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The Sequential Nature of Engineering Problem Solving

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The Sequential Nature of Engineering Problem Solving

Iron Range Engineering (IRE) is an innovative, problem-based-learning (PBL) program in Virginia, Minnesota. Part of its innovation comes from the program's strong emphasis on developing metacognitive skills necessary for students to become self-directed learners of the knowledge and skills required for professional engineers. Students in the IRE program learn about skills they need to direct their own learning and to solve problems. In our NSF IUSE project, we have been investigating the cognitive processes involved in engineering problem solving, focusing specifically on the role of metacognition. To this end, we have collected data from interviews of students, alumni, and employers; in addition, we have collected think-aloud data from students as they solve open-ended design problems.

The think-aloud data were gathered using verbal protocol analysis. We recorded students' utterances as they solved two engineering design problems: a pre problem at the beginning of their engineering program and a post problem at the end. We identified categories of utterances, some metacognitive and some non-metacognitive, and measured the frequency of those utterance categories. However, because problem solving does not reside in a single utterance nor in the frequency of utterances but rather in the sequence of the utterance categories, we examined the sequences of students' utterances as they solved the two problems.

This poster will address the sequential nature of the cognitive processes revealed in students' utterances as they solved engineering design problems and identify the role that metacognition plays in that sequencing. We hypothesized that as students acquired greater engineering knowledge and were exposed to greater use of metacognitive thinking and strategies that focused on that knowledge across their education at IRE, the sequencing of their utterances would indicate the following differences from the pre to the post problem:

(1) greater sustained use of engineering knowledge when solving the post problem;
(2) increased metacognitive monitoring occurring before and after the use of engineering knowledge on the post problem;
(3) greater elaboration of solutions on the post problem;
(4) increased metacognitive monitoring before and after providing solutions on the post problem;
(5) greater use of metacognitive knowledge of strategies on the post problem.

We begin with a brief discussion on metacognition and methods of measuring metacognition.

What is Metacognition?

Metacognition can be defined as "knowledge of one's knowledge, processes, and cognitive and affective states; and the ability to consciously and deliberately monitor and regulate one's knowledge, processes, and cognitive and affective states" [1, p. 3]. This definition, as well as others [e.g., 2-8], identify both *declarative* and *procedural* components of metacognition (see Figure 1). Included in metacognitive declarative knowledge is one's knowledge or beliefs about: (1) his/her cognitive and affective states and those of others; (2) a task and its demands; and (3) strategies for completing the task and how and when to use those strategies [9, 10]. Metacognitive procedural knowledge consists of one's monitoring and control of his or her cognitions [9, 11, 12]. Metacognitive monitoring consists of processes that involve a person's ability to: (1) identify the task at hand, (2) check on the current progress on the task, (3) evaluate that progress, and (4) predict whether the task will be successfully completed [1, 3]. Metacognitive control refers to processes that involve a person's ability to: (1) allocate cognitive resources to the task at hand, (2) determine and direct the steps toward task completion, (3) set the intensity of the work, and (4) set the speed of the work on the task [1, 3]. The double-headed arrows shown in Figure 1 indicate that information processing at lower levels of the model is influenced by higher levels and vice versa.

