High School Students’ Cognitive Activity While Solving Authentic Problems through Engineering Design Processes

Dr. Amy Alexandra Wilson, Utah State University - Teacher Education and Leadership

Dr. Amy Alexandra Wilson, assistant professor at Utah State University, studies adolescent literacy in engineering and science.

Ms. Emma R. Smith, Utah State University
Dr. Daniel L. Householder, Utah State University

Dr. Daniel L. Householder is a research professor in the Department of Engineering Education, Utah State University.
High School Students’ Cognitive Activity While Solving Authentic Problems through Engineering Design Processes

Abstract

This exploratory multiple case study describes the cognitive activity of two groups of adolescents as they used engineering design processes to address authentic challenges. These challenges were ‘authentic’ in the sense that they aligned with the students’ interests, were ill-structured, and met the needs of actual clients. The following data were collected in relation to these students’ design processes: pre- and post-challenge interviews with each of the seven students, transcriptions from video-recordings of their conversations during the challenge, and products made during the design process (e.g., sketches). Constant comparative analyses revealed differences and similarities across the two groups in terms of their problem definition strategies, research strategies, and communication strategies. Neither of the groups outlined criteria and constraints in the problem definition stage; instead, these criteria and constraints were only articulated in the ‘evaluate the solution’ stage as the students evaluated individual ideas for the design. Moreover, the groups generally did not consider competing criteria and constraints in their evaluations. The study concludes with possible instructional implications for high school engineering teachers to consider as they seek to enhance their students’ cognitive activity at each stage of the engineering design process.
Purpose of the Study

The number of K-12 students enrolled in formal engineering curricula has mushroomed from fewer than five million students in the early 1990s to over 56 million today, a number that is expected to increase due to the current national emphasis on STEM learning. Moreover, according to the National Research Council, even students who are not enrolled in separate engineering courses will be expected to learn and practice engineering design as part of their science coursework. National frameworks and standards have specified what ‘engineering design’ means at various stages in K-12 students’ educational development. However, these standards are largely based in literature on how professional engineers or college students approach engineering problems.

Research on advanced practitioners’ design processes may provide a useful starting point for identifying the types of engineering activity expected of adolescents, but this study is based on the premise that it is also essential to understand adolescents’ approaches to engineering design processes while approaching authentic problems. By first understanding adolescents’ approaches to these problems, researchers can identify ways in which they might more fully support adolescents in developing the habits of mind practiced by professional engineers. Although a handful of previous studies have studied adolescents’ cognitive activity during engineering design processes, many of these studies have focused on time allocation rather than offering a qualitative description of what adolescents do at each stage of the process. Moreover, most research on novices’ design activity (which studies undergraduates rather than adolescents) has examined their work on pre-determined design challenges that do not necessarily relate to students’ interests or backgrounds. This approach to engineering design, which does not consider adolescents’ interests or backgrounds, may fail to encourage young people to pursue careers in engineering.

The purpose of this exploratory multiple case study was to describe the cognitive activity of two groups of adolescents as they solved authentic, ill-structured problems through engineering design processes. The high school students had identified these problems as being important, socially relevant, and personally meaningful to them. Framed in theories of situated learning, this qualitative study resulted in a framework that qualitatively categorizes and describes adolescents’ cognitive activity during each stage of the engineering design process. This framework may serve as a heuristic for future researchers who seek to categorize and understand other adolescents’ engineering design processes as they work on authentic problems. This framework may also serve as a useful heuristic for secondary engineering and science teachers who seek to bridge adolescents’ existing engineering practices to the formal practices of engineering by identifying gaps and commonalities between the two groups’ practices.
Adolescents’ Enactment of Engineering Design Processes

Researchers and practitioners of engineering have offered models of engineering design processes (EDP), which outline stages through which engineers flexibly and iteratively progress in a non-linear fashion as they seek to address a variety of problems.\(^{13,14,15}\) Most of these models, however, are not based in the authors’ observations of adolescents. Instead, they are based in the authors’ experience as engineers or based in their work with college-level engineering students. Drawing from these previous models of engineering design processes, Hynes et al.\(^{16}\) developed an EDP model that was grounded in decades of experience with adolescents in Massachusetts, the first state to adopt standards for engineering education at all grade levels in public schools. This model was adopted and recommended by the National Center for Engineering and Technology Education as an appropriate model for describing K-12 engineering activity.\(^{10}\) The following section briefly reviews Hynes et al.’s model of K-12 engineering design processes and reviews the available literature on what is known about how adolescents approach each stage of the design process.

**Step 1: Identify and define problems.** Clients oftentimes identify problems for the engineers whom they hire, describing their problems or needs with varying degrees of specificity while at times leaving several aspects of the problem unstated.\(^{17}\) Although adolescents “are capable of identifying a need or a problem in a given situation” (p. 10),\(^{16}\) clients, teachers, and researchers may similarly give high school students a pre-determined design challenge that minimizes the amount of work the students must do to identify a need. As in professional settings, these design challenges may outline the problem with greater or lesser degrees of specificity, leaving the adolescents to infer several additional needs or aspects of the problem based on available information.

Even after a problem has been identified, students must interpret and define the problem in their own terms, identifying the criteria and constraints that will characterize a successful solution. Lemons et al. found that framing and accurately interpreting the problem were “of paramount importance,” representing “crucial and pivotal turning points” for undergraduate engineering students who sought to complete a design task (p. 1).\(^{18}\) Despite this stage’s importance in the design process, previous studies of adolescents’ engineering design processes suggest that adolescents spend very little time defining the problem when presented with an engineering task.

Mentzer and Park, for example, found that adolescents spent about 2.37% of allotted time in defining the problem, or about 3.14 minutes out of three hours.\(^{7}\) This finding that was later echoed by Becker and colleagues who likewise found that adolescents spent very little time in the problem definition stage—in their case, 5.6 minutes out of 92 minutes.\(^{6}\) Although these previous studies identified the time allocation of adolescents’ problem solving, the current study seeks to expand on their work by qualitatively categorizing and describing the types of problem definition in which the adolescents were engaged, including identifying when in the design process they engaged in problem definition.
Step 2: Research the need or problem. This stage of the design process subsumes what other EDP models call the “information gathering” phase, during which students “look for information about their design problem or solution” (p. 13). Based on their studies of expert engineers, Ennis and Gyeszly argued that gathering information can be an essential precursor to later stages of the design process, such as generating and evaluating solutions, because engineers’ ideas are often influenced by the information that they find. In his ethnography of professional engineers, Bucciarelli suggested that engineers gather information across several domains depending on the nature of the problem, including studying the physical location in which the design will be placed, reviewing relevant codes and regulations, and identifying costs of material and labor. Bursic and Atman identified similar categories of information gathered by freshman and senior undergraduate engineering students, finding that the more expert students identified information across more categories, which led to designs of higher quality.

