

Comparing Challenge-Based and Traditional Instruction in Biomedical Engineering

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Abstract - This paper presents the results of a study comparing student learning in a challenge-based and a traditional course in biotransport. Collaborating learning scientists and biomedical engineers designed a challenge-based method of instruction that followed learning principles presented in the U.S. National Research Council report "How People Learn." In this study, the intervention group was taught a core biomedical engineering course in biotransport using this method. The control group was taught by traditional didactic lecture methods. The study compared the two methods' effects on the early development of adaptive expertise (AE). AE requires a combination of two types of engineering skills: the ability to use subject knowledge appropriately and efficiently (efficiency) and the ability to think innovatively in new contexts (innovation). Therefore, student learning in biotransport was measured on both efficiency innovation on a pre- and a posttest. Students in the challenge-based instruction (CBI) and traditional groups' test scores were compared. Results show that CBI students made greater gains in both efficiency and innovation. We discuss these results in terms of their implications for improving undergraduate engineering education.

Index Terms - adaptive expertise, how people learn, biotransport instruction, challenge-based learning, teaching methods, student learning measurements

INTRODUCTION

Successful performance in engineering requires technical expertise and innovation [1, 2]. Due to the rapidly changing core knowledge and guiding regulations in biomedical engineering, these engineers in particular need a solid understanding of the fundamental principles and knowledge in their discipline in addition to an ability to adapt as opportunities and applications in this field evolve.

Achieving this type of practical adaptability is not trivial. Often, people can develop advanced technical expertise in a field independent of innovation. Learning scientists have described the combination of high levels of technical and innovative competence as Adaptive Expertise (AE) [3]. Our research is based on a model for the development of AE adapted from [4] (see Figure 1). This model proposes that there are two essential and complementary dimensions of AE: efficiency and

innovation. Adaptive experts are efficient: they apply their well-developed knowledge base appropriately and efficiently to solve core problems in the domain. In addition, they are innovative: they are flexible in novel problem-solving or design situations. They often consider multiple perspectives on problems, seek out new challenges, accurately assess their own knowledge state, and view their knowledge base as dynamic [3, 5–7].

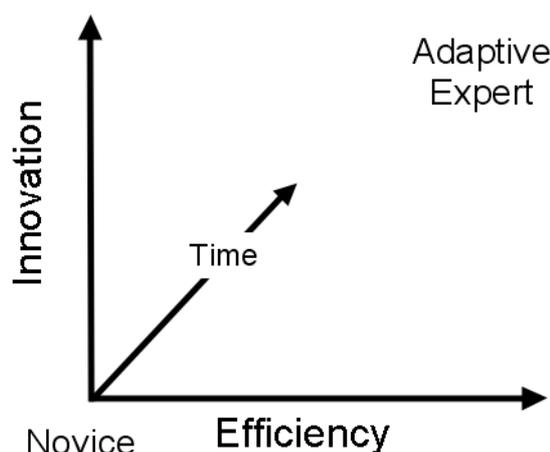


FIGURE 1
DEVELOPMENTAL MODEL FOR ADAPTIVE EXPERTISE.

AE usually requires many years of postgraduate industrial or academic experience to develop [8, 9]. Therefore, undergraduate students are unlikely to fully develop AE within a single semester of study. However, the educational method students experience may affect their development along a trajectory towards AE. Figure 2 shows a framework that addresses these differences.

Traditional instruction in undergraduate engineering involves lectures, textbooks, tests, and practice problems [2]. This is the typical learning environment for most engineering students. These learning environments can have clear benefits, such as clarity of objectives for students and teachers and frequently good coverage of the core knowledge students need to learn [5, 10]. These environments often lead to effective routine learning (see Quadrant 1 in Figure 2).

While traditional instruction has advantages, it also has drawbacks. One problem is that student learning in these

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environments can often be short lived and surface level [5, 11]. In these environments, students may focus more on learning strategies that help them succeed in the short term than those that lead to long-term learning. Some examples of these strategies are mimicking example problems for their problem solutions without developing deep understanding, examining the units of quantities in the problem, or attempting to insert numbers from the problem into equations given in a book or in class.

