practices.

Thus, OC seed model may lead to design fixation but it may evoke very different responses from student designers – some extending it immediately, some returning back to it after exploring other design options, and some likely having an implicit effect. Fixating on the OC seed model actually helped the teams optimize their model. By emulating the OC seed model's optimal design for the partial system, teams were able to reduce the number of pipe bends and use efficient combination of pipe diameters. This suggests that design fixation may not always be a negative characteristic as suggested in the existing research with adult designers and fixating on partially optimal designs could help students engage productively with disciplinary practices.

Also such a fixation effect was not seen in any of the teams using the SS seed model likely because the seed model represented a suboptimal solution and reusing it would not have helped teams optimize their model.

8.4 Procedural, Reflection, and Disciplinary Prompts Along With Technology Resources Scaffolded the Use of Improvable Models and Engage Productively with Disciplinary Practices

Different instruction prompts and resources were provided to the students for scaffolding the use of Improvable Models for solving the design challenge. Procedural prompts were given to describe some steps that teams had to perform, assist with calculations, keep students on task, and encourage students to keep revising their design. Reflection prompts encouraged students to monitor their work by comparing their model with the Improvable Models and prior design revisions. Metacognitive activities like monitoring and regulating have been found to be beneficial for students (e.g., Brown, Bransford, Ferrara, & Campione, 1983; White & Frederiksen, 1998). Such prompts help students develop "coherent ideas" and deeper understandings of complex topics (Davis, 2003). Disciplinary prompts encouraged students to form rationales and share design decisions. Along with these prompts, students were also given resources like software simulator, audio recorders, and iPad™ that they used during the optimization process for record keeping and organizing their work. These prompts and resources helped by problematizing the quality of a system, problematizing design decisions, giving students authority, maintaining accountability, and providing resources (Engle & Conant, 2002).

The reflection prompts supported revisiting prior work and articulation of design ideas for model improvement (Quintana et al., 2004). Disciplinary prompts emphasized attention to the design goal and rationale. They provided reminders and guided students to monitor their team's progress (Quintana et al., 2004) and helped create further opportunities for problematizing the design decisions and think deeply about the optimization task.

As plumbing companies, the teams (and members in the team) had the agency to be critical of each other's design ideas. Every company was treated as a "local expert" (Engle & Conant, 2002) and was held responsible for deliberating on design ideas as a team, negotiating with peers and defending their design suggestions. This gave authority to the students and established the students and their teams as stakeholders in the design task.

Students were given further authority by means of the ambiguity in the design challenge. The design challenge specified the minimum pressure constraint of 10 psi at every tap and the maximum budget limit of $3000 but did not provide the exact value of pressure and cost that would make the model optimal. This created an uncertainty regarding what the final optimal model should look like and students had to negotiate this uncertainty by forming design decisions. I highlighted how teams using the SS seed model tried to negotiate an optimal value for the output pressure (e.g., Team SS-A trying to decide between maintaining the output pressure around 21 psi or 10 psi) and in the process made tradeoff decisions. I had shown how the range of pressure (0 – 42 psi) highlighted by the SS seed model possibly provided a reference to the students and primed them to have this interaction. While some students favored output pressure of 21 psi, a value that was above the 10 psi minimum constraint and closer to 42 psi, other students preferred having a lower pressure and determined that their model would be optimal as long as it satisfied the 10 psi minimum. On the other hand, for teams using the OC seed model only one pressure was highlighted (10 psi for tap B). Thus, they had only one point of reference. Thus the ambiguity regarding the expected optimal outcome inherent in this design challenge and the presence of these reference values seem to have scaffolded engagement with disciplinary practices during the design session. Prior research into formation of decisions when the outcomes are not well defined reveal that such reference points become critical during such decision making process. In their seminal work related to making judgment under uncertainty, Tversky and Kahneman (1974) asked two groups of people to quickly estimate the value of 8 x 7 x 6 x 5 x 4 x 3 x 2 x 1 and the opposite order 1 x 2 x 3 x 4 x 5 x 6 x 7 x 8 (every group was assigned one sequence). The authors reported that in the second group (people who were given the sequence starting with 1 x 2 x 3) made significantly lower estimate for the value than the other group. The authors suggested that people multiplied the first few digits in the sequence (e.g., 1 x 2 x 3) and anchored on that number while making an estimate of the total value. Hence they had a lower estimate. The other group multiplied the first few terms of their sequence (e.g., 8 x 7 x 6) and anchored on that number while making their estimate. Hence they had a higher estimate. In another experiment, Tversky and Kahneman (1974) gave participants a random percentage (e.g., 65% or 10%) before asking them to estimate the percentage of African nations in the UN. However, before making the estimate, participants were asked to predict if their estimated percentage would be higher or lower than the given percentage. After this task, when the participants were asked for their exact estimates, it was seen that participants who had been given the higher anchor (65%) had made a higher estimate (around 45%) and others with the lower anchor (10%) had made a lower estimate (around 25%).

