

# Development and Transfer of Innovative Problem Solving Strategies and Related Confidence in Biomedical Engineering

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## Abstract

Twenty-nine biomedical engineering (BME) undergraduates participated in a challenge-based instruction biotransport course, offered by the UT Austin BME Department in an accelerated format, at the University of Cambridge. Students' attitudes toward, and aptitude for solving genuine and complex biomedical problems were assessed throughout the semester through surveys, interviews, observations, and in-class examinations. Students' aptitude for problem solving improved throughout the semester, in a manner independent of content knowledge development. By the end of the semester, students readily transferred the problem-solving framework, learned within a biotransport context, to solve biomechanics problems. Additionally, we observed significant increases over time in students' confidence in their ability to complete challenges within and outside of the biotransport domain. We believe that this illustrative case study provides significant quantitative evidence supporting the effectiveness of challenge-based pedagogies for engineering courses.

## 1. Introduction:

In 2000, a multi-institution, interdisciplinary team (VaNTH) of researchers developed challenge-based instruction modules for biomedical engineering courses, ranging from biotransport, to anatomy, or optics<sup>1</sup>. A key philosophical component of these modules was to shift emphasis away from memorization and repetition of facts and instead emphasize students' ability to apply new knowledge innovatively<sup>2</sup>. The UT Austin BME department has offered a challenge-based biotransport course annually for more than a decade as an abroad learning experience at the University of Cambridge. A previous study, which compared students' development of routine and innovative knowledge in this course to a traditional biotransport course at a peer institution, identified that the students who participated in the challenge-based course obtained a similar level of content expertise and a superior ability to apply the knowledge in new or unfamiliar contexts<sup>3</sup>. In this study, we hypothesized that students in challenge-based biotransport would successfully transfer the problem-solving framework, developed over the semester, to alternate content areas. This framework, developed by the second author, is

termed the Generate Ideas Method (GIM), which is an expert-oriented method for approaching complex or unfamiliar problems<sup>4</sup>.

The GIM consists of three main components (Figure 1). In the first, an initial considerations step, students dissect the challenge prompt for important information, insights, and directional guidance, and then organize and document their thoughts. An important aspect of the initial considerations step is the legitimacy it gives students' daily life experiences, observations, and previous knowledge within which any new content is ultimately situated. During initial considerations students sort through the available information to establish an initial hierarchy of relevance and importance and to identify if there are any materials key to subsequent analysis that appears to be missing. After formulating the problem, students move on to the second step, analysis, that involves identifying and defining the system(s) being studied, and interactions that occur between the system(s) and the environment. Conservation laws (i.e. mass, energy, momentum) frame the challenge's phenomena within rational physical constraint, and guide mathematical definition and assessment of the system using constitutive equations. Once the resulting governing differential equations are identified, students examine their solution methods by synthesizing or solving the expressions. The most noteworthy aspect of the analysis steps in the GIM is that it prioritizes students' ability to access, contextualize, and employ new information and mathematical expressions. This emphasis contrasts with the common notion of content memorization as a focus of learning.

The key postulate of this study was that once students have achieved mastery of the structured problem-solving framework inherent in the GIM, they would readily transfer it to alternate content areas. Transfer, a term used to describe students' ability to access and apply skills or processes attained in one domain context to solve problems within another, is widely considered a principal goal of education.<sup>1,3-10</sup> We argue that parallel to the process of skill transfer is also confidence transfer. Essentially, students that master the problem solving frameworks presented in the biotransport course will not only successfully transfer the skill to alternate content areas, but also will do so with enhanced conviction.

We use biomechanics problems throughout the study during probes of strategy and confidence transfer, as all of the enrolled students successfully completed a biomechanics course prior to biotransport enrollment. This strategy assumes that students are able to access the routine or content knowledge, acquired in biomechanics, at the time of our study. Our observations within and outside of the class led to confidence in this assumption, as students readily recalled fundamentals of Newtonian physics, force balance, statics, and dynamics during problem solving sessions. As students were not asked to solve challenges through to a numerical answer – formulaic recall was not essential. An example challenge is given in Appendix A.