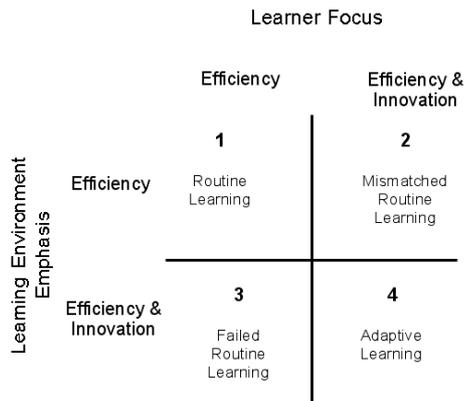


FIGURE 2
ALIGNMENT OF LEARNERS AND THEIR ENVIRONMENTS.

Another problem is that traditional environments can stifle the development of innovation (Quadrant 2). Students who have learned a topic in primarily traditional ways sometimes show less innovation in new environments than those whose only exposure to the topic was through more inquiry-oriented teaching [12]. In contrast, many students report enjoying inquiry-based approaches, such as problem-based learning, because they find more opportunities to innovate. In traditional learning environments, they have little opportunity or direction to develop their innovative abilities. In summary, traditional learning environments often help students develop along the efficiency dimension of AE, but less often promote development along the innovation dimension.

Challenge-based instruction (CBI) addresses both the innovation and efficiency dimensions of AE. Our CBI courses are based on learning principles explained in the U.S. National Research Council's report, "How People Learn" (HPL) [5]. These principles are consistent with many learning approaches that attempt to include more innovative components [5, 13–16].

The HPL principles state that learning environments should be:

- Student centered: use students' current capabilities as a starting point for learning
- Knowledge centered: focus teaching on achieving mastery in the key content in the domain
- Assessment centered: build in opportunities for students and teachers to acquire feedback on students' progress throughout the learning process, and
- Community centered: are appropriate to the discipline and the community context.

We implement these principles using a challenge-based inquiry cycle called the STAR.Legacy (SL) Cycle (see Figure 3) [17]. In the SL Cycle, students begin by encountering a realistic and novel problem that is stated in a non-prescriptive context (the Challenge). Next, they generate ideas in small groups about how to solve the challenge (Generate Ideas), and then explore various views on important aspects of the challenge (Multiple Perspectives). Next, they revise their ideas, often via homework assignments (Research and Revise) and complete formative assessments (Test Your Mettle). Finally, students publicly present and defend their solutions to the challenge (Go Public).



FIGURE 3
THE STAR.LEGACY (SL) CYCLE.

The CBI method avoids some of the pitfalls of traditional instruction by including a focus on innovation (particularly in the Generate Ideas and Multiple Perspectives phases). However, it also focuses on efficiency (particularly in the Research and Revise and Test Your Mettle phases). Research on problem- and project-based instruction (PBI) has shown that these innovative methods often motivate students [14, 15, 18–20]. This aspect of PBI can be very positive, but if not structured to clearly include opportunities to develop efficiency, it can also lead to lower knowledge gains than traditional instruction [15, 16, 18].

The SL Cycle helps instructors ensure that they have incorporated both innovative and efficiency building experiences into their learning materials. It also helps students understand that they need to use and develop both efficient and innovative learning strategies. Innovative learning strategies require students to develop and rely on innovative problem-solving skills, such as going back to first principles when they are not sure how to solve a problem or developing a model of the system in the problem and reasoning from that model.

CBI environments teach and encourage practice of both efficient and adaptive learning strategies [21, 22]. In these learning environments, many students initially attempt to use only their efficient learning strategies and find that they are inadequate (Quadrant 3). In contrast, if students use or develop some adaptive learning strategies in addition to their efficient ones, they are more likely to develop along a trajectory toward adaptive expertise (Quadrant 4). Our

primary hypothesis is that CBI will lead to greater development of innovation than traditional instruction.