Thus, the baseline or reference value has a remarkable effect on how people make estimates about the final value. This suggests that the minimum pressure requirement (10 psi) and the high value (42 psi) likely gave rise to simultaneous divergent strategies (reducing pressure and increasing pressure) within the teams and sustained the generation of ideas for determining the optimal pressure in both the treatment conditions. This indicates that it may be valuable to have such ambiguity along with reference values integrated in the design challenge for student designers to help them engage with the disciplinary practices.

8.5 Conclusions

This study aimed at understanding how students used Improvable Models as resources for solving engineering design challenge, how use of these models influence students' design of engineering solutions and what scaffolds might be useful for supporting the use of the models. The findings have implications for both research and teaching.

8.5.1 Implications for research

The findings from this study advance our understanding about how sixth grade students use Improvable Models to engage with engineering design practices. The findings show that sixth grade students can productively engage with five different disciplinary practices using the Improvable Models – (a) attend to either the input or outcome parameters (D_P), (b) make explicit or implicit connection between an input and single outcome parameter (D_S), (c) reason with multiple interconnected input and outcome parameters and make tradeoff decisions (D_T), (d) weigh outcome parameters and making tradeoffs (D_W), and (e) form design heuristics informed by implicit or explicit rationale.

This study demonstrates the potential value of the Suboptimal System model in scaffolding the process of heuristics generation and productive engagement with disciplinary practices. While heuristics have been identified as an important part of engineering design process (Dym, 1985), not much is known about whether middle school grade students can generate it and the conditions that can scaffold the generation and use of these heuristics. Thus, findings from this study advance our understanding in this regard. The Optimal Component model also supported productive engagement with disciplinary practices of tradeoff decisions but was not conducive for generating heuristics. In the case of OC seed model, three types of design fixation emerged in the context of sixth grade students – (a) delayed fixation, (b) immediate fixation, and (c) implicit fixation. The issue of design fixation has received a lot of attention in the context of adult designers but research about how this phenomenon unfolds in the context of middle grade students is in its early stages. This study points at the value of investigating this phenomenon further in the context of young students and provides insight into the ways in which the effects of design fixation can be leveraged within a classroom environment. This study lays the groundwork for further research to understand the design strategies and design trajectories that can be fostered by using Improvable Models as seeding agents in various engineering design contexts.

8.5.2 Implications for Teachers

This research has implications for STEM educators since it advances our understanding of how to support sixth grade students' productive engagement with the engineering design practices. This study highlights different types of prompts, instructional resources, and activities that supported the students' productive disciplinary engagement. In addition, it highlights the value of focusing on the engineering design process rather than using it solely as a medium to learn science and mathematics in classrooms. Students have very limited experience with classroom activities that embody the uncertainty inherent in engineering design problems and rarely get to engage with iteratively redesigning an engineering system, forming design rationale, and making tradeoffs. This study presents a curricular unit that teachers can use to help their students engage productively with the engineering design practices.

8.6 Future Study

This study has advanced our understanding of the different ways in which sixth grade students use two types of Improvable Models for engaging productively with the engineering design practices. The findings highlight the value of Suboptimal System and Optimal Component models as resources for solving an engineering design challenge. However, this study leaves us with further questions and ideas for future studies.

This study highlights the value of Suboptimal System model as a useful resource for supporting generation of heuristics. The Suboptimal System model embodies the aspect of "negation" or "opposites." However, I had created the model and given to the students as a seed model. In the past, researchers have created opportunities for students to create their negative examples since they reasoned that these enabled critical self-evaluation of their design decisions and promoted efficient work towards an improved solution (Bohle, 1986; Davis et al., 1974). This offers an interesting alternative to starting with the researcher created Suboptimal System model, as was done in this study. The process of creating such a model may offer a platform for engaging with the system properties while students try to figure out what design features to include or exclude in their Suboptimal System model. It also gives rise to an interesting scenario. Each team gets to create their own personalized Suboptimal System model, thus providing different starting points for the design optimization process using their personal Suboptimal System model as the seed. Future research can investigate how young students create their own Suboptimal System models and answer questions like – How does the process of creating personal Suboptimal System model influence productive disciplinary engagement with engineering practices? How do students use these personalized Suboptimal System model during the design optimization process? What scaffolds enable the process of creation and then appropriation of these personalized Suboptimal System models?

Suboptimal System model and Optimal Component model belong to a class of models that I call Improvable Models that can be iteratively redesigned and optimized. There can other types of Improvable Models. For example, Suboptimal Component model, could present an incomplete solution that is suboptimal at the component level. In this study, I used Optimal Component model and highlighted the potential of design fixation due to this model. This seed model had an incomplete but optimal solution at the component level. Perhaps having an incomplete but suboptimal solution at the component level, thereby combining the aspects of negation and incomplete examples, could offer further insight into the issue of design fixation and help answer questions like – How do students use these types of Improvable Models for solving an engineering design challenge? What might be the benefits or disadvantages of using different types of Improvable Models with respect to productive disciplinary engagement with engineering practices?