Time allocation studies of adolescents’ engineering design processes have produced somewhat discrepant findings: Mentzer and Park found that high school students spend about 34.74% of allocated time on gathering information while solving a challenge, whereas Becker found that they spend only 10.3% of time on gathering information. This current study sought to expand these previous studies by describing the types of information that the adolescents deemed to be important and the ways in which they sought that information.

Step 3: Develop possible solutions. According to Hynes et al. another stage in adolescents’ engineering design processes includes developing possible solutions based on available information and based on their analysis of criteria and constraints. Although Atman et al. found that experts spent more time than novices in the problem scoping stage (the previous two stages of the design process), they found that freshman undergraduates allocated a greater percentage of time (11.7%) to generating ideas than did experts (5.0%). Their findings suggest that, perhaps because the novices defined their problem with less specificity and focus than the experts, they did not have a clear framework to help them narrow and hone the ideas they generated.

Interestingly, studies of high school students’ design processes have found the opposite: High school students spend less time on problem generation than experts, and they allocate a smaller percentage of overall time to this stage of the design process than experts. The current study does not describe time allocation, but it does identify the number of conversational turns that were devoted to idea development, and it describes the adolescents’ approach to developing possible solutions.

Step 4: Select the best possible solution. According to Hynes et al., this stage not only entails choosing a solution, but justifying the solution “with proper consideration of evidence and issues that were discovered through problem definition and research” (p. 5). In this way, effective selection of a solution requires adolescents to justify why they selected particular ideas from the previous phase while discarding other ideas. Consequently, this phase subsumes “feasibility
SOLVING AUTHENTIC PROBLEMS THROUGH DESIGN PROCESSES

analysis,” in which students determine whether or not a solution “meets workability in general” and whether it “meets problem definition criteria or constraints” (p. 367).\textsuperscript{13} It also subsumes the “evaluation stage” as adolescents specify or debate trade-offs among alternative solutions and as they compare and contrast the solutions offered in the previous stage. Previous research has suggested that experts spend more time than undergraduate novices and high school students in these phases of the design process. In contrast to these previous studies, the current study qualitatively describes the criteria by which adolescents evaluated the design and analyzed its feasibility prior to making a decision.

**Step 5, 6, & 8. Construct a prototype, test and evaluate solution, and redesign.** Hynes et al.\textsuperscript{16} emphasize that “building is often the only concept students have about engineering prior to engineering design exposure” and that students should be allowed “to physically construct a model of the solution” when possible (p. 11). However, as in previous studies of high school students’ and undergraduates’ engineering design processes, we did not study the students’ construction of a physical model that they could test and evaluate. Moreover, students did not test a mathematical model or virtual model, as alternatively suggested by Hynes et al. Instead, when they drew and labeled sketches of their designs to share with each other and with the client, we coded those instances as “communicating a solution.” This approach coheres with Atman’s model,\textsuperscript{13} in which “communicating the solution” follows the selection phase in the design process.

**Step 7. Communicate the solution.** Hynes et al.\textsuperscript{16} emphasize the importance of communication in the design process, asserting that “part of engineering is sharing your ideas and findings with others for feedback and marketing purposes” (p. 12). This phase of the design process may include oral reports to clients, contractors, and manufacturers. In addition to presenting ideas through verbal speech, this phase includes communication through written language, sketches, and diagrams. It may include instructions for manufacturing, a list of materials needed for construction, a report of estimated costs, and visual representations of what the product should look like when it is finished. Previous research with adolescents has suggested that the percentage of time they spend on communicating solutions varies considerably: from 7.2\%\textsuperscript{6} to 24.47\%.\textsuperscript{7} In both cases, adolescents spent a significantly greater percentage of time on this task than experts, perhaps because they were less familiar with engineering terminology and modes of representation than professionals with more practice.

**Engineering Design and Situated Learning**

This study is based on the premise that engineering design is inherently complex and ill-structured in several ways: Clients often do not specify all relevant criteria and constraints, leading to ambiguity in the engineers’ overall goals;\textsuperscript{17, 22} there is no pre-determined solution path to reach a solution, and the ‘best solution’ may never be known;\textsuperscript{23, 24} and it requires the integration of multiple knowledge domains, often through discussion and consultation with several people and extant written/visual sources.\textsuperscript{25} Because many ‘design challenges’ in schools
require students to build clearly specified products with known pathways and solutions, they are best characterized as “well-structured (story) problems, which are inconsistent with the nature of the problems” faced by people in settings outside of school, such as professional engineers (p. 63).  

In accordance with this view that engineering design processes are best understood through studying people’s work in ill-structured problem spaces, we studied two groups of twelfth-graders’ cognitive activity as they worked on authentic problems for which there were no pre-determined solutions. These design challenges met the criteria for ‘authenticity’ as outlined by Hung, Lee, and Lim.  

They argued that, in order for problem solving to be ‘authentic,’ it must not be pre-determined by a teacher or authority figure, but co-determined by participants who negotiate with each other and with relevant stakeholders. In this study, the structure of the adolescents’ problem spaces met these criteria, and it was further ‘authentic’ in the sense that their final designs were presented to clients with pressing needs who evaluated the designs.  

Another body of research has suggested that many STEM curricula are not ‘authentic’ to adolescents in another sense as well: They do not bear any relation to their lives at home, to their interests, or to their desired life trajectories. Thus, although a task may be ‘authentic’ in the sense that it approximates the work of an engineer, it may not be authentic in the sense that adolescents view it as being genuinely relevant to their lives. To address this problem, researchers have suggested that school curricula, including engineering design challenges, should be grounded in students’ ‘funds of knowledge,’ or the resources that can be found in their homes and neighborhoods. When engineering tasks seem unrelated to students’ interests and home backgrounds, students may believe that engineering is ‘not me.’ Consequently, we identified an additional criterion of authenticity: relevance to students’ interests, life trajectories, and/or existing funds of knowledge. We purposively selected design challenges—co-constructing them with research participants and other engineers—so that they met these criteria for authenticity (see Methods section).