METHODS

Experiments

Our prior research has demonstrated that CBI increases students' adaptive expertise in biomedical engineering [21, 23, 24]. However, these experiments were conducted over short periods of time: 1–2 weeks. Therefore, a more sustained investigation of the comparative outcomes of CBI and traditional instruction is needed. In this paper, we report on a study that compared the two methods over a longer time period: an entire course in biotransport.

Biotransport is a core course in biomedical engineering aimed at upper level students. It is important to test the effectiveness of innovative educational programs in courses that convey core bodies of knowledge for students. If these programs are effective, they will provide students with the key knowledge they need to progress in their fields as well as the added value aspects of innovative problem solving.

Participants

We solicited the participation of all members of two CBI and two traditional classes. Each course was taught at a Research I university in the United States (the two classes in each condition were at different universities). In total, 106 students participated in the study (54 in the CBI condition and 52 in the traditional condition). Most of these students were in Year 3 in the standard 4-year undergraduate U.S. program of study (approximately 20–21 years old). In both conditions, approximately one third of the students were female and two thirds were male. The SAT math and verbal scores for the students in the CBI and traditional conditions were not significantly different (Math: CBI $M = 710$, $SD = 80$; Traditional $M = 702$, $SD = 112$. Verbal: CBI $M = 668$, $SD = 97$; Traditional $M = 656$, $SD = 73$). Students did not receive compensation for participation.

Materials

CBI instruction. The CBI courses each used 10–13 modules that addressed fluid, heat, and mass transport processes in biological systems. The instructors ordered the modules with two goals in mind: to ensure that students learned the targeted biotransport taxonomy and to lead the students through a learning sequence, starting with core fundamentals and progressing to acquisition of specific analysis tools [25]. (See an example module in Appendix A.) Though the two CBI instructors implemented the modules somewhat differently and even used some different modules in their courses, they followed the basic structure of the SL Cycle.

Traditional instruction. The two traditional classes primarily employed a lecture-exam methodology. They focused on addressing the core taxonomic knowledge components of biotransport presented in a textbook specified for the course. Student activities included textbook readings, lectures, question and answer sessions, homework assignments, tests, and quizzes.

Assessments

All students completed a pre- and a posttest with two sections (see Appendix B). The Knowledge section measured students' understanding of fundamental principles of biotransport transfer. The Generate Ideas section measured how students' marshaled the tools of biotransport transfer to analyze a state-of-the-art research problem. We refer to these problems as Generate Ideas problems because they are similar to the activities in the Generate Ideas phase of the SL Cycle.

Knowledge section. This section presented the knowledge questions in multiple-choice format. We did not attempt to cover the complete biotransport taxonomy. Instead, we sampled from it with a few questions that addressed core concepts. Any student who completed a general biotransport class would be expected to learn the material covered in these questions.

Generate Ideas section. This section presented the Generate Ideas question. This question is innovative because students need to go beyond their current capabilities and develop an approach to a novel problem that embeds technical issues with which they are unfamiliar. This question also assesses efficiency. Although the problem is novel, it is not completely foreign. The governing principles, solution methods, and constitutive equations students learned in the class could, if applied adaptively, help them develop a viable approach to the question, even though it is unlikely they would completely solve the problem.

Our goal in using the SL Cycle is to accelerate the acquisition of adaptive problem solving. The SL Cycle makes the process of adaptive reasoning explicit, which should help students appropriate the process [17]. Therefore, we wanted our coding scheme to capture adaptive reasoning in novel situations, so we needed to define this type of reasoning. The research on expert problem solving in truly novel situations is not extensive, but we based our coding scheme on the available data.

We based our coding scheme for the Generate Ideas problem on the model for AE presented in Figure 1 4]. This model represents AE as a combination of innovation and efficiency. We based the operationalization of both innovation and efficiency on findings on expert problem solving.