The goal of this study was to assess the following sequence of hypotheses systematically:

1. Innovative problem solving is an independent skill that students develop, through deliberate practice, over time;
2. Because innovative thinking is an independent skill, students will transfer it to technical contexts outside of the domain where they originally developed it;
3. Challenge-based instruction enhances student growth in innovative thinking by increasing in-class engagement, offering frequent and diverse formative assessment, and promoting metacognition; and
4. Following challenge-based instruction in Biotransport, students are more confident in their ability to solve biomedical problems.

It was beyond the scope of this study, which was a mixed-methods case study, to compare challenge-based and traditional instruction. Assessment of inquiry-based pedagogy, relative to lecture and other traditional teaching methods, has been studied extensively.<sup>2,3,9-12</sup>

To summarize, we will draw upon qualitative and quantitative data to posit explanations for growth in the challenge-based setting through in-class engagement and diverse sources of formative assessment. We also discuss unique attributes of the Cambridge study abroad experience, which acted in a cooperative manner with the challenge-based instruction paradigm.

## 2. Methods

This study, and the methods presented in this paper, were reviewed and approved by the University Institutional Review Board at UT Austin (study number 2017-03-0017). Informed consent was requested from, and given by, all 29 students enrolled in the class. The first author (JRC) had no teaching role in the biotransport course, offered students a full explanation of the study scope, collected all data, and obtained informed consent. The second author (KRD) was the course instructor and was blind to students' participation decision

until the completion of the course to avoid bias. Students were not compensated in any way for participation in this study.

### 2.1 Observation:

The first author, according to the Behavioral Engagement Related to Instruction (BERI) protocol<sup>13</sup>, conducted in-class observations. Briefly, the first author recorded an observation note every five minutes, at the initiation of a given interval. First, the number of students exhibiting disengaged behavior were tabulated, which could include, but was not limited to, unrelated electronic device usage, off-topic discussion with peers, or physical disengagement. Second, the class activity was categorized according to the nature of the instructional activity (i.e. content-oriented lecture, storytelling, group work, challenge problem solving, student presentations, routine example solving, instructional transition) and any relevant teaching-tools employed (i.e. board writing, electronic media). Regression analysis of observation data provided insight into the impact of in-class activities facilitated by challenge-based instruction on student engagement. With student disengagement as the response variable, the observation categorical variables and the following numerical variables were included for control purposes (class number, time). The entirety of every class session was observed, qualified, and recorded (2130 minutes total).

### 2.2 Written Assessments:

The second author was the instructor, and wrote all exams to include two "routine" problems, which required proper identification and employment of formulae to compute a correct numerical solution, followed by one "challenge" problem that involved application relevant content knowledge to construct and defend a solution. An example routine and challenge problem are each given in Appendix A. The second author and undergraduate learning assistant graded all class assessments, and the first author conducted subsequent analyses of student learning trajectory. Performance on routine and challenge assessments were analyzed in a quantitative manner both separately and in tandem.

### 2.3 Interview:

The first author interviewed a random sample of six students twice during the course (after classes 3 and 13 out of 17) and once more than two months following the final exam to assess transfer of problem-solving frameworks to biomechanics problems. Interviews were conducted one on one, so that students solved problems independently, and were each twenty minutes in duration. To control for problem content three biomechanics challenges were used, where two out of six students completed each problem during each interview session. At the completion of the study, each student solved each challenge exactly one time. All interviews were audio and video recorded for subsequent analysis. In addition to qualitative analysis of students' statements and feedback during these problem-solving sessions, the number of interview students employing a GIM analysis was tabulated.

## 2.4 Survey

Students' attitudes and opinions toward solving open-ended challenges were assessed using a survey instrument administered by the first author at the beginning, midpoint, and end of the course. This survey used semantic differential scales to allow students to identify the position on various continua that their current feelings toward problem solving resided (i.e. from motivated to indifferent, from comfortable to intimidated). An example semantic differential scale, used during the study, is given in Appendix B. Student were also given an open-ended biomechanics challenge, which they were asked to ponder and then qualify their confidence toward reaching a correct solution according to a 7-point Likert scale. In the same manner as the interview sessions, three biomechanics challenges were used, where one-third of the students received each problem during each survey.