This study is framed in theories of ‘situated learning’ in accordance with this idea that authentic engineering design is best understood in the context of ill-structured problem spaces, which are co-determined by the participants and are relevant to their interests as they seek to improve the quality of life for clients. These theories assert that learning is not primarily an act of cognition that occurs within an individual’s mind in controlled settings such as classroom and laboratories. Rather, learning is fundamentally social and material. It is related to people’s identities, including what they are interested in and who they want to become, and it is situated within their activity as they seek to jointly solve problems through physical and representational tools. In Lave and Wenger’s terms, a theory of situated learning emphasizes the relational interdependency of agent and world, activity, meaning, cognition, learning, and knowing. It emphasizes the inherently socially negotiated character of meaning and the interested, concerned character of the thought and action of
persons-in-activity [...] Given a relational understanding of person, world, and activity, participation, at the core of our theory of learning, can be neither fully internalized as knowledge structures nor fully externalized as instrumental artifacts or overarching activity structures. (p. 50-51; italics added for emphasis)\textsuperscript{11}

Participation is placed at the center of theories of situated learning under the core assumption that authentic learning occurs when students engage in activity that approximates the work of the target communities of practice—in this case, engineering communities of practice.\textsuperscript{12} This activity includes social negotiation of meaning with other people who are engaged in similar types of activity, such as other adolescents who seek to solve the same problem, as well as conversations with clients or with ‘experts’ whom the students consult. In this sense, cognitive activity is never fully understood as the intangible thoughts of an individual mind, but rather it is articulated, constituted, and re-negotiated with and through dialogue with others in the course of activity. Under this theory, cognitive activity can be studied through analyzing participants’ conversation and activity with others, rather than relying strictly on verbal protocol analyses with individuals as they seek to solve a task by themselves, as has previously been done in much of the literature on novices’ cognition during engineering design.

\textbf{Method}

To study the cognitive activity of adolescents’ engineering design processes in a situated setting, we conducted descriptive multiple case study research by collecting data from two groups of adolescents who sought to address authentic engineering design challenges. Stake\textsuperscript{33} has argued that multiple case studies are useful for examining a “phenomenon…of which we might seek examples to study” (p. 6). He asserted that this approach necessitates a shift from understanding one case as a whole to developing in-depth understandings of one phenomenon—in this instance, adolescents’ cognitive activity as they enacted engineering design processes—across multiple cases. Although this exploratory approach does not enable statistical generalization to other populations, it enables the development of frameworks and heuristics that can be applied to and tested across other groups of students.

\textbf{Selection of Research Participants and Design Challenges}

We purposively selected seven adolescents to participate in this study because they had previous experiences with using engineering design processes to solve problems. Although their past experiences with engineering were varied, all of them had attended Engineering State at a local university. Throughout the week-long Engineering State program, they worked in teams to design and build buggies, magnetic cannons, small-scale steel bridges, and protective gear using spider silk. The students received feedback on their designs from professional engineers in a variety of fields, including civil and environmental engineers, mechanical and aerospace engineers, and electrical and computer engineers.
In addition to this experience, six of the adolescents had taken engineering or pre-engineering courses in their high schools. Two of them had participated in engineering competitions held by Vex Robotics. By selecting students who were somewhat familiar with engineering—albeit at a novice level—we hoped that we would obtain data on how students with engineering experience approached design challenges. We assumed that students with no experience in the field of engineering might be less likely to use design processes or ‘engineering approaches’ to solve problems, and we wanted to study how students with (at least some) background in engineering enacted the design process in an ill-structured problem space.

In order to find the seven research participants, we contacted all students who had attended Engineering State and who lived within 60 miles of the university. Eleven of approximately 30 students responded to our invitation to participate in the study. We conducted individual interviews with each of the 11 students, asking them about their interests, their anticipated life and career trajectories, and the kinds of activities they liked to do with their families and friends. Questions about these and other topics enabled us to ascertain relevant funds of knowledge and interests upon which we could base design challenges.

In the interviews, four students (two girls and two boys) expressed an interest in improving the quality of life for people who had been disabled due to illnesses or injuries. All four of them wanted to be engineers whose products helped people in need, especially people who had been injured in war or who had incurable medical illnesses. In the words of one participant: “I have family members with medical problems that there’s not a cure for, and so it’d be cool to work in that kind of area just because I’d be helping people and it’s really close to home. So that’s something that I’m kind of passionate about.”

To find an appropriate challenge for these four students, we met with a technician who worked in a local university’s Assistive Technology Lab, whose mission was to provide assistive devices to people with disabilities in order to increase their independence. The technician was currently trying to improve an existing device that helped a man with muscular dystrophy to enter and exit the bathtub. With his input, as well as input from the man and his family, we identified a list of ways that the man hoped to improve the current device, which was bowing under his weight and was not draining water. This list formed the basis for the Assistive Technology Design Challenge, which can be found in Appendix A. The students presented their solution to the technician, to the man with muscular dystrophy, and to his caregiver, all of whom evaluated the design.

Three other students (two boys and one girl) lived in farming communities and at times had helped their neighbors or relatives with farm work. One student was employed by his grandfather’s farm during the summer, and one of his primary tasks was improve the irrigation system that brought water to alfalfa crops. The other two students identified the lack of clean water in Africa as the greatest problem facing the world today, and they sought to find ways to
provide people in Africa with better access to drinking water. One of them wanted to pursue a degree in international relations and engineering in order to address this problem.

To find an appropriate challenge for these three students, we met with a civil engineer who often worked with Engineers without Borders (EWB) and who had developed and implemented water sanitation and distribution systems in a variety of developing countries. She provided us with a recent EWB report, which documented the actions of a team that had repeatedly visited an orphanage/boarding school in Uganda. We also met with the EWB team leader who had worked to provide clean drinking water for the children and faculty in this school. Based on their feedback and input about the school’s current needs, we developed a water acquisition, distribution, and disposal challenge for the second team of students. We shared it with the current team leader and civil engineer so that they could present the solution to the school board of the orphanage if they believed that the solution warranted further discussion and consideration. See Appendix B for the Water System Design Challenge.

Although we had interviewed four additional students, their interests and background experiences were not comparable to the other group members’ interests and background experiences. Because it was more difficult to develop a design challenge that met criteria for ‘authenticity,’ in which the participants’ interests were considered in constructing the challenge, we did not ask the other four students to address a design challenge. Thus, the seven focal participants were selected in part because their life experiences and interests enabled us to group them with other adolescents who had similar life experiences, passions, interests, and career goals.

**Data Collection and Analysis**

Three types of data were collected. First, we conducted an individual pre-and post-challenge interview, which lasted an average of 36 minutes, with each adolescent. The pre-challenge interview was designed to ascertain students’ interests, backgrounds, and career interests, while the post-challenge interview included questions that enabled students to evaluate their overall design, identify aspects of the design challenge that were easier or harder for them, explain the thought processes behind the sketches they produced and the websites they selected in the information gathering phase, and so forth. The second—and primary—data source was written transcriptions of video- and audio-recordings of the adolescents as they worked on their designs. The first group worked on the challenge for four hours and 29 minutes, while the second group worked for two hours and 55 minutes. Student-generated products, the third data source, were collected during students’ work on the challenge. These products including sketches and writings the students produced as well as a list of the websites they visited while working on the challenge, as recorded by tracking software.

We analyzed the data in two phases. First, we used Hynes et al.’s model as an a priori framework for identifying when the adolescents engaged in each stage of the design process. The first and
third author read through the transcripts of the design challenges and identified verbal phrases that fell under each stage of the design model. For instance, when addressing the water system design challenge, two students said the following (all names are pseudonyms):

\textit{Anna:} It talks about how the storage tank is filled once per day and it’s carried by hand up to the latrines. And, which as we looked at, is uphill with gallons of water, like this picture.