For innovation, all experts tend to address problems initially from a global perspective to understand the primary issues of importance and then move toward developing specific equations or other solution methods [8, 26, 27]. In contrast, novices often skip the step of developing a deep understanding of the problem and attempt to quickly apply equations or solution methods that match the problem on surface features [8, 28]. In addition, adaptive experts tend to expand the problem space and consider multiple possibilities before they settle on a solution path [5, 7]. Therefore, to code innovation, we examined whether students considered the Generate Ideas problem globally and expanded the problem space by considering the system and its interactions with the environment.

For efficiency, adaptive experts transfer in useful and appropriate knowledge and procedures to solve problems [5, 7, 9]. We operationalized efficiency by examining whether

students had gained core knowledge in the course on the knowledge section of the test and whether students applied appropriate governing principles and constitutive equations to model the process in the Generate Ideas problem.

Coding

Innovation. The coding scheme for the Generate Ideas problem is a rubric with two categories with two elements in each category (see Table I). One category was innovation. We operationalized innovation as the inclusion and quality of a system definition (picture, diagram, or written definition) and identification of system interactions with the environment in the student's problem solving effort.

TABLE I
CODING FOR INNOVATION SECTION

Code	Innovation		Efficiency	
	System	Interactions	Governing Principles	Constitutive Equations
0	Absent	Absent	Absent	Absent
1	Picture or written description present but missing heat exchanger	Incorrect interactions	Incorrect governing principles	Incorrect constitutive equation(s)
2	Heat exchanger, fuel source, patient are all included in the system	One or more but not all (of 3) interactions: correct heat transfer to the blood, heat transfer from the fuel and heart as pump	Conservation of energy <u>or</u> momentum only	One or more but not all (of 4) correct: heat source from burner, convective exchange to blood, force of pumping, F>flow resistance
3	System is heat exchanger, that interacts with butane and person	All 3 correct	Both conservation of energy <u>and</u> momentum	All 4 correct

We coded each element on a 4-point scale (0–3). A response received a 0 if the category was missing from the student solution. A response received a 1 if the students did some work that was in the coding category but was primarily incorrect or irrelevant to the problem they were given to solve. A score of 2 covers a wide range. A response received a 2 if it included some of the necessary information, but some incorrect information as well. A response received a 3 if all the information was present and correct. Therefore, the range for the innovation score was 0–6.

Efficiency. Students' efficiency score combined their knowledge section score and their efficiency score on the Generate Ideas problem. Both core disciplinary knowledge and an ability to apply this knowledge adaptively are required for AE.

The questions on the knowledge section of the test all had well-defined correct answers. Therefore, a student's score on this section was the number of questions answered correctly out of six (range 0–6). The efficiency score for the Generate Ideas section also involved two elements: a statement of the governing conservation principles and an application of transport constitutive equations. We coded

each element using the same rubric as the innovation score (see Table I). Therefore, the range for the efficiency score on the Generate Ideas section was 0–6. The total efficiency score was the sum of the knowledge score and the efficiency score on the Generate Ideas section (range 0–12). A high score on innovation and efficiency indicates that a student is approaching the problem similarly to an adaptive expert in the area considering how to solve a novel problem. We had developed these coding schemes a priori and used them in earlier experiments [29].

Reliability. The coding procedure for the knowledge section was straightforward. Students received one point for each problem they answered correctly. The coding procedure for the Generate Ideas section was as follows. First, research staff who did not participate in the coding collected and blinded the completed tests as to time of test and condition of each participant. Next, a primary and a secondary coder trained on a subset of tests. Then, the primary and secondary coders checked reliability using new tests (30 tests, 10% of the sample) drawn randomly from the pre- and posttests. Inter-rater agreement was 92%. The primary coder subsequently scored all the Generate Ideas sections.