In my review of prior work, I had highlighted the lack of research promoting understanding of design fixation in the case of student designers. In this research, I found that there might be variations in design fixation in the case of young student designers. Further research is needed investigating this variation and how fixation can be leveraged for solving such a design challenge. The idea of a "design fixation gradient" could be a potential avenue for future research. Such a gradient would take into account the temporal point along the design trajectory when fixation might occur and its range of influence on the design trajectory as well as the final designed product. This could help answer questions like – How does variation in design fixation along a gradient influence students' productive engagement with engineering design practices?

The form factor of the models could also be varied. The physical model could be replaced by a simulator-only version that could provide immediate feedback about the effects of design changes in terms of the pressure and cost value (instead of having the students calculate these values). This could change the way students interact, both within the team as well as with the design challenge. They might be able to explore more design options (quicker iterations) using the simulator due to the prompt feedback but at the same time the problem-solving process may become a plug-chug activity where they explore more design options without reflecting on their design decisions. Future research can explore the effectiveness of such a variation and the scaffolds that may be necessary in such a situation and answer questions like – How do students use a computer based Improvable Model for solving an engineering design challenge? What type of feedback and scaffold can support the productive use of such a computer based Improvable Model?

Finally, the process of generation and use of heuristics needs to be investigated further in the context of young students. This study shows that sixth graders can generate and use heuristics using Suboptimal System seed model in different ways. Existing research into heuristics in the context of engineering education has primarily focused on college level engineering students (Daly, Christian, Yilmaz, Seifert, & Gonzalez, 2012). Even then, the focus is on heuristics use, rather than on heuristics generation. So further research is needed in order to understand how we can support heuristics generation and use across various age groups of learners.

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APPENDIX 1

Prior Enactments that Informed this Study

In my first two iterations of the study, I had used antecedent models that represented plausible prior points on students' trajectory of understanding. The goal was to investigate students' appropriation of antecedent models as resources for constructing their own "informed" model.

Iteration #1: Pilot study

I conducted a pilot study in Spring 2012 to investigate whether there were important differences between current models and antecedent scaffolds. I also wanted to know how students made sense of and used antecedent scaffolds. 19 fifth-grade and 20 third-grade students were recruited from a school in the Midwest US. The teachers for both the grades assigned students to small groups of three to four members each (i.e. 6 groups in fifth grade and 5 groups in third grade). The two grades worked in their own classrooms separately. Every group received a construction kit with a PVC pipe, flexible straws, pipe cleaners, popsicle sticks, small paper cups, modeling clay, balloons and a 15 inch x 20 inch foam board. The prompt used for the modeling activity for both the grades was – "Explain with the help of a model how water flows through a house with two sinks on two floors." The study was conducted in two phases. In the first phase, third graders constructed their models in an hour using the materials provided and then explained how their model worked. These explanations were videotaped and edited for use in the second phase. In the second phase, fifth graders were shown the antecedent scaffolds built by third graders. They critiqued the antecedent scaffolds as a whole-class (guided by me) and generated a list of design specifications for their own models. They then constructed their own models addressing these design specifications and explained how their model worked. Both the phases were videotaped and the groups were interviewed separately to understand fifth graders' perceptions about the antecedent models. Fifth graders also filled out a survey aimed at finding their perception of the authenticity of the 3rd grade models.

Findings from iteration #1:

I analyzed all the models and explanations provided by the third graders and fifth graders using a rubric. The rubric included four conceptual areas—Source water system, Waste system, Interaction of source water and waste system, and hot/cold water system; and sub-criteria that underlie each of these conceptual areas (e.g., source water and waster system do not share any pipes). For each sub-criterion, student understanding was ranked from 1 to 3 – rank 1 for inaccurate or low level of understanding, rank 2 for partially accurate or medium level of understanding, and rank 3 for accurate or high level of understanding. I then calculated average ranks within the two grades for each sub-criterion across all the models. The rankings were then used to highlight general differences and similarities between third and fifth grade models and find out differences between antecedent and informed models. This analysis revealed that differences existed between fifth grade models and antecedent scaffolds (representing third grade level understanding of the plumbing system) given to them. Antecedent scaffolds were simplistic representations of the phenomena with conceptual gaps. Fifth graders identified these conceptual gaps in the antecedent scaffolds and addressed them in their informed models and explanations. They also appropriated the structural styles of the antecedent scaffolds while designing their current model. Thus fifth graders were able to make sense of and use antecedent scaffolds. Students wanted to use all of the construction materials provided to them. While this was not required of them, all the groups showed a natural inclination to using as much materials as possible even though it wasn't required to represent their design idea. The presence a large assortment of design materials proved to be distracting and often led to inaccurate models. The design activity called for creation of 3D models, which were not always easy to make and depended on the dexterity of the students. This may have led to differences in the quality of representation of design ideas between various groups. While developing modeling skills is an important part of the engineering practice, it was not at the core of my research focus. The goal of building the complete plumbing system that includes the source water system, hot/cold water system, and waste water system required more time than was originally planned for. This made it impossible for the students to iterate and try multiple design ideas. The fragile 3D nature of the antecedent models and the presence of audio explanations authored by third graders that could not be accessed on a need basis by the fifth graders prevented these resources from being used persistently for reference throughout the design activity.