## 2.5. Statistical Analysis

Unless otherwise specified, averages and error bars represent the distribution mean and standard error, respectively. On semantic differential scales, the flat surface of an arrow represents the point of complete agreement (-100 or 100). Statistical analyses were conducted using GraphPad PRISM (ANOVA, t-test) or R (regression and related analyses). Points of statistical significance are noted with asterisks (\* $p < 0.05$ , \*\* $p < 0.01$ , \*\*\* $p < 0.001$ , # $p < 0.05$  with the null hypothesis of a neutral response).

# 3. Results

## 3.1 Learning Trajectory within Routine and Innovative Contexts

Students' performance on challenge-based assessments increased linearly with respect to assessment number ( $r^2 = 0.927$ ) while having minimal correlation with routine knowledge performance ( $r^2 = 0.338$ ). (Figure 2). Performance on routine assessments had no correlation with time ( $r^2 = 0.07$ , data not shown). Students' familiarity and confidence toward implementing the GIM effectively was most important in performance on challenge assessments, but less critical for routine problems. This result is consistent with a previous study by Martin *et al.*<sup>3</sup>

## 3.2 Feedback and Assessment

The abroad learning experience afforded productive community building amongst the students that provided formative peer feedback throughout the course. All homework assignments were completed collaboratively in teams, facilitating immediate and iterative feedback. The teaching assistant or instructor also provided feedback pertaining to routine and innovative knowledge within 24 hours of a homework submission or exam. This prompt feedback from a diversity of sources (peer, assistant, instructor) was noted to increase students' willingness to iteratively solve homework challenges. Some initial resistance was observed with the

open-ended nature of challenge homework and assessments, with one student commenting,

“While we are definitely learning some in lecture, I feel that the homework [is] much harder and more complex than the lectures. I know [name] doesn't want to teach us based off equations, but it is difficult to decide which equation to use when we don't cover them too much in lecture.”

This resistance quickly dissipated, and we attribute some of the newfound comfort with both the teaching method and problem-solving methods to prompt and diverse formative assessment.

## 3.3 Class Preferences and Student Engagement:

Students prefer numerous aspects of challenge-based instruction, relative to traditional lecture pedagogy. Specifically, they like the collaborative, applied, and creative aspects. By the third class week, students' initial reservations toward the difficulty and time required to complete challenges dissipated ( $p < 0.05$ ) (Figure 3). Observation analysis also revealed that the group work and challenge problem solving in-class activities, as facilitated by challenge-based instruction, enhanced student engagement relative to lecture segments ( $p < 0.001$  and  $p < 0.05$  respectively). (Figure 4)

## 3.4 Transfer of Problem Solving Strategies

Students were given a biomechanics challenge in an interview setting, and were asked to construct a solution using any suitable method. While in the second class week, only 33% of students used a GIM framework to solve the challenge, 66% used the GIM in the fourth class week and 83% did so more than 2 months following course completion. This demonstrated superior transfer and retention of the GIM framework for solving open-ended challenges (Figure 5). Illustratively, when asked to reflect on the biotransport learning experience, one student explained,

“[Now] I don't immediately jump to solving [a problem], but think about how to approach it and often find several ways to [solve] it. If one way doesn't work, I'm not thrown off and can work to find another solution. The GIM model has provided me a structured approach to engineering problems that I can utilize in other classes and my research.”

## 3.5 Transfer of Confidence:

Students' confidence toward solving open-ended biotransport and biomechanics challenges increased between the first and third class week ( $p < 0.01$ ) and even more so by the end of the course ( $p < 0.001$ ). Initially, students were most confident in their ability to approach challenge prompts taken “from a course taken previously,” but by the end of the course, there was no difference in students' confidence toward completing biotransport, biomechanics, and “previous class” challenges.