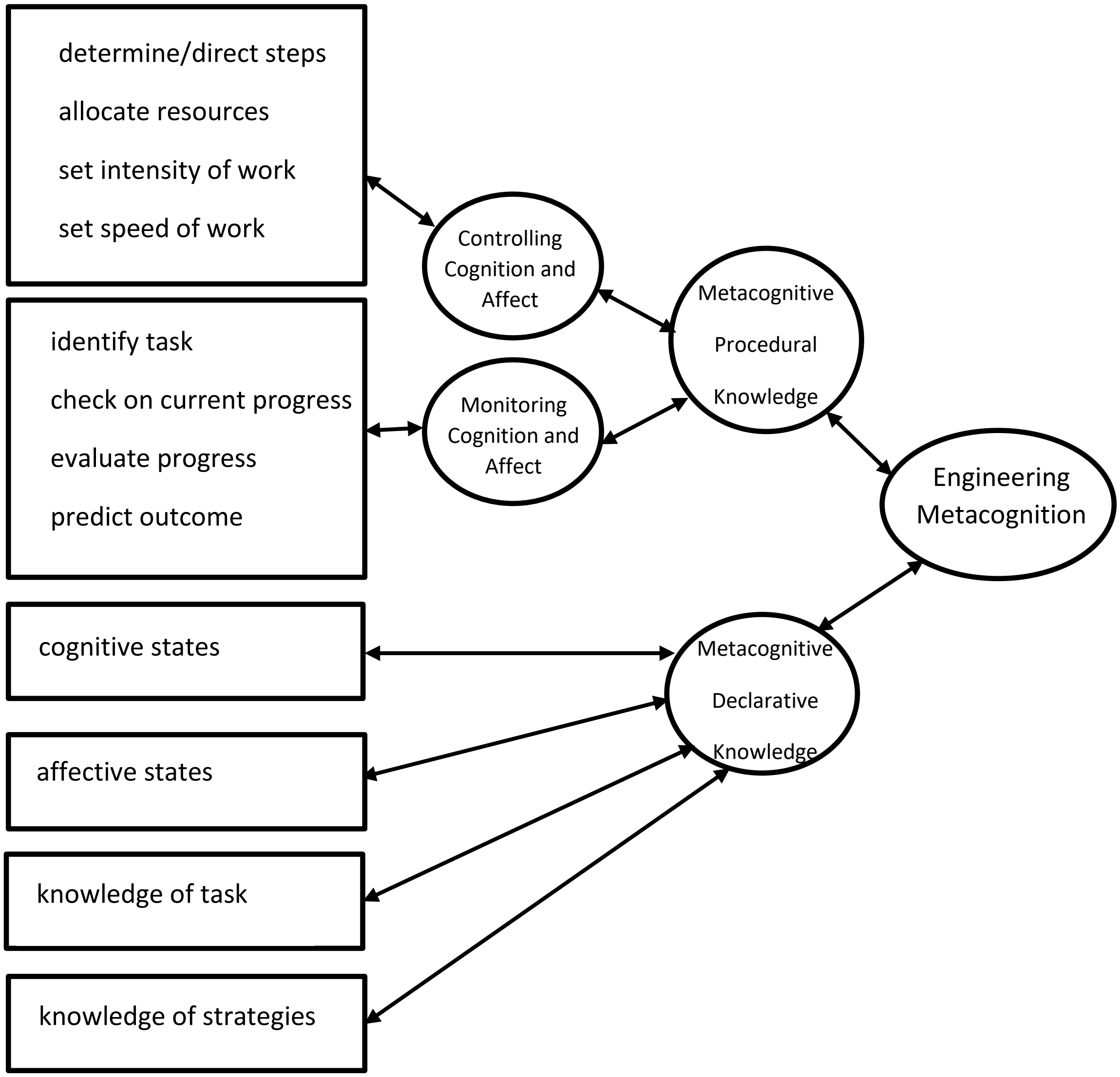

Figure 1. Model of engineering metacognition and categorization scheme for coding verbal utterances.

How is Metacognition Measured?

Metacognition is measured by two categories of approaches: Off-line measures are those that collect data either before or after learning and on-line or real-times measures collect data during learning. The debate regarding which measures provide the best information about how well people can self-direct their learning [13, 14] is understandable considering the complexities of the metacognition construct (i.e., consisting of declarative and procedural components) as well as a valid concern about whether the measures actually portray the psychological processes involved.

Off-line measures of metacognition include interviews or questionnaires. On-line measures, on the other hand, are obtained primarily through real-time think-aloud protocols or accuracy ratings. A think-aloud protocol involves a person verbalizing while solving a problem. The verbalizations are recorded, then they are transcribed and divided into units that can be coded via a coding scheme that is based on *a priori* theoretical assumptions about the processing involved in the task at hand. Both the frequency of the coded verbalizations and the sequence of the coded verbalizations can be used as measures of metacognition.

Metacognitive declarative knowledge is more likely to be validly measured by off-line measures. [15]. Metacognitive declarative knowledge reflects stable knowledge and beliefs about oneself as a problem solver and stable traits that one has about performing specific cognitive skills. A person’s stable knowledge, beliefs, and traits, although potentially influencing one’s cognitive activity, can be retrieved at any time, are resistant to change, and can be independent of cognition during actual problem solving. For example, perceiving oneself to be a good mathematics problem solver despite getting all the problems incorrect on a mathematics test. In contrast, metacognitive procedural knowledge, that is, monitoring and control of thinking, is more likely to be validly measured by on-line measures such as think-alouds [13, 16]. Think-aloud protocols have been used for over 100 years in psychological research [17] and have been used extensively in writing research [18]. In addition, think-alouds have been used to some extent in engineering problem solving [19-24]; however, think-alouds have shortcomings. The validity of think-alouds depends greatly on the coding scheme and the procedure for using the scheme [16]. In addition, they are time consuming to analyze, cannot tap into highly automatized cognitive or metacognitive processes, and may provide incomplete information when research participants fall silent.