Modifications incorporated in future designs of the study:

Changes in the study design:

1. The analyze/critiquing phase happened as a whole-class discussion and I led the discussion. This helped the fifth graders generate a common set of design requirements for their own model. However, the next step of making the model happened in small groups and my unit of analysis was small group (model and discussion at the group level). Thus, there was a confound because the small groups were making their models based on a whole-class discussion so I could not really say for sure that the models reflected the small group's understanding only. *Thus, in the following iterations, the analyze/critique phase happened within small groups instead of a whole-class discussion.*
2. One of the teachers participating in this study suggested that I should have the students draw their model before actually allowing them to build it. This would help students

remain focused while building their model and not get distracted by the construction materials. *Thus, in the following iterations, students made a diagram before seeing the construction materials and building the model.*

3. During the pilot study, one of the challenges was to identify and analyze the recapitulation process in fifth graders that might be happening upon seeing the antecedent scaffolds. I believed that understanding fifth graders' perception of the authenticity of the antecedent models would help me identify and analyze the recapitulation process. Hence I gave them a survey at the end of the study. The fifth graders overwhelmingly responded that they would have made similar antecedent models when they were in third grade. However, I cannot be certain whether they were indeed thinking like third graders or not when they were analyzing the antecedent scaffolds. The recapitulation process could not be identified with the survey. Also, I was increasingly getting more interested in using the antecedent models as prompts for the model building and explanation process, instead of trying to find whether it helped the students recapitulate. *Thus, in the following iterations, in the interest of implementation time and also because of my shift of interest away from the recapitulation process, I dropped the survey and focused on the design process.*

Changes needed in the instruments:

4. After the students completed their task of model building, I conducted a semi-structured interview with the group. Students explained to me how their model worked and also used their model to predict how the plumbing system might work under certain scenarios. However, the student responses and discussion during the interviews made it evident to me that I should also have open-ended questions related to science and engineering practices as the activity was affording them to get involved in those practices. *Thus, in*

the following iterations, I included questions related to science and engineering practices in my interview guide. This realization eventually paved the way for focusing on engineering practices and it subsequently became a core part of my framework.

Changes needed in the prompts:

5. During the pilot study, it became evident that the fifth graders mostly ignored the antecedent scaffolds while constructing their own models after the critiquing process. They did not refer to the antecedent models during the model construction phase. There was a need to make the antecedent scaffolds more persistent and easily accessible for the fifth graders (the antecedent scaffolds were in my laptop in the form of video files which I was playing for the students). *Thus, in the following iterations, I took colored printouts of the antecedent models and give each group one copy.*
6. I was not sure what the contents of the construction kit (that the students use for constructing their models) should be. I started with construction materials that were similar to those used by Penner et al. (1997) in their elbow design study. Balloons were also part of my construction kit. During the pilot study, it became evident that balloons were distracting the students from the construction task. Students were more interested in blowing them up and playing with it rather than using them constructively in their models. I also found that the students felt obligated to use all the construction materials in their models. *Thus, in the following iterations, the construction kit was simplified by reducing the construction materials included in it and my prompts at the beginning of the construction session clarified that using all the construction materials was not mandatory.*

Iteration #2:

Based on the findings from the first iteration, I conducted the second iteration in Fall 2012 with 19 third-graders and 22 fifth-graders recruited from a school in the Midwest US. The fifth graders were assigned to two groups – control and treatment group – randomly and made to sit in two different spaces (such that they won't be able to influence each other). Students were also randomly assigned to small groups of 3-4 students each.

Preliminary findings:

Based on preliminary analysis of models and explanations of one group from the treatment condition and one from the control condition, it seemed that the group in the treatment condition discussed about hot and cold water (missing in some of the antecedent models), and also referred back to their design requirements during the model construction phase (a key engineering practice). The model and explanation generated by the control group was more simplistic and less accurate. They also did not refer back to their design requirements during their model construction phase. This indicates that the treatment might have had some positive impact.

Modifications incorporated in future designs of the study:

Changes needed in the study design:

1. The treatment group spent around fifteen minutes with the antecedent scaffolds. Although the printouts seemed to have helped them understand the antecedent scaffolds a little bit better, they needed to spend more time with the antecedent scaffolds. Also, the antecedent models were in my laptop and the students did not have access to them easily. *Thus, in the following iterations, I used iPads^{TM} for making the antecedent scaffolds*

accessible to students so that they could play/replay the video as many times and whenever they want.