## 4. Discussion

### 4.1 Discussion of Skill and Confidence Transfer:

The nature of collaborative challenge homework, provided by the instruction model, led to many active hours of engagement, peer and instructor feedback toward both biotransport content and problem solving strategies. By our estimation, from observation and student interviews, this additional time exceeded 40 hours by the end of the course. The students' consensus was that the challenge homework, and group collaboration therein, influenced their learning to a greater extent than any other aspect of the course. Challenge problems set the nature of these homework problem solving, study and revision sessions, which we characterize from observation as highly engaged and interactive.

Students developed innovative problem solving ability over the length of the course, and readily applied it to new engineering contexts in interview and survey settings. From students' commentary during surveys and class observation, we believe that initial difficulty with challenge prompts is derived from unfamiliarity with approaching problems without a prescribed solution process. This leads to the initial belief that the challenges are "harder" than routine problems, as well as some early dissatisfaction that in-class examples differ in context and scope from homework's challenge prompts. Over time, students' familiarity with approaching open-ended challenges increased. As this happened, they became much more confident in their ability to approach biotransport, biomechanics, and alternate biomedical engineering challenges. From students' comments, we concluded that mastering the GIM model was of paramount importance to this transition, as it usefully organized their prior knowledge and innovative thinking in a suitable manner for application to new problems. This manifested across all tested content domains as students' Biotransport challenge performance improved over time, concurrent with a greater frequency of students applying suitable GIM analyses to novel biomechanics problems in interview settings.

Students find open-ended challenge problems engaging, motivating, and interesting. The real-world applicability and the collaborative and creative nature of their solution also suits students' class structure preferences. With deliberate practice in problem solving and a framework within which to operate (GIM model), challenge-based instruction became the students' preferred class structure. When asked, in open-ended format, to offer advice to another professor who will teach Biotransport in the future, students specifically commented to keep both the challenges and the GIM.

One of the chief purposes of our study was to quantify students' transfer of innovative problem solving to new contexts following challenge-based instruction. We attribute students' metacognition, related to problem solving, for the fact that the progression of confidence coincides with noted

improvement in problem solving strategy in both exam and interview settings. Given the significant gains in students' problem-solving confidence, we cannot help but consider if self-confidence related to innovation has not only correlation but also explanatory power related to performance on challenge-based examination.

Ultimately, it is critical that students can apply the knowledge obtained during undergraduate engineering programs to genuine problems in the workforce. Therefore, students' newfound confidence toward approaching such problems was perhaps the most encouraging facet of our findings. Two students explained,

(S1) "I no longer feel very nervous when I first encounter a problem, so I am very grateful for that. I also use the GIM model in everyday life now, so that is pretty neat." (S2) "I am confident that, given the right resources and background information, I will be able to tackle problems that are complex and were [previously] unfamiliar to me. I understand how I need to approach a problem in order to develop an effective solution."

### 4.2 Relevant Observations and Reflections

In this paper, we identified and analyzed an array of evidence for the effectiveness of challenge-based instruction that we collected during and immediately following class sessions held at the University of Cambridge. Many aspects of the Cambridge study abroad were unique and important to the student experience. Prior to departure for Cambridge, the instructor invited all of the enrolled students to his home for an orientation, panel discussion, and a picnic lunch. Upon arrival, a sense of student community within the class quickly established, with housing arrangements, tours, and social activities that facilitated mutual experiences, conversations, and friendships. In between scheduled class and informal homework sessions, students went together to lunch, where the first author was also present, and participated in dialogues ranging from the class work to career plans, summer travel, generic complaints, current events, and the rain in England (or lack thereof). Students had the opportunity to discuss their respective backgrounds, interests, goals, aspirations, and challenges with the instructor during class trips, formal dinners at the beginning and end of the course, and small-group dinners on campus at the University of Cambridge.

From the current study, it is impossible to discern the effect size of these extracurricular activities on students' learning, both in general problem solving and the specific Biotransport content knowledge. Undoubtedly, the individual student-instructor relationships developed and the learning community established and positively influenced learning. The former seems to have most significantly impacted the students' immediate experience at the University of Cambridge, while



the latter is likely to positively impact students' learning moving forward in their respective BME curricula.