We acknowledge the shortcomings of think-alouds and, in our research processes, took steps to lessen them. For example, we provided a verbal prompt to encourage additional verbalizations when students were silent for 5 seconds. We also worked from theoretically and empirically grounded coding schemes and maintained high levels of interrater agreement during our categorization procedure.

Study Participants and Methods

Study participants were students in their junior and senior years at IRE. At the time our data were collected, IRE was a two-year, ABET-accredited engineering program, and students completed pre-engineering courses at other community colleges or universities. Currently, IRE offers a four-year engineering program at the same location, Mesabi Community College. Students graduate with a B.S. in Engineering, and most have a specialization in either mechanical engineering or electrical engineering, although other specializations are available. The two-year, junior/senior program is non-traditional, in that students take few traditional courses; rather, students work in teams every semester to solve real-world problems presented by local industry partners. All work is supervised and mentored by faculty as well as industry mentors. Direct instruction in self-directed learning is included throughout the program.

All students read and signed an approved IRB Human Subjects consent form. They were selected from two cohorts of IRE students, one beginning the program in January of 2015 and one beginning August of 2015. After attrition and the random selection process for the think-alouds, we had a total of 12 students who participated in pre- and post-think-aloud protocols. One of these 12 students produced a transcript that was too short to use for data analysis, so we ended up with 11 students. The pre think-aloud was administered in the first month of the junior year, and the post think-aloud was administered in the last month of the senior year.

Students were asked to verbalize their thoughts while solving the two engineering design problems. The think-aloud process was not familiar to the students; therefore, immediately before reading the first design problem, students were given a short warm-up problem to introduce them to thinking aloud and make them comfortable with verbalizing their thoughts. For both the pre think-aloud and post think-aloud design problems, students were encouraged to verbalize all thoughts as they read and worked through the problems. If they fell silent for more than 5 seconds, the researcher prompted them to continue to verbalize. All sessions were audio recorded for later transcription. The think-aloud sessions ranged from 15 to 25 minutes.

The first design problem, given to students at the beginning of the program (see Appendix A), was adapted from Dixon [23]. The design problem required a redesign of a motorcycle for use as a taxi in a mountainous tropical island. The problem had been judged to be similar to the open-ended problems that beginning engineers might be asked to solve on the job [23]. The problem consisted of 397 words and had a Flesh-Kincaid Grade Level rating of 10.4. The second design problem was given to students at the end of their program and was developed by our research team (see Appendix B). This problem asked students to redesign a propane-fueled camp stove for use by the military in a desert combat zone. The problem consisted of 432 words and had a Flesh-Kincaid Grade Level rating of 9.4. The two problems were designed to be as similar as possible. Two professional engineers judged the design problems to be similar in complexity. Each problem included eight analogous constraints. For example, each problem addressed maintaining low costs in the redesign, considering climate effects, and incorporating human factors such as comfortability.

Data Analysis

After transcribing the audio files, each transcription was divided into T-units (i.e., minimally terminable units). T-units are “the shortest grammatically allowable sentences into which the theme could be segmented” [25, p. 21], and are generally a main clause plus any modifying subordinate clauses.

During the analyses of the verbal data, we used our categorization scheme (Figure 1) and further refined our definitions of each category in the scheme by constant comparison methods. Changes to categories were made and agreed upon via discussion between the two coders [25]. We added three categories to our categorization scheme, all of which were not metacognitive: a category for utterances relating to the student’s reading of the problem, a category that reflected domain knowledge of the context of the problem, and a category relating to solutions for the various problem constraints. Some examples of our categorizations taken from students' verbal utterances are: monitoring/evaluation—"As far as that goes, I think I've pretty well worked the idea of the problem"; monitoring/check on current progress—"Okay, so I resolved the issue of the cargo carrying capacity is going to be up front"; monitoring/identify the task—"Rack must be nonmetallic sufficient sturdiness to withstand rugged terrain"; metacognitive declarative knowledge/cognitive states—"I'm a horrible drawer"; domain knowledge—"Metal carriers that's probably gonna be what most people use is a metal rack because its sturdy, its cheap, and its relatively rugged." Two raters independently categorized each T-unit into one of the categories. Cohen's Kappa was used to statistically compare the categorizations of the two raters. Agreement between the two raters ranged from .64 to .91, with a mean of .81 (*SD* = .06). Any disagreements were resolved through discussion between the two raters.