Changes needed in the instruments:

2. The interview questions (especially the science and engineering questions) were very lengthy and some of the groups got bored towards the end. In order to keep them engaged during the automated interview session, the questions have to be trimmed down and presented differently. *Thus, in the following iterations, I used a smaller set of questions.*

Changes needed in the prompts:

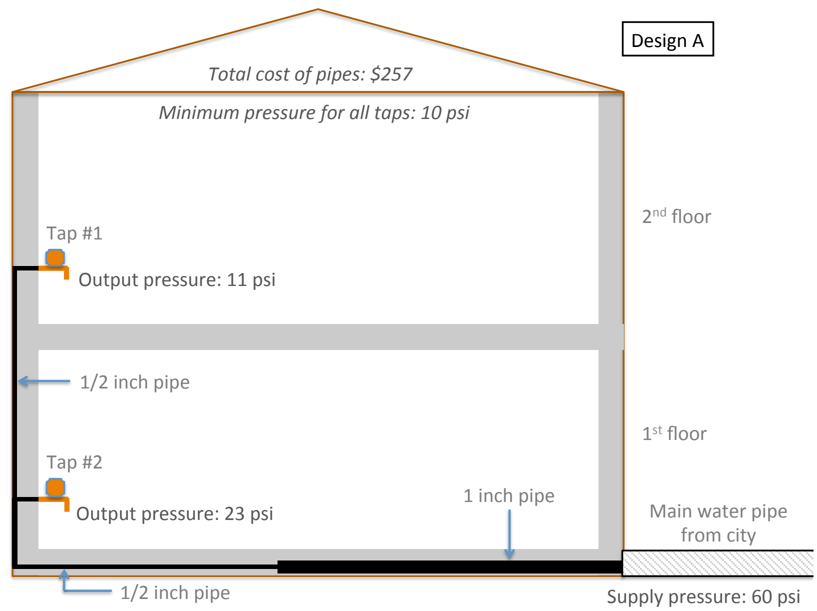
3. The explanation process till now had been structured as a semi-structured interview with each group. All the responses were for an audience of one – the interviewer. Prior research suggests that richer explanation can be captured if the students are talking to each other and generating the answers to the interview questions for each other. *Thus, in the following iteration, every group recorded their explanations while discussing responses to the interview questions as a team without the presence of the interviewer.*

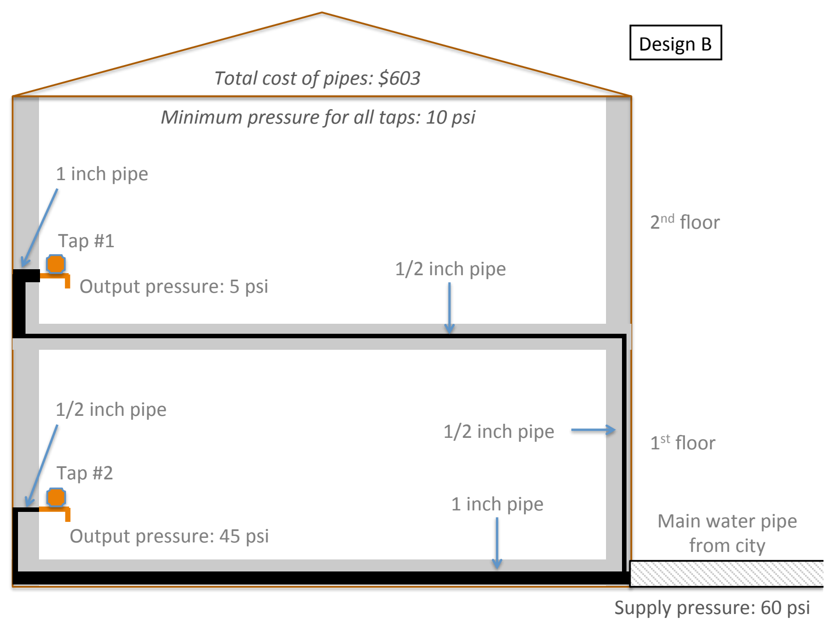
Over the course of these two iterations, I realized that the essential ingredient of the antecedent models that formed the core of my thesis was the gap in the understanding that these models represented. Whether they accurately represented prior points in the learning trajectory that went back as far as two grades in the past didn't matter to me that much. Also, inaccurate or accurate models were not the most effective ways of thinking about designing engineering systems. It was more important to think of design in terms of being optimal. Thus, the notion of Improvable Models as priming agents was formed. These models reflected potential gaps in students' understanding of an engineering system and highlighted the design elements that could be optimized. Around the same time, efforts to simplify the design task in order to facilitate more student iterations resulted in the decision to focus on just the cold water plumbing system within the house without attending to the hot water system or waste system. Challenges during the construction process due to the presence of a lot of construction materials resulted in the decision to focus on a very selective set of materials that had direct implications on the optimality of the design. Also, it was decided that in order to make the priming agent along with various design revisions accessible throughout the designing phase, the students would be asked to document their iterations using a dedicated iPad™ that they would always have access to during the design process. This would enable the students to refer to these resources whenever required. Explicit prompts were also devised that guided students to reflect on their design and compare the iterations to understand if they were actually making a better model or not. Audio recorders were also provided in order to create an audio-journal of their design rationale. Finally, the opening design charge was modified and couched as a design challenge that couched groups of three to four students as "plumbing companies" competing to win the bid for building the plumbing system of a house, with the winner being the company that satisfied the design constraints and specifications.

APPENDIX 2

Schematic Diagrams for Class B (Suboptimal System Seed Model)

Can you find differences between the two designs – Design A and Design B?