A second important observation was the relevance of the timing of this abroad learning experience in the students' education. The majority of the enrolled students were in the summer separating their second and third years (of four) in the BME program at UT. It was very apparent, from informal discussions with students outside of the classroom that this particular summer involved increased pressure to make decisions regarding career trajectory (i.e. aptitude and preparedness for medical school, graduate school, or industry). This matter of professional decision-making is likely the case for all engineering students, but especially pronounced in this case, due to the diversity of career paths typically pursued by BME students. The timing of this immersive Cambridge experience and the community built within seemed to occur in optimal timing for many students who were struggling with questions of academic direction and professional identity. We observed that this, in combination with managing living arrangements and navigating travel throughout Europe, lead to significant emotional growth in many cases.

#### 4.3 Summary

Students prefer challenge-based instruction, as compared to lecture pedagogy. Solving open-ended challenges, as a part of exams, homework assignments and class exercise, led to higher levels of class engagement, increased aptitude toward solving biotransport challenges, enhanced confidence toward solving biomedical problems from multiple content domains, and retention and transfer of an expert-oriented organizational framework. These results, in synergy with existing literature on challenge based instruction in BME<sup>1</sup>, provide evidence to support continual integration of challenge-based modules in engineering curricula. We also hope that the student-centered, content-specific nature of methods in this case study can serve as a basis for unique and instructive assessment of active learning environments in engineering.

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## Appendix A: Routine and Challenge Assessments

**Routine Problem:** On a hiking expedition in the Himalayas, a climber has an accident, losing his boot and sock, and his bare foot becomes wedged into a crevasse that is full of snow. The climber and his comrades have a radio and are able to call for help to come with equipment to release his foot. Help is expected to arrive in thirty minutes. Although the ultimate survival of the trapped climber is not in doubt, there remains a concern as to whether he will suffer frost bite to his exposed skin. Assume the conditions that produce frostbite are for the temperature to be reduced to  $-3^{\circ}\text{C}$  at the base of the dermis, which is 2mm thick. The temperature of the snow is  $-15^{\circ}\text{C}$ , and the initial temperature of the climbers' skin at the time of the accident was  $34^{\circ}\text{C}$ . What can you tell the trapped climber about his prospects for avoiding frost bite? The following information is available for your use.

|                              |      |                  |
|------------------------------|------|------------------|
| Density of skin              | 1040 | $\text{kg/m}^3$  |
| Density of snow              | 500  | $\text{kg/m}^3$  |
| Specific heat of skin        | 4.0  | $\text{kJ/kg.K}$ |
| Thermal conductivity of skin | 0.21 | $\text{W/m.K}$   |
| Thermal conductivity of snow | 0.19 | $\text{W/m.K}$   |

2013 edition of *Science*, about how they are advancing world public health through their Gates Foundation. In the interview, they listed the number one initiative, aimed to save the lives of 3,000,000 babies who die annually within 30 days of birth, is to use kangaroo care. The preferred arrangement is skin-to-skin and chest-to-chest placement of the infant between the maternal breasts, sometimes augmented by covering with a pre-heated blanket; thus the descriptor “kangaroo care.” There have been a number of clinical studies that document higher infant average skin and core temperatures during and subsequent to kangaroo care in comparison to babies who have been separated from their mothers. Kangaroo care is advocated as an acceptable and more effective alternative to placement in an incubator to combat hypothermia under normal circumstances.

In view of compelling data for its efficacy, kangaroo care is being adopted ever more widely. Examination of the literature finds that the most rigorous studies of kangaroo care present data on infant skin and core (usually measured rectally) temperatures over post-birth time, and there are some discussion of possible physiological mechanisms. However, a more comprehensive and quantitative understanding (derived via the perspective and methods of an engineer) of the kangaroo care phenomenon would be beneficial to its further development and more optimal and widespread implementation.