In order to examine the sequences of students' utterances as they solved the two problems, a lag-one sequential analysis was conducted for each of the 11 participants for the pre and post problems. Each sequential analysis consisted of tallying the number of transitions going from one utterance (lag 0) to the utterance directly following (lag 1). The frequencies of these tallies were then placed in a frequency matrix, examples of which are shown in Tables 1 and 2. The frequency matrices in the two tables are from the same student's pre and post data. The matrices show the total number of each type of sequence. The vertical column on the left indicates a sequence that starts with monitoring, declarative, etc., and the horizontal row indicates what followed. For example, for the pre problem, this student started with a monitoring utterance and 44 times he/she went to another monitoring utterance, 15 times to a declarative utterance, 15 times to a non-metacognitive domain knowledge utterance, and 12 times to a non-metacognitive solution. So, the probability that the student started with a monitoring utterance and went to some other type of utterance was .42; and, the probability that the student went to a monitoring utterance after any other kind of utterance was .40.

Table 1. Pre-program think-aloud data for a student shown in a Lag-1 frequency matrix

	Monitor	Declarative	Domain	Solution	row totals	probability of rows
Monitor	44	15	15	12	86	0.42
Declarative	17	10	8	4	39	0.19
Domain	13	14	24	3	54	0.26
Solution	9	1	7	9	26	0.13
column totals	83	40	54	28	205	
probability of columns	0.40	0.20	0.26	0.14		

Table 2. Post-program think-aloud data for a student shown in a Lag-1 frequency matrix

	Monitor	Declarative	Domain	Solution	row totals	probability of rows
Monitor	47	10	38	11	106	0.34
Declarative	9	20	11	1	41	0.13
Domain	37	9	68	10	124	0.40
Solution	9	2	11	19	41	0.13
column totals	102	41	128	41	312	
probability of columns	0.33	0.13	0.41	0.13		

Based on each frequency matrix, a Chi Square goodness of fit test was conducted to determine whether the frequencies in each cell differed from expected values as determined by chance (and thus would be considered significant). Tables 3 and 4 show the Chi Square matrices that were calculated for the data displayed in Tables 1 and 2, respectively. The Chi Square tables show whether the frequencies in the cells in Tables 1 and 2 are different from the frequencies expected by chance, and significant. With 9 degrees of freedom and a critical Chi Square value of 21.67 at an alpha level of .01, the example in Table 3 shows a significant Chi Square value of 32.78, and the example in Table 4 shows a significant Chi Square value of 105.24. In addition, this student showed a significant difference from pre problem to post problem. The Chi Square statistic for the post problem was considerably greater than the Chi Square statistic for the pre problem, indicating that the transitions for the post problem diverge to a greater extent from chance than the transitions for the pre problem.

Table 3. Chi square from Lag-1 frequency matrix for pre data

	Monitor	Declarative	Domain	Solution	Chi Square
Monitor	2.421	0.189	2.586	0.005	32.78
Declarative	0.093	0.751	0.503	0.330	
Domain	3.593	1.138	6.718	2.596	
Solution	0.221	3.270	0.003	8.360	

Table 4. Chi square from Lag-1 frequency matrix for post data

	Monitor	Declarative	Domain	Solution	Chi Square
Monitor	4.399	1.109	0.692	0.616	105.24
Declarative	1.447	39.629	2.014	3.573	
Domain	0.309	3.266	5.767	2.432	
Solution	1.447	2.130	2.014	34.391	

In addition to the previous two matrices, for each frequency matrix a *z*-score matrix was calculated to standardize the differences between observed versus expected frequencies for each cell, which allows for a direct comparison of the transitions indicated in each cell and provides a statistical test for whether the frequencies in each cell are significantly different from chance. Tables 5 and 6 below show the *z*-score matrices for the frequency data for this student. Ideally, the mean of all the *z*-scores in a matrix would be 0.00, and the standard deviation would be 1.00. Because our standard deviation was somewhat higher than 1.00, (that is, the *z*-scores are spread out slightly more than desired), to control for Type I errors, we used an alpha level of .01, which placed the critical *z*-score at 2.58. Any *z*-score greater than 2.58 indicates that the frequencies from that cell were significantly greater than chance, and any *z*-score less than -2.58 indicates that the frequencies from that cell were significantly less than chance. Table 5 shows that there were four significant cells (identified by the gray-shaded cells). For example, the 44 monitoring-to-monitoring sequences shown in Table 1 are significantly greater than what is expected by chance as is the post frequency of 47 monitoring-to-monitoring utterances shown in Table 2. The domain knowledge-to-domain knowledge sequences and the solution-to-solution sequences are significantly greater than expected by chance in both pre and post problems. In addition, the magnitude of the differences in the *z*-scores from pre to post problems indicate greater divergences from chance. For instance, the 6.752 *z*-score for the solution-to-solution frequencies in the post problem compared to the 3.330 *z*-score for the same cell in the pre problem indicates that the 19 transitions in the post problem diverged from chance to a much greater extent than the 9 transitions in the pre problem.