\textit{Steve:} So we want to look at making it so they don’t have to carry it uphill? Is that the main problem? Or is it fine that they carry it?

We assigned the number one to each statement because that number corresponded to “Step 1: identify a need or problem” in Hynes et al.’s model. We assigned a new number whenever a new speaker entered the conversation or the current speaker expressed a new idea related to the design process.

Phase one of data analysis enabled us to identify adolescents’ general design activity as described in previous literature, but phase two of data analysis enabled us to provide a more detailed description of the sub-types of cognitive activity that fell under each category. To this end, we employed a modified form of constant comparative analysis (CCA) in which researchers use the dual strategies of “asking questions” and “making comparisons” across data points. We used the stages of the design process as major categories, while we developed sub-categories to describe activity at each stage of the design process.

For instance, under stage three of the design process, \textit{Develop possible solutions}, we asked the question, “What information do the adolescents use as a basis for this solution?” Although the adolescents at times used information gathered in stage two of the design process, “Research need or problem,” we noticed that they more frequently cited experiences with previous devices they had seen, such as conveyer belts or lawn chairs. In interviews, they identified their experience with previous devices as being the most useful form of knowledge that enabled them to complete the design process. Consequently, under the category, “Develop possible solutions,” we identified the sub-category: \textit{Content knowledge used: experience with previous devices}.

To meet standards of evidence for qualitative research, the study’s design included several safeguards for ensuring trustworthiness. After the first and third author established a coding system, the first author coded the entire data set while the third author coded over 30% of the data. We achieved over 85% agreement in our codes, indicating that they were reliable. Furthermore, the second author, who was present during the data collection phase, conducted an ‘audit’ of the data, confirming that the analysis aligned with his perception of the adolescents’ activities and discussing the analysis of randomly-selected data points with the first author.
Limitations

This study is limited in several ways. First, its small sample size precludes generalizability to a larger population. Second, we only studied part of the design process while omitting several stages such as the construction of a physical model or prototype. Further research can be conducted on adolescents’ cognitive activity at all stages of the design process. Third, the students in this sample did not represent a broad population of students: They were all Caucasian; their cumulative grade point averages were all above 3.7; they all had some experience with engineering design challenges; and they all expressed some degree of interest in engineering prior to the study. Other studies can be conducted with different populations of students to determine whether they would enact the engineering design processes differently. Despite these limitations, however, this exploratory study outlines a framework of cognitive activity that can be tested and modified as other researchers work with other populations.

Findings

Figures 1-4 show the results from the first phase of data analysis, in which we identified the adolescents’ overall engineering design processes while addressing the design challenge. As indicated by the figures, the group that addressed the assistive technology challenge (AT group) approached the problem differently than the group that advised Engineers without Borders regarding how they might address the water acquisition, distribution, and disposal needs of the boarding school (EWB group). The following section describes the types of cognitive activity in which the two groups engaged at each stage of the design process, comparing and contrasting the activity of the two groups.

Identify a need or problem. The two groups differed considerably in the number of conversational turns they spent on identifying a need and defining the problem: The EWB group’s remarks related to this aspect on the design process over four times more often than the AT group’s remarks did. Atman has asserted that this stage of the engineering design processes consists of three activities: (a) reading, re-reading, or rehashing the problem; (b) identifying criteria and constraints and what they imply for the solution; and (c) summarizing, elaborating, and re-framing the problem.

In contrast to Atman’s coding system based on her analyses of undergraduates’ and professionals’ work, this study found only one instance in which a student explicitly stated a criterion or constraint in the first stage of the design process. Arguably, a handful of their comments implied possible criteria or constraints. For instance, the comment, “You’re not just going to take showers over the rainy months” could mean “The system must distribute shower water during all months of the year, including the months where there is no rain.” Nonetheless, during this phase, students rarely expressed that their designs must, must not, should, or should not possess certain attributes, meet certain specifications, or perform certain functions during this stage of the design process.
Figure 1. The engineering design processes of the AT group. 

Step 1. Identify a need or problem; Step 2. Research need or problem; Step 3. Develop possible solutions; Step 4. Select best possible solution; Step 7. Communicate solution.

Figure 2. Percentage of comments related to each stage of the design process for the AT group.
Instead, we identified eight total different types of cognitive activity in which one or both groups engaged during this phase of the design process. The EWB group, which dedicated more conversational turns to identifying a need or problem, used the widest array of problem definition activities. These types of cognitive activity are listed in order of frequency below (e.g., Figure 3. The engineering design processes of the EWB group. Step 1. Identify a need or problem; Step 2. Research need or problem; Step 3. Develop possible solutions; Step 4. Select best possible solution; Step 7. Communicate solution.

Figure 4. Percentage of comments related to each stage of the design process for the EWB group.
the group “restated the problem” most frequently and “clarified confusing information” least frequently), followed by examples of comments that fell under each category.

(1) *Restate the overall problem, aspects of the problem, or aspects of the current situation in their own words, including verbally stating what they learned from images and numerical information.*

“It says they carry large containers of water next to the latrine so they can wash their hands.”

“So the kids actually carry everything up.”

“The water tower’s right next to the kitchen.”

“There’s just the two of those [55 gallon drums].”

(2) *Identify and prioritize which aspects of the problem should be addressed, including which aspects of the current device and system may not need to be addressed.*

“It kind of seems like the distribution is more of a pressing need.”

“That’s [distribution is] going to be the biggest one to address for sure.”

“I feel like the tank they have as far as how they get it to that tank is fine.”

(3) *Identify gaps in available information, identifying the types of information they will need to gather during the research phase.*

“I wonder what they do use the water from the rain barrels for.”

“I wonder how much, what the break down, what it actually is.” [e.g., I wonder how much water is used for each task, such as showering, drinking, and cooking.]

(4) *Make inferences about clients’ needs or about the problem beyond that which was explicitly stated by the client in the design challenge.*

“You’re not just going to take showers during the rainy months.”

“I’m guessing that the faculty uses more water to shower than the children.”

(5) *Make procedural decisions by identifying the order in which they will address the problem.*

“Maybe we should look at that first.”

“I guess we can address them [water acquisition, disposal, and distribution] one at a time.”
(6) **Decompose the overall problem by splitting it into sub-components.**

“So, looks like the three main problems to me are water acquisition, distribution, and disposal.”

“I just numbered the paragraphs, like this first paragraph [of the challenge] talks about acquisition, and the second talks about distribution, and then kind of acquisition again, and then disposal.”

(7) **Clarify aspects of the problem that are still unclear or confusing.**

“So they’re just big drums, is that what they are?”

Although the AT group devoted considerably less of their conversation to identifying a need and defining the problem, they still enacted several of the same types of thinking, listed in order of frequency below. Unlike the other group, they also explicitly identified one criterion which the device should meet at this stage in the engineering design process.