The skin of the climber is in direct contact with the snow. Thus, there is an imposed fixed temperature boundary condition on the tissue surface. It is reasonable to assume that the mass and thermal properties of the snow are such that as they receive heat from the warm foot of the climber that their temperature does not change significantly. The thermal consequences of the tissue freezing should not be included in your analysis, as they lead to an extremely difficult mathematical problem.

**Challenge Problem (Biotransport, Exam):** Kangaroo care for enhancing neonatal thermoregulatory function

There is a long established medical literature that advocates skin-to-skin contact between newborn babies and mothers to compensate for frequent deficits in the ability of neonates to thermoregulate, as well as to establish emotional ties and facilitate attachment. Indeed, the American Academy of Pediatrics has recommended that healthy infants should be placed and remain in direct skin-to-skin contact with their mothers immediately after delivery until the first feeding is accomplished (Gartner *et al.* 2005).

An interview of Bill and Melinda Gates was published in the 3 May,

Your job in this challenge is to develop a strategy for formulating a model for the thermal effects of kangaroo care. This challenge should provide a rich opportunity for invoking many of the tools that should now be in your arsenal of bioheat transfer skills. Application of the Generate Ideas Model for series of iterative analyses should serve you well in this challenge.

**Challenge Problem (Biomechanics, Interview/Survey):** Carrying Clean Drinking Water

In Ethiopia, 76 percent of the population (77 million people) lack access to water. Therefore, in order to get water for families to drink, prepare food, or bathe, individuals must fill containers with water at the nearest source and carry it to their home or village. In Ethiopia, the average individual needs four gallons of water per day. Each gallon of water weighs 8 lbs (approximately 3.6 kg). This act of carrying water often falls on women and children in the village, who have the time during the day to make the round trip to the water source. To put in perspective, these loads of water are typically no less than 20% and no more than 35% of their body weight.

The average Ethiopian family lives 6 kilometers (round trip) from the nearest water source. Therefore, women must load jugs and buckets with water and carry each of them for a length of three miles, mostly along gravel or dirt paths. To complete this task, they rely on back carrying (using jugs, which are strapped to the back), or head carrying. Head carrying dates back to ancient times, and involves walking to

one's destination while balancing a significant load on top of the skull.

In 1985, a team of researchers from South Africa and Scotland studied a group of six women from the Luo and Kikuyu tribes and, interestingly, discovered that the women could carry a load of up to 20% of their body weight on their head without expending any more energy than they would in an unencumbered walk (no water). Aspects of the gait that these women had developed included, but were not limited to, increased bone density in the spinal cord, and the strengthening of specific muscle groups.

In 2010, a team of researchers at Cape Peninsula University of Technology in South Africa disputed the experimental design of the 1985 study, and conducted their own controlled experiment of head carrying. They found that experience with head carrying (10 years, on average) provided no benefit to women, in terms of energy expenditure. Additionally, they found head carrying and back carrying to be equally effective, in terms of energy expenditure.

You have been called as an engineering consultant by the authors of the original study (1985). They have extensive experience studying African tribes, but they have no significant knowledge in the area of biomechanics. They want you to develop a biomechanical model of head carrying that could reinforce or dispute the findings of their original work.

Your challenge here is two-fold. First, to develop a model for head carrying. Relevant free body diagrams will be especially important here. Second, to make a recommendation to the

Please read the given statements. Each of the adjectives under a given statement could be used to qualify the statement. Mark the position on the continuum which best matches your opinion. A position in the middle signifies a neutral response, whereas one closer to one adjective indicates a greater level of agreement.

I prefer when homework, quiz, and exam problems in my classes...

-100 0 100

Require creativity : Are Procedural

Are cumulative : Are specific to a single chapter or unit

Are Qualitative : Are Quantitative

Have one correct answer : Have many correct answers

Are from the real world : Are hypothetical

Are solved individually : Are solved collaboratively with a team

**Appendix B:** Semantic differential scales were used to quantify students' attitudes toward, and opinions of, challenge-based learning environments (class, homework, quiz, and exam problems).

researchers as to whether their original conclusion, which was that loads of up to 20% could be carried without additional energy expenditure, was likely legitimate or the result of an experimental design error.