Table 5. *Z*-score matrix for pre data

	Monitor	Declarative	Domain	Solution		
Monitor	2.647	-0.636	-2.459	0.105	0.011	mean
Declarative	0.439	1.073	-0.918	-0.688	1.981	std dev
Domain	-2.863	1.386	3.519	-2.020		
Solution	-0.653	-2.157	0.072	3.330		

Table 6. *Z*-score matrix for post data

	Monitor	Declarative	Domain	Solution		
Monitor	3.146	-1.390	-1.333	-1.036	0.057	mean
Declarative	-1.573	7.248	-1.983	-2.176	3.276	std dev
Domain	-0.873	-2.498	4.028	-2.156		
Solution	-1.573	-1.680	-1.983	6.752		

To interpret the differences between pre- and post-problem solving, we examined the *z*-score cells that were statistically significant either in the pre- or post- problem matrices and then the magnitude of the differences. The monitoring-to-monitoring transitions were significantly greater than chance in both problems, but the magnitude of the *z*-score in the post problem was greater than the pre problem, which suggests that monitoring was more sustained in the post problem. Another large difference between pre and post is from declarative-to-declarative, which is not significant for the pre problem but shows a large difference, and is significant, in the post problem. Part of metacognitive declarative knowledge is knowledge of task and knowledge of strategies, so the student could be using knowledge of strategies more often in the post problem. In addition, the student was much more likely to follow a solution utterance with another solution utterance in the post problem than in the pre problem; thus, the student added to the solution utterances or explained them in more depth in the post problem. The student also followed a domain knowledge utterance with another domain knowledge utterance more often in the post problem than the pre problem, so use of domain knowledge was more sustained in the post problem

In order to test our hypotheses, we averaged the *z*-scores in each cell across all students' pre and post problems and computed a Chi Square statistic to analyze differences between the two. Table 7 below shows the results for the pre data, and Table 8 shows the results for the post data. Cells that are shaded in gray are those that diverge from chance and are considered significant.

Table 7. *Z*-score matrix for pre data across all participants (n = 11)

	Monitor	Declarative	Domain	Solution
Monitor	3.128	-0.362	-2.413	-0.406
Declarative	0.178	0.910	0.223	-1.020
Domain	-2.364	0.278	2.637	-0.641
Solution	-1.237	-0.475	-0.284	2.106

Table 8. *Z*-score matrix for post data across all participants (n = 11)

	Monitor	Declarative	Domain	Solution
Monitor	3.367	-0.064	-1.548	-1.222
Declarative	-0.849	4.271	-0.416	-1.691
Domain	-0.992	-1.276	3.230	-1.839
Solution	-1.404	-1.387	-1.849	4.525

Table 9. Chi square from matrix for comparison of pre data and post data

Chi Square
30.014

	Monitor	Declarative	Domain	Solution
Monitor	0.057	0.089	0.748	0.666
Declarative	1.055	11.296	0.408	0.450
Domain	1.882	2.415	0.352	1.435
Solution	0.028	0.832	2.449	5.852

Our results are preliminary, but the Chi Square was significant (Table 9). With 9 degrees of freedom and a critical Chi Square value of 21.67 at an alpha level of .01, a Chi Square value of 30.014 shows a significant difference between the pre- and post-problem sequences. We found support for hypotheses 1, 3, and 5, partial support for hypothesis 2, and no support for hypothesis 4. From pre to post problems, students increased their use of engineering domain knowledge, elaborated their solutions, and made greater use of their metacognitive knowledge of strategies, as reflected in their sustained use of metacognitive declarative knowledge. In addition, they made greater use of metacognitive monitoring before but not after the use of their engineering knowledge. Metacognitive monitoring remained stable before a solution but decreased after a solution.