(1) **Clarify aspects of the problem that are still unclear or confusing.**

“So is this (pointing to one photograph of the AT device) without the mesh”? 

“So this side is on the far end of the bathtub, right?”

“Wait, so did we need to account for a larger piece this way, or a smaller piece?”

(2) **Restate the overall problem, aspects of the problem, or aspects of the current device in their own words, including verbally stating what they learned from images and the physical device.**

“I think the bathtub is more just kind of the basin where the water goes instead of the actual washing place because this [puts hands on device] is the actual washing place.”

“It really, really seems to be stressed out of its range right now.”

(3) **Identify criteria or constraints for the design.**

“You don’t want it [the device] much bigger than that because you’re not going to be able to get it into the bathroom.”

The AT group’s lack of conversation in the problem scoping stage proved to be problematic later in the design process. After they had almost finalized their report to the lab technician and client, Joe touched the frame of the device and said, “I guess none of that is detachable then.” Mandy responded: “I think that’s maybe what they want more portable, the top part.” As this example illustrates, with fewer than five minutes left before students ended their work on the challenge, Mandy interpreted the problem by stating that the client wanted the frame, or “top part,” to be detachable so that it was easier to transport. Although the students’ proposed design had made
the base or “bottom part” more detachable to improve transportability, the group did not address making the frame or “top part” more transportable as well. Because the students had devoted so little of their conversation to re-stating the problem and clarifying what the client wanted, one aspect of the problem did not emerge until after the design had already been produced.

**Research a need or problem.** Many previous studies of novices’ design processes have been in a laboratory study where the only available source of information was the experimenter. In these studies, the researchers defined the ‘information gathering’ stage as asking for information from the experimenter, reading information statements from the experimenter, or stating how they would go about getting information. This challenge, however, was ‘authentic’ in the sense that students had to locate their own information or use their own background knowledge to solve problems, rather than ask a designated researcher who held all of their answers. Consequently, we sought to identify which sources of information the adolescents consulted and which sources they considered to be more valuable and useful in terms of shaping their subsequent decisions. We defined the “research the need or problem” stage as any activity that the students used to discover unknown information relevant to the challenge, including inspecting and testing the current device to ascertain how it worked, calling the client to ask additional questions, looking up additional information on the Internet, asking each other for information, or asking questions of the experimenters.

Just as the two groups’ approaches to step one of the design process differed, their approaches to researching problems and gathering information varied considerably as well. The EWB group allocated a greater percentage of comments to researching problems than the AT group, as suggested by Figures 2 and 4. Moreover, as indicated by Figure 3, most of the EWB group’s research occurred in conjunction with, or soon after, they identified the problem. By contrast, as indicated by Figure 1, the AT group’s most sustained conversation about research occurred near the end of the design process as students were communicating their design to the client. As they tried to decide which materials to purchase for the construction of their own device, they researched aspects of the device’s current design. For instance, they researched which parts of the existing device were permanently attached together and which were not, what size the existing pipes were, and where the current design included additional steel rods for reinforcement. They ‘bootstrapped’ off of this information by using aspects of the current design in their own modified design. In other words, it was only when they had to communicate their design to the client that they realized there were relevant aspects of the original design that they had not researched before.

In addition to differing in terms of when they conducted their research, the two groups also differed in terms of the types of resources they consulted and valued. The AT group, which had the current bathing transfer system in the room with them, primarily conducted research through examining, testing, or manipulating the current device. 90.67% of their comments in this stage of the engineering design process (n = 75) related to research they had conducted on the actual physical device itself or on other available material devices. For instance, in order to research the
porousness of the current cot material, they poured water over it; in order to research its current weight-bearing capacity, they placed a student on it; and so forth. This group preferred examining or manipulating actual physical material devices to conducting research on the internet. For example, when they realized they needed to know the dimensions of a standard bathtub in order to build the device, they asked the experimenters if they could go to a room in the hotel to measure the bathtub. (The challenge was being held in a hotel meeting room.) In researching possible materials for the cot, they walked to the hotel swimming pool so they could feel the material on the pool chair and examine how it had been placed around the frame. The remaining 9.33% of comments related to ‘researching a problem’ indicated that the AT group sought information from websites (5.33%) and from the experimenters (4.00%). The adolescents sought information from these sources only when they could not obtain the information from the device itself: For instance, they went online to find the dimensions of a standard bathtub when they could not measure a bathtub in the hotel.

Unlike the AT group, the material apparatuses associated with the EWB group were in Masaka, Uganda. The EWB group thus could not physically touch, manipulate, or test the current devices related to water acquisition, distribution, and disposal. In the absence of a physical device, they relied on other sources of information. They phoned the EWB team leader three times to ask him questions about the current design and the clients’ needs, such as questions about how many gallons of water were used for cooking, washing, and drinking per person per day; questions about how the water from the rain barrels was currently being used; questions about which water sources were currently filtered and which were not; and questions about how often the children showered.

The adolescents consulted an additional person as well. After Jerry had suggested the installation of a septic tank as a possible solution to the water disposal problem, he called his father, explained the design challenge to him, and said, “I was thinking a septic tank would work. What do you think?” Jerry’s father, a farmer, then proceeded to explain the differences between black water (sewage water), gray water (potentially reusable water), and white water (fresh, potable water). He suggested that the group pipe the materials from the tank into a drainage field whose size would vary from 50 to 200 feet depending on the soil type. Although Jerry did not ask pointed research questions of his father, the phone call was an important source of information for the group, one that was valued highly in the post-challenge interviews and one that shaped the subsequent design when the group decided that the “gray” shower water could be reusable.

The adolescents ranked these phone conversations as among the most useful resources for their research, even though their conversations with these people constituted only 5.93% of their total remarks in phase two of the design process. The most commonly consulted source was the Internet: 89.84% of comments in this stage of the design process recounted what they had found from websites. Most of their searches related to the costs of various materials, such as the costs of polytanks and PVC pipes, but other searches entailed asking Google: “What are the options for waste disposal?” Steve read the answer from a website he found: “Ocean dumping, sanitary
landfill, incineration, open dumping onsite.” The group decided this information was not helpful because “you can’t incinerate water.” In post-interviews, the adolescents valued the Internet sources primarily in terms of how they enabled them to calculate costs, and not in terms of how it helped them generate useful ideas for solutions.

In sum, whereas first group primarily conducted research through testing and manipulating the device, the second group conducted research through calling somebody with experience at the orphanage or somebody with experience on water distribution. They valued these people’s experiences highly, and at times these people shared relevant information that the students did not know they needed, such as information about the types of water. The adolescents’ search strategies generally did not enable them to find useful information online; for instance, the search for “what are the options for waste disposal” related to solid waste, rather than gray water waste. Consequently, they did not value the information they found on the Internet as highly as they valued the information provided by the experts. However, the Internet did provide especially useful information in terms of cost, and the group used this information in estimating the overall cost of the design in their final report to the EWB team leader.