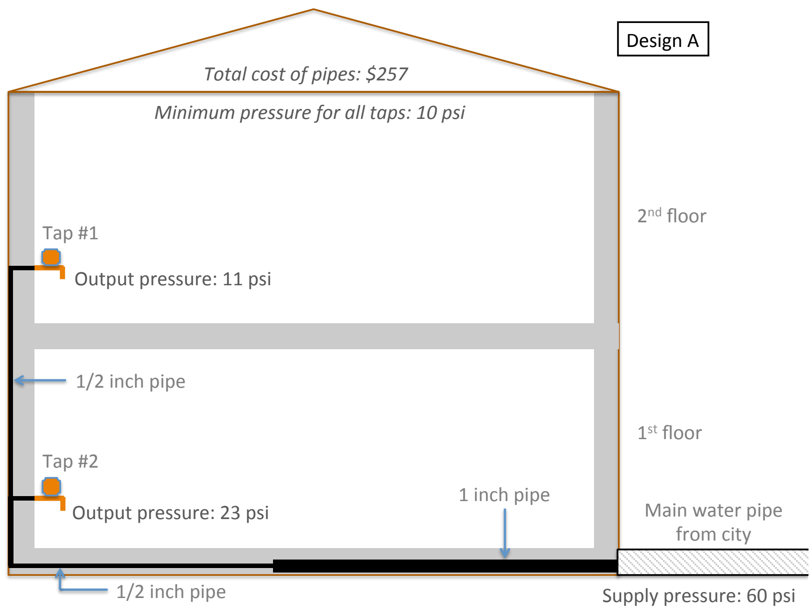


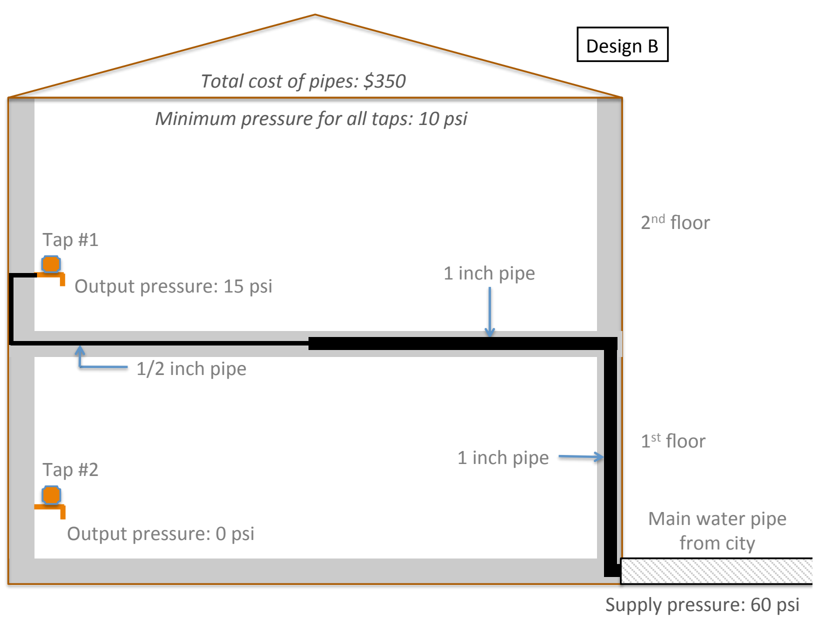


APPENDIX 3

Schematic Diagrams for Class A (Optimal Component Seed Model)

Can you find differences between the two designs – Design A and Design B?





APPENDIX 4

System Properties from the Table

What is the effect of length of pipe on the water pressure?

What is the effect of diameter of pipe on the water pressure?

What is the effect of length of pipe on the cost?

What is the effect of diameter of pipe on the cost?

What is the effect of a 90 degrees pipe bend on the water pressure and cost?

What happens to pressure and cost when a pipe branches out?

What happens to water pressure and cost when different sized pipe segments are placed one after another?

APPENDIX 5

Prompts for Recording Design Decisions

1. How is your design better than the original one that was given to you?
2. How many of each type of pipe have you used?
3. What are the psi values at each tap?
4. What is the total cost of your design?
5. Talk about your design decisions and why you built your design this way?
6. How is it better than your previous designs?
7. Is your design optimal? Give reasons.

APPENDIX 6

Hagen–Poiseuille's Equation

The software simulator computes the output pressure for the students using the Hagen–Poiseuille's equation. It is also known as Hagen–Poiseuille law and determines the drop in pressure across a given cross section of pipe through which an incompressible and Newtonian fluid like air or water flows (Sutera & Skalak, 1993). In standard fluid dynamics notation, this is how the equation is represented:

$$\Delta P = \frac{8\mu L Q}{\pi r^4}$$

where:

ΔP is the pressure loss

L is the length of pipe

r is the radius of pipe

μ is the fluid viscosity

Q is the volumetric flow rate

π is the mathematical constant Pi

APPENDIX 7

Worksheet: Using the Plumbing Simulator

Size of pipe used: _______________________

Total pipe length (feet)	Pressure drop (psi)	Total cost of pipes ($)
1		
2		
3		
4		
5		

Notes (your observations):

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Ph.D. Candidate in Learning Sciences **GPA: 4.0/4.0**
University of Illinois at Chicago, Chicago, USA; 2009 – 2015