In conclusion, students in the IRE program showed positive growth in both their engineering knowledge and in their metacognitive use of that knowledge. Our use of a lag-one sequential analysis to examine series of think-aloud utterances is unique, and the analysis may offer other researchers an additional way to understand the complex procedural aspect of metacognition. Understanding how engineering students develop metacognitive skills may help engineering programs improve instruction in this area which, in turn, could help students transition more effectively into professional practice.

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Appendix A

DESIGN TASK

Instruction

The objective of this engineering design activity is to understand the cognitive process of engineering designers as they solve a design problem. Verbal Protocol Analysis will be used. This means that as you solve the problem you will be required to **"think aloud"** (say aloud) what you are thinking. If you stop speaking I will remind you to resume speaking aloud as you solve the problem. Please include all the notes and sketches of your solution on the sketch pads that are provided.

Duration: 1 Hr

The context

Fonthill is a hilly terrain in the District of St. Mary with narrow tracks and virtually non-existent roads. This area also experiences high amounts of rainfall yearly. There are several communities like Fonthill on this mountainous tropical island. Because of the very poor state of the roads the most frequent mode of transportation are motorcycles. Motorcycles are used to take residents to and from work, market, and school. While the residents see this system of transportation as essential, the government has serious concerns about the safety of the riders and their passengers. The government therefore secured a loan to purchase a fleet of motorcycles that are specially built to handle these rugged terrains. These motorcycles will be leased as taxis to specially trained riders.

The design problem

The Honda CRF230 shown on the next page is a cross between a dirt bike and a street bike.

Modify the Honda CRF230 so that it is robust enough to handle repeated journeys through these mountainous terrains that are prone to a lot of rainfall annually. The average cost of a new car in this country is about US $25,000.00 and the government expects that the cost of this motorcycle will not exceed one third this cost. The motor cycle must also:

- Be equipped with more cargo carrying capacity and at the same time make the rear seating (pillion) more comfortable.
- Have an improved rack or a holding system for carrying packages, books, or a reasonable amount of groceries on the motorcycle. The rack must be non-metallic but of sufficient sturdiness to withstand a rugged terrain, occasional brushing against rocks, and a lot of rainfall.

- Be capable of enough horsepower to climb sections of mountains with slopes of 30 degrees, carrying the rider and the pillion passenger.
- Have a device to prevent the theft of helmets from the motorcycle.

Honda CRF230

Figure 1. The engineering design task.

Appendix B

DESIGN TASK

Instruction

The objective of this engineering design activity is to understand the cognitive processes of engineering designers as they solve a design problem. Verbal Protocol Analysis will be used. This means that as you solve the problem you will be required to **"think aloud"** (say aloud) what you are thinking. If you stop speaking, I will remind you to resume speaking aloud as you solve the problem. Please include all the notes and sketches of your solution on the sketch pads that are provided.

Duration: 1 Hr

The context

The United States Army has issued a public request for proposals (RFP) to anyone interested in designing a two-burner cook stove that is to be used by troops who are actively on extended patrol duties under desert conditions. The stove will be used to prepare meals for patrols of up to six soldiers. I CAN DO IT, a small startup company in Minnesota, has decided to submit a proposal and a design for a contract with the Army. To minimize costs, I CAN DO IT has decided to start with a two-burner cook stove shown on the next page and to make modifications to it to satisfy the parameters specified in the request for proposals. The stove shown on the next page is easily available and reasonably priced.

The design problem

The camp stove shown in figure 1 is a two-burner stove, measuring about 12 inches wide, 20 inches long, and 3.5 inches high when folded up. The stove is fueled by propane canisters that attach/detach from the stove. The stove costs about US $60, and the small startup company needs to keep design costs down and to make the cost-per-stove low so that they have a more attractive proposal. The stove must also:

- Be robust enough to withstand rough conditions that can be expected in an active war zone.
- Be built to be used in a dry, dusty, and windy environment so that the clogging of valves and burners is avoided.

- Have increased capacity for carrying more fuel so that the stove can be used over extended periods of time on patrol.
- Be equipped with a carrying rack so that it can be attached to a soldier’s backpack.
- Have burners that are sufficiently powerful to heat food for six soldiers in a short amount of time.
- Be light weight and compact for easier carrying.
- Have a device for locking the stove onto a backpack to deter the theft of the stove by other patrols that may have had theirs stolen or lost.

Figure 1. The engineering design task.