### Develop possible solutions; evaluate/select best possible solution.

We report these two stages together because they most commonly occurred in conjunction with each other. Among both groups, a majority of the comments in these phases consisted of the adolescents suggesting an idea and then evaluating the idea based on one or more criteria. One example from the AT group and the EWB group will illustrate this common conversational pattern:

*Danny:* You could put a roller on that you know, like at the airport when you’re putting like your stuff in the bin and you slide it across and they’ve got like the rollers. You could put something like that here and here [points to corresponding location on PVC pipe]. Then that [the frame] wouldn’t come off [of the base] because you put like a roller on top and a roller on the bottom and you have a bar on each side of the roller. And then you wouldn’t have to worry about it coming off of track.

*Tom:* And it would be less friction.

*Annette:* Yeah, it would be less friction.

In the above example, Danny suggested putting wheels on the frame so it would slide easily across the base (coded as ‘develop possible solutions’). He evaluated his idea in terms of a criterion: the frame must stay on track, which was an implicit safety concern for the client (coded as ‘evaluate solution’). The other students evaluated the idea according to another criterion: the frame must slide easily across the cot (coded as ‘evaluate solution’).

The EWB’s conversation also followed this pattern:
Jerry: So if we had a way to control the runoff like into a septic tank that’s underground and then they can like, like I just know of septic tanks, we had to take ours out last year. Like it goes into the septic tank and then it just gradually lets it out like into a field, so it would be all underground. But it would keep it so it wouldn’t have any plumbing at all.

Anna: So we could build a septic tank for their shower. That’s a good idea…but the thing is, I think it would have to be downhill, the septic tank would have to be downhill from it so it would run off, you know into it without, you know, having to pump it out.

As in the previous example, a student suggested an idea—in this case, a septic tank for the used shower water. He evaluated the idea according to an implicit desired criterion: If the engineers implemented his idea, they wouldn’t have to “have any plumbing,” a criterion which suggests that he was perhaps concerned with finding a simple, easy-to-construct solution that would require minimal changes to the current design. Another student, Anna, evaluated his idea by stating “that’s a good idea”; however, the criteria by which she decided the idea was ‘good’ were not evident to the researchers. Anna then generated an additional idea (the septic tank should be downhill) as a modification of Jerry’s previous idea, and she evaluated her own idea based on the implicit criterion that a downhill tank would be energy efficient because it would not require the use of pumps.

Although almost no criteria or constraints were explicitly articulated in the ‘problem definition stage,’ as recommended by professional engineers, it was evident that both groups of students held a range of implicit criteria and constraints by which they evaluated their design ideas in Stage 4 of the process. Figures 5 and 6 indicate the criteria by which both groups of students evaluated their designs. As indicated by these figures, the AT group spent more conversational turns evaluating their ideas according to a wider range of criteria. Although both groups used various criteria and constraints to evaluate aspects of their design solution, their evaluations were limited in several important ways. First, professional engineers are encouraged to consider trade-offs across multiple solutions when a given idea might meet one set of criteria or constraints, but not others. Of the AT group’s 470 total comments that were related to the idea generation and evaluation stage, only 10 comments (2.12%) considered how multiple solutions might compete with each other, or how the evaluative criteria for a single solution might at times compete with each other. For instance, they evaluated a “tripod idea,” by which each leg on the current design would become a tripod. They asserted that, although this idea would enable the design to bear more weight, it might also take up too much space and interfere with the caregiver as s/he stood beside the device. The EWB group did not consider any competing criteria or constraints in their conversation, instead offering individual suggestions and then evaluating those individual suggestions according to how well each one met a given criterion.
Overall device should…
Bear man’s weight without bowing or buckling (40)
Be stable (17)
Be easy for caregiver to use (14)
Be easily transportable (13)
Be comfortable for client (12)
Be easy for caregiver to disassemble (9)
Be easy to construct (6)
Be cost efficient to construct (3)
Not require changes to bathroom (3)
Be easy for caregiver to reassemble (2)
Be waterproof (2)
Be made of rust-proof material (1)
Include parts that are easy to replace (2)

Base should…
Stay on track (8)
Fit over bathtub (4)
Be large enough to hold client (2)

Cot material should…
Be porous (8)
Dry quickly (2)
Clean easily (6)
Be non-absorbent (5)
Maintain strength over time (3)
Not shrink when washed (1)
Be mildew-resistant (1)

Frame and cot should…
Move easily across base (21)
Lock in place (11)

Whole water system should…
Be cost efficient (13)
Be sanitary and prevent illness (12)
Be energy efficient (5)
Be easy to construct (5)
Not interfere with existing buildings (2)
Not take energy from lighting system (2)

Water distribution pipes should…
Be located away from latrines (3)
Be located away from water disposal pipes (3)
Last for a long time (2)

Onsite water should…
Be available all day (4)

Septic tank should…
Have sufficient capacity (2)

Figure 5. List of criteria and constraints by which the AT group evaluated their ideas. Numbers indicate the number of times they evaluated an idea according to the listed criterion or constraint.

One final question is worth considering. Given that the AT group dedicated so little of their conversation in researching information, upon what information did they base their idea generation? During the “develop possible solutions phase,” they constantly referred to previous devices that they had seen, assuming that if something worked in a previous device, it would
work for their proposed device. For instance, they assumed that if poles with gradually
decreasing diameters, inserted into poles with slightly larger diameters, were strong enough to
bear the weight of a tent, then using these types of poles for the base would also bear the weight
of the disabled man. (See Figure 7 for a list of previous devices to which they referred as a
justification for their design ideas.) In this way, students’ thinking was attached to how they had
seen previous devices work, rather than to scientific principles or mathematical generalizations
behind why a device might work. Presumably, the students were familiar with scientific
principles and mathematical formulae related to force and strength: Three of the students had
excelled in physics courses, and they collectively had taken many engineering design and
drafting courses. Nonetheless, the adolescents’ experiences with previous devices informed their
ideas more than these courses did, a finding that was confirmed in the post-interviews with the
adolescents who said their previous experiences with other devices were the most valuable
source of information for planning the current design.

Conveyor belts (5) Belay device (1)
Tent poles (5) Bungee cords (1)
Lounge/pool chairs (4) Door hinge (1)
Rollercoaster wheels (3) Folding table joints (1)
Suspension bridge (3) Hammock (1)
Water wings (3) Lego wheels (1)
Backpack straps (2) Rollers that massage legs (1)
Camera tripods (2) School desk (1)
Folding chairs (2) Shocks (1)
Lawn chairs (2) Shoes with wheels on bottom (1)
“Air things for packaging” (1) Washer (1)
Air mattresses (1) Winches (1)
Bamboo trees (1)

Figure 7. Previous devices or objects mentioned by the AT group when suggesting ideas for
current device. Numbers in parentheses indicate the number of times students mentioned that
device as a justification for their current design.