**Figures:**

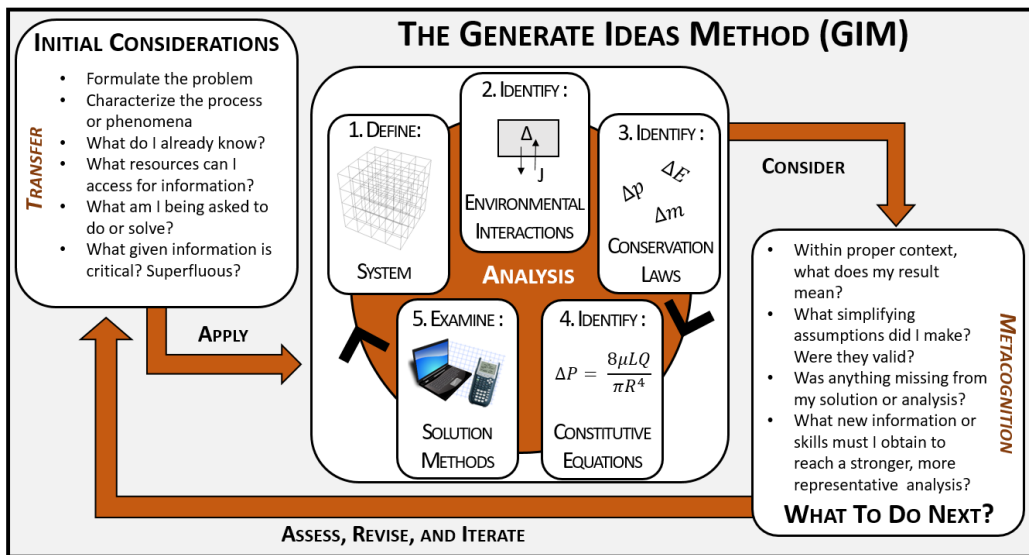


Figure 1: Graphical depiction of the Generate Ideas Method (GIM). The GIM is designed to facilitate the iterative, expert-like solution of previously unfamiliar open-ended challenges. Students in this study transferred the GIM framework from biotransport to alternate content domains (biomechanics).

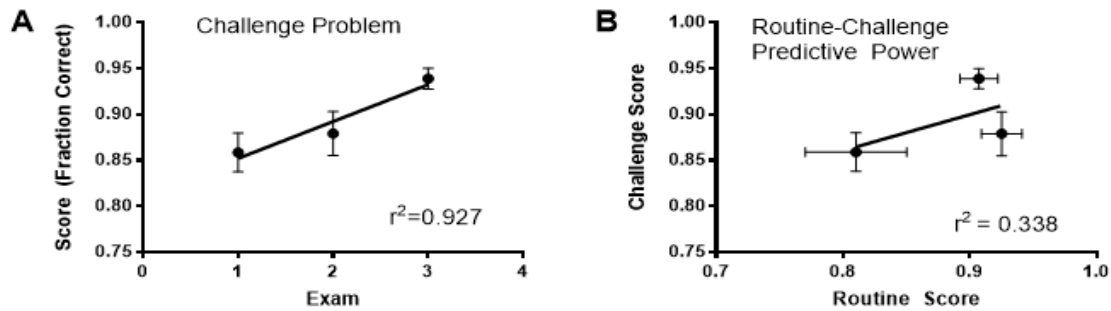


Figure 2: (A) Trajectory in students' biotransport challenge solving performance. (B) Routine knowledge is only modestly predictive for challenge performance. Performance quantified from exam scores.  $n=29$ , mean  $\pm$  standard error.