Procedure

Each instructor administered the pre- and posttests in class. Students took the pretest on the first day of class prior to any instruction. They completed the posttest on the last regular class day. Instructors did not answer any questions regarding the test and did not discuss it explicitly during the semester. They passed out the tests and read the instructions provided. Students had 10 minutes to complete the knowledge section and 15 minutes for the Generate Ideas section of the test. Instructors told students when to proceed to the second section. Students did not have access to any resources other than calculators during the tests.

Study Design

The design for this study was a pre–post comparison with an experimental factor of CBI versus traditional instruction. We examined both pre–post changes in and between group comparisons of student performance on innovation and efficiency.

RESULTS

Innovation

To examine the effects of instructional method on the development of innovation, we conducted a 2 x 2 repeated-measures ANOVA on innovation score with time (pretest vs. posttest) as the within-subjects factor and instructional treatment (CBI vs. traditional) as the between-subjects factor.

The two groups developed innovation differently (see Figure 4). We found that there was an interaction between time and instructional treatment, $F(1, 101) = 14.66$, $MSE = 1.75$, $p < .001$. Post hoc tests confirmed what Figure 4 demonstrates regarding the meaning of this interaction. The two groups' scores on the pretest were not different. However, the CBI group scored significantly higher than the

traditional group on innovation score on the posttest ($p < .01$). The CBI group's scores significantly increased from pretest to posttest ($p < .05$), while the traditional group's scores decreased significantly ($p < .01$). There were no other significant effects.

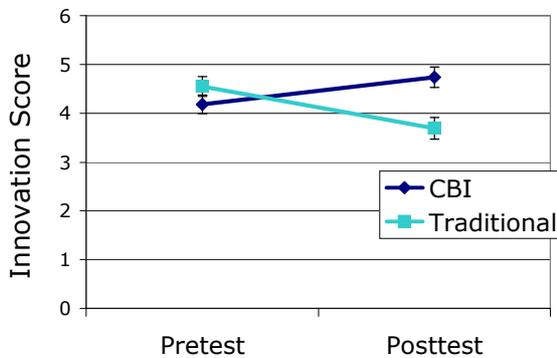


FIGURE 4
INNOVATION SCORES.

Efficiency

We analyzed these data using a 2 x 2 repeated-measures ANOVA on the efficiency scores with time (pretest vs. posttest) as the within-subjects factor and instructional treatment (CBI vs. traditional) as the between-subjects factor. Efficiency scores improved over time (pretest $M = 3.90$, $SE = .16$; posttest $M = 4.89$, $SE = .19$), $F(1, 76) = 17.54$, $MSE = 1.32$, $p < .001$. The CBI group ($M = 4.89$, $SE = .18$) scored higher than the traditional group ($M = 3.89$, $SE = .19$) overall, $F(1, 76) = 14.33$, $MSE = 2.71$, $p < .001$.

Furthermore, the two groups performed differently on efficiency on the two tests (see Figure 5). There was a significant interaction between time and instructional treatment, $F(1, 76) = 15.68$, $MSE = 2.18$, $p < .001$. Post hoc tests confirmed the patterns Figure 5 shows. While similar on the pretest, the CBI group scored significantly higher on efficiency on the posttest ($p < .001$). Moreover, the CBI group improved significantly from pretest to posttest ($p < .001$), while the traditional group did not change significantly. This effect also reveals that the main effect for improvement over time was likely due to the CBI group's improvement on efficiency, as the traditional group did not contribute to this improvement.

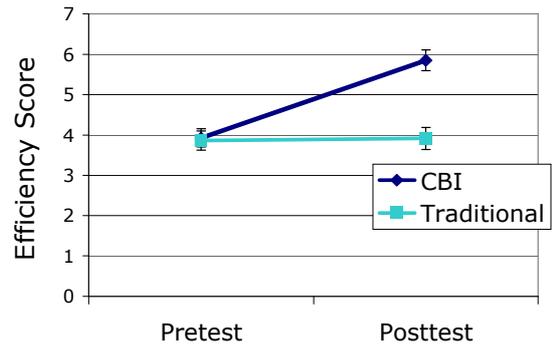


FIGURE 5
EFFICIENCY SCORES.