Communicate solution. The term ‘satisfice’ has been used in much of engineering research
literature to describe a solution that meets an acceptability threshold, even if it is not the optimal
solution. Although this term has been applied to practitioners’ thinking in the ‘develop and
evaluate solutions stage,’ in the case of both groups of adolescents, this term could also be
applied to their approach to communication. When it became clear that several details of their
device had not been clarified in during Stages 3 and 4 of the design process, they communicated
their solution in a manner that they thought was ‘good enough’ to enable the construction of the
device, even if it was not specific about all aspects of the design.
For instance, when the AT group had not calculated precise measurements for the frame of their device in previous stages of the process, they wrote to the client that the frame would stay the same as the frame of the current device. Their bill of materials to the manufacturer included “lots of PVC pipes and joints” instead of pipes that fit the specific measurements of the frame. When they had suggested bolts to lock the frame in place on the base, and they were not sure what size of bolts to use, they commented to each other that the bill of materials should include, “quarter inch to half inch bolts, just put that…three inches long, two inch, two and a half inch, I don’t know, two to three inches, just put two to three inches long.” They ended up asking the technician to purchase bolts and wheels of different sizes and “play with” them to see which would fit.

The EWB group likewise realized during the communication stage that they had not calculated precise measurements for several aspects of their design. They realized, for instance, that they had not calculated how much cement should be mixed to fill the water disposal pit. Rather than going through the effort of calculating how much cement would be needed, they simply stated that the pit should be filled and they wrote an estimated maximum cost of the cement based on price information they located online. In this way, the adolescents viewed ‘communicating’ as ‘providing enough information so that a builder could figure out how to build the design,’ rather than ‘providing specific information about all aspects of the materials, costs, and structure of the design.’

**Discussion**

Unlike previous studies of novices’ time allocation as they approached EDP in controlled laboratory settings, this exploratory study sought to qualitatively identify and describe adolescents’ cognitive activity as they approached authentic problems of interest to them. In many ways, the authentic nature of the design challenge caused the findings of this study to differ from previous studies. For instance, in previous studies in controlled settings, novices asked pointed questions of experimenters who answered the questions but did not provide additional information. However, in this study, novices consulted experts who not only answered their questions, but who provided relevant information beyond what they had requested, as would likely happen in a conversation among engineers with different domains of expertise. In the case of the AT group, the physical presence of the device also shaped the design process as students’ research related to testing the current device, a practice that is also authentic to engineering.

Although this study does not presume to be generalizable to a larger population, it provides a framework of issues that high school engineering teachers can consider as their students select a problem of interest and solve those problems through design processes. These issues are detailed below.
**Issue 1.** Both groups of adolescents held implicit criteria and constraints by which they evaluated their designs, but neither of them systematically articulated them in the “define the problem” stage. Moreover, Stages 3 and 4 of the design process primarily consisted of a student suggesting an individual idea, then evaluating that individual idea according to one or two criteria without considering trade-offs among competing criteria. These findings suggest that students can be supported in more explicitly articulating criteria and constraints early in the design process and systematically evaluating each solution in accordance with potentially competing criteria and constraints.

**Issue 2.** Even at the end of the design challenge, at least one member of the AT group did not understand aspects of the problem. Because authentic design challenges often leave many aspects of the problem implicit—at times leaving out relevant information that the client did not think to share—engineering teachers may need to spend time explicitly modeling and engaging students in the types of cognitive activity practiced by the EWB group, such as (a) restating the overall problem and subcomponents of the problem; (b) decomposing the overall problem by splitting it into sub-components; (c) identifying and prioritizing which aspects of the problem should be addressed or not addressed; (d) identifying gaps in available information; (e) making inferences about the problem beyond that which is stated by the client; (f) clarifying aspects of the problem that are confusing; and (g) making procedural decisions about how they will address the problem.

**Issue 3.** Neither group demonstrated proficiency in using the Internet to locate information relevant to the challenge. The AT group’s proposed design was informed primarily by their background experiences and by their observations and examinations of the current device. Although the EWB group successfully found the costs of some elements of their water system, they could not locate the costs of other elements. Moreover, the EWB group experienced problems in searching for helpful, relevant information, as evidenced when they searched for “options for waste disposal” instead of “options for water disposal.” This study suggests that engineering teachers can support students in identifying print sources, human sources, and online sources by evaluating which ones are appropriate for providing certain types of information. Teachers can also model the search process for students, including evaluating search terms and evaluating the credibility of the sources that the students find. (The suggestion to dump human waste into water bodies, as recommended by the website Steve found, seems to be a highly questionable solution from a non-reputable source.)

**Issue 4.** This study confirmed Crismond’s finding that adolescent “naive designers made few connections from their work to key science ideas, and instead used mechanical advantage preconceptions” (p. 791). Similar to the students in Crismond’s study, the AT group’s design decisions were largely based on what they had experienced with previous devices, without an explicit consideration of the mathematical or scientific ideas behind why the previous devices worked. Instead, they focused on the mechanical device itself, assuming that what worked for one device would work for another.
To some extent, the EWB group engaged in similar activity: Jerry observed the use of a septic tank on his farm and suggested that it might work for water disposal. This study suggests that engineering teachers can solicit students’ ideas for designs and discuss when this type of ‘transfer’ is and is not appropriate. For instance, the class could discuss why, when, and how a sewage septic tank would or would not be relevant to water disposal. This discussion could entail a consideration of differing contextual factors. It could also entail a consideration of key scientific and mathematical ideas that—when applied to different situations—require different types of solutions.

Issue 5. In communicating their design to clients, the students omitted several aspects of their design that would be expected in professionals’ bills of materials. For instance, they omitted how much concrete the design would require, the size of bolts and wheels that should be purchased, and so forth. Their approach seemed to be to buy enough materials to enable the manufacturer to complete the design, so that even if a few bolts or wheels or bags of concrete went unused, the manufacturer would still have the needed materials to finish the design. To assist students in optimizing their communication, engineering teachers may show examples of final engineering reports to students, identifying where they could be more specific and persuasive, and asking students to rewrite the reports with optimal specificity so they had practice with communicating clearly.

In sum, both groups of students demonstrated several strengths throughout the design process: The AT group used a wide array of criteria to evaluate their designs, while the EWB group used various approaches for clarifying the problem. At the same time, despite these strengths, both groups of students demonstrated ways in which their design thinking could have been improved, including through more efficient search strategies, more selective ‘transfer’ of information, and a commitment to optimizing communication. This study highlighted some of these areas for improvement and outlined instructional implications for K-12 teachers to consider as they seek to support their students in solving authentic problems through engineering design processes.