Master of Science in Human-Computer Interaction **GPA: 3.8/4.0**
Georgia Institute of Technology, Atlanta, USA; 2007 – 2009

Bachelor of Engineering (Honors) in Computer Science & Engineering
Maharshi Dayanand University, Rohtak, India; 2000 – 2004

SKILLS

Research and Analysis:
Curriculum design, Constructing hands-on learning tools, Qualitative research, Quantitative research, Classroom observation, Video and Audio data analysis, Semi-structured interviews, Teacher training

Interactive Computing:
User interface design, User study, Wireframes, Processing programming

AWARDS & HONORS

2013 University of Illinois at Chicago Chancellor's Graduate Research Fellowship Award

Research showcased during the American Education Research Association 2013 Division C (Learning and Instruction group) Business Meeting

2012 University of Illinois at Chicago Chancellor's Graduate Research Fellowship Award

Doctoral Consortium of the International Conference of the Learning Sciences, Sydney, Australia

Liberal Arts and Sciences Student Travel Award

Learning Sciences Research Institute Travel Award

2010 Graduate College Student Presenter Award

2009 Graduate Student Council Travel Award

Anne Robinson Clough Conference Grant

PROJECTS & RESEARCH EXPERIENCE

University of Illinois at Chicago (UIC) **Chicago, Illinois**

- *Dissertation project:* Investigating the Use of Suboptimal Priming Artifacts for Helping Students Productively Engage with Tradeoff Decisions and Design Optimization
(01/2013 – Present)
    - Disciplines: Learning Sciences, Engineering Education, Curriculum & Instruction, Human-Computer Interaction, Computer Science
    - Investigate the outcomes of an intervention that engages learners with science and engineering practices using improvable models as priming artifacts
    - Design research, develop lesson unit and teaching materials, construct hands-on learning tools, develop simulation software for elementary grade students, observe classroom, conduct semi-structured interviews and analyze video and audio data
    - Design-Based Research, classroom observation, qualitative and quantitative analysis

- *Research assistant:* Using Technologies to Engage Learners in the Scientific Practices of Investigating Rich Behavioral and Ecological Questions (NSF-1124495)
(09/2012 – Present)
    - Disciplines: Learning Sciences, Human-Computer Interaction, Ecology
    - Investigate the design of classroom instructional units that would help children study the behavior of animals in their neighborhood by designing and conducting their own experiments using camera-traps
    - Design curriculum to scaffold the use of camera-traps and collected video data

- *Research assistant:* Integrated Study of Natural Resources, Human Impact, and Environmental Policy: Making Complex Systems Accessible for Secondary Learners (NSF-1020065)
(06/2011 – 01/2013)
    - Disciplines: Learning Sciences, Urban Planning and Policy, Human-Computer Interaction
    - Evaluated the problem solving skills and collaborative strategies that emerge when groups of experts and novices use a new paper based input method.
    - Conducted lab based user studies and interviews with novices and experts
    - Transcribed and analyzed group discussions using qualitative and quantitative methods

- *Research assistant:* Enhancing Stakeholder Participation in Environmental Planning with Visualization Tools that Support Complex Systems Learning and Spatial Thinking (NSF-1135572)
(08/2009 – 05/2010)
    - Disciplines: Urban Planning and Policy, Learning Sciences
    - Conducted field observations of meetings at Chicago Metropolitan Agency for Planning (CMAP) and interviewed urban planners to understand their attitude towards planning models

- Generated software design guidelines for a new model that was more "trustworthy" and helped the planners predict the outcome of their policy decisions

➢ *Research assistant:* A Library of High School Mathematics Teaching and Learning Videocases (NSF-0942147)

(01/2010 – 11/2012)

- Disciplines: Math education, Pre-service and in-service teacher training, Learning Sciences
- Developed case library of high school mathematics teaching and learning videos, along with facilitator guides for training pre-service and in-service high school mathematics teachers
- Implemented the case library with pre-service and in-service teachers at UIC and collected research data
- Analyzed data to understand effect of the case library on their teaching methods

Museum of Science and Industry **Chicago, Illinois**

➢ *Team member:* Chicago Incubator for Innovation in the Art of Science Learning program hosted by Museum of Science and Industry

(09/2014 – 12/2014)

- The Art of Science Learning is a National Science Foundation-funded initiative that uses the arts to spark creativity in science education and the development of an innovative 21st Century STEM workforce.
- Role: Develop curriculum and sensor-based technology scaffolds for teaching upper-elementary grade students about how plants can be grown in classroom using hydroponics

Georgia Institute of Technology **Atlanta, Georgia**

➢ *Research assistant:* Learning by Design - Integrating and Enhancing the Middle School Math, Science and Technology Curricula

(05/2008 – 05/2009)

- Disciplines: Human-Computer Interaction, Cognitive Psychology, Learning Sciences
- Developed an interactive case library for supporting middle school science-learning through construction of models of hovercrafts
- Conducted user study and performed qualitative data analysis

➢ *Research assistant:* Effect of robot 'emotions' on participants' attitudes toward them

(01/2008 – 05/2008)