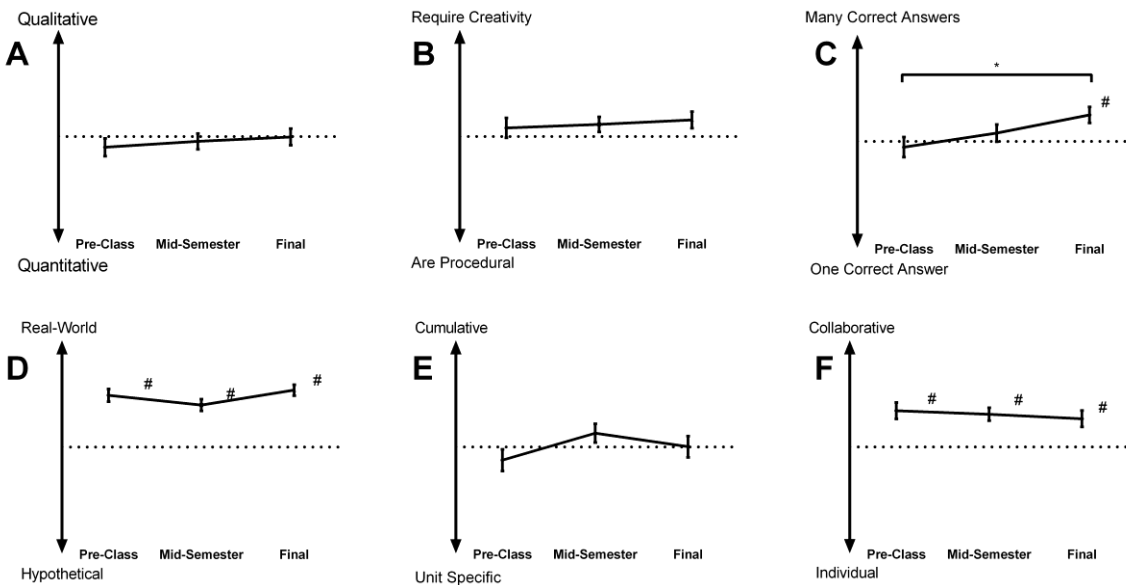


Figure 3: As assessed via survey, students increasingly preferred homework, quiz, and exam problems that were qualitative (a), required creativity to solve (b), and had many correct answers (c). Students consistently preferred problems from the real world (d) that were solved collaboratively (f). No trend was observed in preference for cumulative or unit-specific problems. \* $p<0.05$ . # $p<0.05$ , relative to expected neutral response (dotted line).  $n=29$ , presented as mean  $\pm$  standard error.

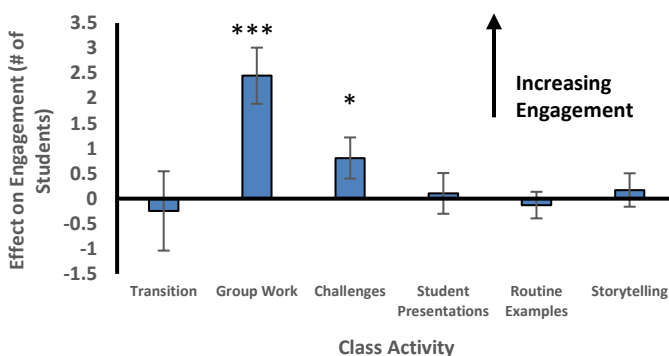


Figure 4: Impact of class activity on student engagement, relative to lecture.  $n=426$  observations. Presented as regression coefficient  $\pm$  standard deviation.

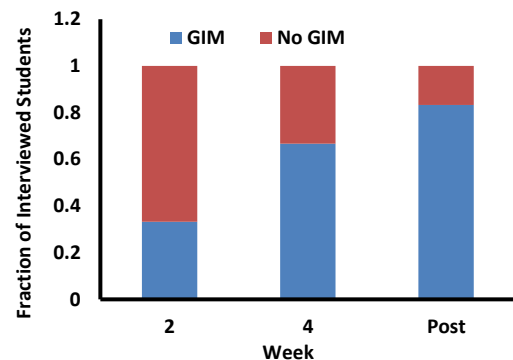


Figure 5: Evolution of proportion of students that transferred the GIM framework to biomechanics problems. In interview settings.