This material is based upon work supported by the National Science Foundation under Grant No. 0426421. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.
Bibliography


32. Aschbacher, P. R., Li, E, & Roth, E. J. (2010). Is science me? High school students’ identities, participation, and aspirations in science, engineering, and medicine. Journal of Research in Science Teaching, 47, 564-582.
Appendix A  
Engineering Design Challenge for AT Group

**Assistive Technology Design Challenge**

A man with muscular dystrophy needs a Bathing Transfer System (see below) to get over the bathtub for a shower and to get back away from the bathtub after the shower.

*Example of a Hoyer Lift*

The man, who weighs about 110 pounds, is placed onto the black mesh cot through the use of a Hoyer Lift (see photo below). Alternatively, a strong person can pick him up and set him there.

*Example of a Hoyer Lift*

After the man is placed onto the black mesh cot, it slides horizontally over the bathtub, although it cannot be lowered vertically into the water. While lying on the cot, the man can receive a bath as his caregiver uses a handheld shower nozzle to spray water over him.
The Bathing Transfer System includes two basic components: a base and a top. The base of the device (see below) is made out of aluminum tubing reinforced with steel. The legs can be vertically adjusted to accommodate different tub heights. The gray plastic rings attached to the bars prevent the cot from sliding past those bars.

The base is about 44 inches long and 16 inches wide. When fully raised, the base is about 39 inches high; when lowered, the base is about 31 inches high. The base can be detached and disassembled for loading into an automobile.

![Base](image1)

The frame of the top (see below) is made of one-inch PVC pipe reinforced with steel and aluminum rods. It is attached to the base with Teflon fittings. Teflon is a smooth plastic material that enables the frame of the top to slide back and forth on the base until it is stopped by the gray rings.

![Base](image2)

Reinforcing bars strengthen the frame supporting the top.
The frame of the top, from its uppermost bars to the bottom bars of its supporting grid, is approximately eight inches high. It includes three reinforcing bars made of PVC pipes. Unlike the rest of the PVC pipes in the framework, these three bars are not reinforced with steel or aluminum rods.

The top is slightly less than five feet long and two feet wide. Its frame can be disconnected in four locations, indicated by the stars below. The remainder of the PVC pipes are glued together. (Note: the yellow attachments on the photo below are pieces of tape placed on the base intended to keep the cot from sliding.)

A black mesh material is attached to the frame of the cot with Velcro. This black mesh material can be detached and washed.

After speaking with the family members who use the device, Clay [XXX], Coordinator of [Name of University’s] Assistive Technology Lab, has identified several issues with the current version of the Bathing Transfer System:

(a) The current base is 44 inches long. It needs to extend to at least 54 inches in order to provide adequate space for positioning the Hoyer lift.

(b) Although the frame of the top can slide back and forth, it cannot lock in place. A secure catch or lock should keep the frame in position over the bathtub and another catch or lock should secure the frame at the other end of the base to permit the transfer of the user into the Hoyer lift.
(c) Although the device can safely support the client, who weighs 110 pounds, other clients may weigh more and the device might not hold them without buckling. It should be strengthened so it will safely support a 180 pound person.
(d) Although the Teflon attachments can slide across the base, some means should be provided to lessen the friction and make it easier to slide the top and the user over the bathtub.
(e) Cushions are needed to make the frame of the cot more comfortable for the user’s head and feet.
(f) Although the device can now be disassembled in places, it needs to be more easily transportable.
(g) The black mesh is fairly opaque and difficult to wash. It needs to be more porous to allow more rapid drainage and make it easier to keep clean.

**The Challenge**

Our challenge is to suggest specific ways to modify this Bathing Transfer System so that it better meets the needs of this particular client and/or future clients. If you are unable to address all seven problems in the redesign, you may prioritize the problems and modify the design to address the most important issues.

Prepare preliminary plans for your design to submit to Clay for his review and for discussion with family members. The plans for modifications should be specific enough so that they could be implemented even if you did not get an opportunity to speak with Clay or the family.

It would be helpful if you would provide supporting information, indicating the alternatives that you considered in making these recommendations, the reasons for the design decisions you suggest, the sources for purchasing the materials, and the costs of the materials. The report should include sketches or drawings of the modifications and a verbal description.
Appendix B
Engineering Design Challenge for EWB Group

Design Challenge

Anatole Mary Hill School is situated in Masaka, Uganda, and serves 450 children and 50 staff members, many of whom live on campus. Figure 1 is a topographical map of the school grounds, with each line representing an elevation increase of about one foot with the shower area representing the top of the hill.

The students and staff require a minimum 330 total gallons of water per day for cooking, personal hand-washing, and drinking. Currently, a well that is located 1,200 feet from the school provides for all of their water needs. A solar-powered pump draws water from the well, through a PVC pipe and into a 500-gallon water storage tank that is located next to the kitchen (see Photo 1). This storage tank is replenished approximately every 36 hours. This water is treated through a slow sand bio-filter that purifies the water. Students and teachers use water from this storage tank for drinking, washing, cooking, and drinking water for the cattle, carrying the water by hand to needed locations. For instance, they carry large containers of water next to the latrines so they can wash their hands there (see Photo 2).

In addition to this water source, the school also owns two 30-gallon rain-barrels that generally fill up during the rainy months of the year—March, April, and May—during which Masaka receives most of its 55 inches of annual rainfall. These rain barrels are located under gutters that run from the roofs of the classrooms and staff room.

People at this school grow much of what they eat, but they supplement their food with weekly trips to the market. Their crops include beans, plantains, sugarcane, and rice. These crops are watered via rainfall, although in years of drought the crops have struggled.

Recently, a new well, eleven feet deep, was installed 175 feet from the kitchen. It has been estimated that this well could replenish a second 500-gallon storage tank approximately every 24 hours. The school has identified its greatest need as managing the excess water that is produced during people’s showers. Although three pits have been dug beside the showers to catch the water flow (see Photos 3 & 4), they have already become full.

The school administration asked Engineers without Borders to consult with them about how to best use this new water source, and to reconfigure their current water acquisition and distribution system. Ultimately, the school board hopes that you can implement your project (or at least start it) during your two-month stay in Uganda with the $14,000 USD that has been allotted to this project. This cost excludes airfare and travel and lodging expenses.

What advice would you give the governing board of the school in regards to how they could best use the new and existing water sources? Please create a water management plan that you would present to the school board. The plan should be specific enough that people in Masaka could implement it after you presented the plans to them.

You are welcome and encouraged to consult additional resources online. You are also welcome to talk to the person in the room who is a member of Engineers without Borders who has visited this school and who can answer any questions you have about the school and the surrounding area.
Figure 1. Topographical map of the school.
Photo 1. Water storage tank.
Photo 2. Handwashing station beside the latrines.
Photo 3. The leaf structures are the showers, with a pit to the right.

Photo 4. An example of a pit designed to hold excess shower water.
Graph 1. Average rainfall in Masaka.