- Disciplines: Human Factors & Ergonomics, Cognitive Psychology, Human-Computer Interaction
- Developed a Flash based tool to run instructional media and collect user-interaction data for statistical analysis
- Programmed the iCat Robot so that its interaction with older adults could be observed and recorded

TEACHING EXPERIENCE

University of Illinois at Chicago (UIC) **Chicago, Illinois**

- *Introduction to the Learning Sciences:* Required course for all Learning Sciences graduate students (08/2014 – 12/2014)
  - Assisted instructor in planning the classes, facilitate discussions and in-class activities, develop rubric for evaluating student projects, and provide feedback to the students regularly

PUBLICATIONS

Martinez, M., Castro Superfine, A., Carlton, T., & **Dasgupta, C.** (2015). Examining the Impact of a Videocase-based Mathematics Methods Course on Secondary Preservice Teachers' Skills at Analyzing Students' Strategies. *Journal Of Research In Mathematics Education, 4*(1), 52-79. Retrieved from http://www.hipatiapress.info/hpjournals/index.php/redimat/article/view/1195

Dasgupta, C. & Moher, T. (2015). Promoting Productive Disciplinary Engagement in an Engineering Design task. Presented at the *2015 National Association for Research in Science Teaching, Chicago, IL.*

Dasgupta, C. & Moher, T. (2015). Can Do Better: Investigating the Use of Improvable Designs as Priming Agents for Learning about Tradeoffs and Design Optimization. Presented at the *2015 Annual Meeting of the American Educational Research Association, Chicago, IL.*

Dasgupta, C. & Moher, T. (2014). Using Deficient Models as Scaffolds for Learning Engineering Concepts of Tradeoffs and Optimization. *Proceedings of the 11th International Conference of the Learning Sciences, 2014.* Boulder, CO.

Shelley, T., Lyons, L., Moher, T., **Dasgupta, C**., Lopez, B., & Silva, A. (2014). Information-Building Applications: Designing for Data Exploration and Analysis by Elementary School Students. *Proceedings of CHI 2014*, Toronto, Canada.

Dasgupta, C., Shelley, T., Silva, A., Lopez, B., Moher, T., & Lyons, L. (2014). Promoting Productive Disciplinary Engagement in Instrumented Investigations. Presented at the *2014 National Association for Research in Science Teaching, Pittsburg, PA.*

Shelley, T., **Dasgupta, C.**, Moher, T., & Lyons, L. (2014). Supporting learners' construction of understandings of animal behaviors from large image sets. Presented at the *2014 Annual Meeting of the American Educational Research Association, Philadelphia, PA.*

Silva, A., Lopez, B., **Dasgupta, C.**, Lyons, L., Moher, T., & Shelley, T. (2014). Shaping the Construction of Learner Questions. Presented at the *2014 Annual Meeting of the American Educational Research Association, Philadelphia, PA.*

Dasgupta, C. & Moher, T. (2013). Investigating the Influence of Antecedent Models on Learning Science and Engineering Skills. Presented at the *2013 Annual Meeting of the American Educational Research Association, San Francisco, CA.*

Dasgupta, C., Slattery, B., Shelley, T., Lyons, L., Minor, E., & Zellner, M. (2013). Building an Understanding of How to Support Students as they Problem-Solve Within a Spatial Urban Planning Simulation. In S. Chunawala & M. Kharatmal (Eds.), *Proceedings of epiSTEME 5 - International Conference to Review Research on Science, Technology and Mathematics Education, India: Macmillan.*

Dasgupta, C. (2012). Investigating a Recapitulation Strategy for Science Learning Using Multiple Models. Presented at the Doctoral Consortium in the *10th International Conference of the Learning Sciences 2012.*

Slattery, B., **Dasgupta, C.**, Shelley, T., Lyons, L., Minor, E., & Zellner. M. (2012). Understanding How Learners Grapple with Wicked Problems in Environmental Science. *Proceedings of the 10th International Conference of the Learning Sciences, 2012. Sydney, Australia.*

Hyungsin, K., Kogan, A., **Dasgupta, C.**, Novitzky, M., & Do, E.Y. (2011). Grocery Hunter: A Fun Mobile Game for Children to Combat Obesity. *Proceedings of 5th Intl Conf. on Tangible, Embedded, and Embodied Interaction (TEI '11). ACM, NY, 317-320.*

Dasgupta, C. (2010). That is Not My Program: Investigating the Relation between Program Comprehension and Program Authorship. *Proceedings of the 48th Annual Southeast Regional Conference (ACM SE '10). ACM, NY, USA.*

Dasgupta, C., Lyons, L., Zellner, M., & Greenle, A. (2010) Designing for an Informal Learning Environment: Towards a Participatory Simulation Design Process for Public Policy Planning. *Proceedings of the 9th Int. Conf. of the Learning Sciences (ICLS '10), 348-349.*

Dasgupta, C., & Kolodner, J. L. (2009). Designing case libraries to encourage creative design. *Proceeding of the 7th ACM conference on Creativity and cognition (C&C '09). ACM, New York, NY, USA, 361-362.*