DISCUSSION

The HPL-based CBI method led to greater student gains in both efficiency and innovation. Thus, this learning framework is more effective at developing AE that will serve undergraduate engineering students well in future professional endeavors. While we predicted the greater gains in innovation for the CBI group, the greater gains in efficiency result were not explicitly predicted, though not surprising. When examined closely, the data showed that this difference was primarily due to the efficiency section of the Generate Ideas problem. Both the traditional and CBI groups learned the basic knowledge of biotransport, but only the CBI group was able to apply it effectively to work toward a solution to a novel and challenging task.

The significant decrease in innovation performance for the traditional students was another result of interest. While we would like to see this result replicated, we interpret it as an interesting comment on potential long-term effects of traditional instruction. Students in traditional instruction courses may become less willing to engage in challenging problems in adaptive ways. This result is consistent with a cross-sectional study we conducted comparing the development of innovative problem solving over the course of an HPL bioengineering ethics module for two groups: high school and first-year undergraduate students and upper level undergraduate engineering students [12]. The upper level students were less likely to develop innovative problem solving, suggesting that there can be long-term detriments to students' ability to develop innovation in a short period of time if they learn by primarily traditional methods.

In light of current ABET guidelines for program outcomes and industry calls for more innovative engineers, our results are encouraging and significant [30]. It is also important that these results were achieved in a regular class delivery setting. Our CBI classes had no additional teaching assistants, professor office hours, or graded assignments, and they were conducted in fixed-seating lecture halls not adapted for convenient grouping of students to interact during the generate ideas exercise. In addition, the class sizes were in the average range for undergraduate biomedical engineering at the participating institutions.

Next steps in this line of research include examining a longer developmental timeline for AE (e.g., do CBI students carry over their AE skills to later courses or to work and graduate education?) and examination of the role particular phases of the SL Cycle play in developing AE.

We believe these results inform the design of courses that address significant core content in engineering, science, and mathematics. We are not aware of any prior attempts to implement the HPL framework in these disciplines on the scale of entire courses, and they represent a potentially ripe field of application for this educational method. Many of the courses conducted in these disciplines teach core knowledge topics, are conducted with large class sizes, and are not conducted in environments adapted for collaboration. These are the real challenges that college instructors face in implementing inquiry methods such as CBI.

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APPENDIX A: CHALLENGE EXAMPLE

Challenge 6. The Danger of Hot Coffee Burns

Every year in the United States there are thousands of accidents at restaurants in which hot beverages are spilled onto customers causing scald burns that are severe enough to require hospitalization. In the most extreme cases, death results. A small fraction of these accidents result in law suits against various parties involved in the food service industry, the most publicized being the infamous McDonald’s case in which a jury awarded an elderly New Mexico woman more than 2 million dollars in 1994. Part of the public outcry to this case was based on the concept that spilling a cup of coffee is such a trivial event that it could not be worth such a large legal settlement. *Thus, the focus of this challenge is to answer the question “How dangerous is it to spill a cup of hot coffee into your lap?”*

You may use the following information in your analysis. The Coffee Brewers Association recommends that coffee be held at a temperature of 185°F for serving to customers, although a recent survey of the food service industry indicates the actual temperatures at fast food restaurants is somewhat lower. Many of the scald accidents occur while customers are seated in their vehicles at fast food drive-thru windows. A typical container contains 8 oz of liquid. The clothing worn by customers varies over a broad spectrum depending on geographic location and time of year, activity of the customer in conjunction with the visit to the drive-thru, and customer life style.

A consideration inherent to the issue of how dangerous is spilled coffee is how the level of danger can be modulated by altering the coffee temperature. For example, a recent scientific study demonstrated that the preferred drinking temperature of coffee is 140°F. Thus, it is appropriate to ask how a progressive reduction in serving temperature would change the injury hazard associated with a spill.

APPENDIX B: PRE- AND POSTTEST

SECTION I. (10 minutes)

1. The flow of blood through microcirculatory blood vessels can have a large influence on heat transfer and temperature regulation in human tissues.
 - a. As the blood flows through the vasculature is the mechanism of heat exchange with the surrounding tissue most likely to be dominated by a process of
 - i) conduction
 - ii) convection
 - iii) radiation
 - b. Which vascular components will provide the most effective venue for heat exchange between blood

flowing through them and the tissue in which they are embedded?

- i) aorta
- ii) arteries
- iii) arterioles

- c. Consider a comparison of the heat exchanges by the flowing blood and by the tissue in a very small volume of flesh. Is the magnitude of the heat exchange for the blood
 - i) smaller
 - ii) the same
 - iii) larger

2. The alveoli of the lungs present a structure in which there is mass exchange between gas flow (air) and liquid flow (blood).

- a. The fluid flow regimes of air and blood may be matched or different in the alveoli. Is the most likely combination
 - i) air: laminar and blood: turbulent
 - ii) air: laminar and blood: laminar
 - iii) air: turbulent and blood: laminar
 - iv) air: turbulent and blood: turbulent

- b. During one complete respiratory cycle the air pressure in the alveoli when compared to the air pressure in the immediate environment is
 - i) always greater
 - ii) the same
 - iii) always lesser
 - v) fluctuates cyclically between being greater and lesser

- c. During respiration the air flowing in the lungs at the center of a bronchial passageway has a velocity in comparison to air at the bronchial wall surface that is
 - i) always larger
 - ii) sometimes larger and sometimes smaller
 - iii) always smaller
 - iv) always the same

SECTION II. (15 minutes)

3. This is a very complex problem. A full solution would require extended attention and a number of iterations. However, one of the keys to success in extended problem solving is how you get started. Our goal is to access how you get started on a problem. Your task in this problem is to begin designing the device described below.

In severe trauma patients hypothermia is a common occurrence and issues in a significant increase in mortality. This situation is particularly grave for wounded soldiers for which it has been shown that mortality doubles when the body core temperature reaches a value of 34°C or lower. Patients suffering from severe trauma tend to become

hypothermic regardless of the environmental temperature, and in a war zone, such as the recent US involvement in Iraq and Afghanistan, casualties have suffered hypothermia at a rate in excess of ninety percent. Consequently, the prevention and treatment of hypothermia have been identified as being a major deficiency in American combat medical capability.

The Department of Defense is seeking solutions to solving the problem of preventing and treating hypothermia in war casualties. Owing to constraints imposed by the battlefield environment, there are a number of very specific limitations that must be enforced for any possible solution. Rapid evacuation to a Forward Surgical Hospital typically requires five hours and a ride in a cold helicopter. To be effective a warming device must be able to transmit energy to the body core at a rate of 60 watts over the five-hour period. It has been determined that the most effective method of delivering heat directly to the body core is via arteriovenous rewarming, being far more efficient than any surface warming technology. The device must be compact, light in weight, and robust (capable of being dropped from a helicopter at 150 feet onto a concrete surface.) The device must contain its own power supply since there is generally not an external electrical service available on a battlefield and during critical phases of transport. Batteries are too heavy and are inefficient. Thus, the energy source of choice for heating is compressed butane, which can be used to fire a burner in a small heat exchanger through which a minor fraction of the patient's blood flows. A surgical group has proposed designing a unit capable of warming 300 ml of blood per minute. The pumping source to move blood through the heat exchanger is the patient's own heart. Access to the patient's arteriovenous system for this device will be the same as standard practice for a heart lung machine.

The proposed device holds tremendous potential for providing life-saving support for trauma patients in both the military and civilian populations. At the present time it is still in the concept and prototyping phase of development. Since the early studies have been accomplished via some ingenious but intuitive work by a team of surgeons, there is no basis for understanding and predicting performance based on a rational model of the device when attached to a patient.