

High-stakes teaching: Lessons from two decades of problem-based engineering education

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ABSTRACT

Author MKH has taught a senior-level engineering course in a problem-based learning environment for more than two decades. This paper (a) defines a new term “high-stakes teaching” in an engineering context, (b) shares lessons learned from those decades of experience, and (c) argues that high-stakes teaching methods are beneficial for shaping Christian engineers of the future. Evidence from student focus groups supports the arguments. Readers are invited to consider other courses or learning environments in which these techniques could be employed.

INTRODUCTION

Engineering is a multifaceted activity that involves math, science, heuristics, analysis, design, written and oral communication, project management, and other professional skills. Introductory courses in engineering design typically involve a project that introduces students to the design process, despite students not yet knowing any actual engineering. The intent is for students to experience first-hand how a structured design process can aid solving open-ended problems. Courses in the middle years of an undergraduate engineering program typically expose students to engineering science and involve the middle levels of Bloom’s taxonomic pyramid [1]: application and analysis. A typical senior design course in the fourth year involves small teams of students applying semesters of accumulated engineering knowledge to an open-ended design challenge. However, few engineering programs simulate aspects of the engineering design process that involve coordination among several small teams toward a larger, shared objective.

The degree to which opportunities are provided for students to develop professional skills beyond engineering design and analysis (sometimes called “soft” skills) varies from school to school and from program to program. Development of professional skills in engineering courses can be accomplished via “high-stakes teaching” (HST), a new term defined later in this paper. Further, we argue that such skill development comports well with development of Christian virtues within students at Christian engineering programs.

This paper is about process and outcomes and invites readers to apply HST in their own classrooms. The next section defines high-stakes teaching and other concepts used to frame discussion of pedagogy. Then, we share lessons learned from both students and professor. Finally, we argue that HST is a good way to prepare virtuous Christian engineers for lives of service in the field.

DEFINITIONS

Research is the focused attempt to acquire unknown information, beginning from a place of ignorance. *Personal research* is the acquisition of knowledge that is new to the individual but known to others (e.g., “I’m researching different models of dishwashers”). *Primary research* is the creation of knowledge that

no human yet possesses (e.g., research done to obtain the Ph.D.). Primary research addresses questions that no one has yet answered. Conducting primary research may involve some design (see definition below), in that the research process may involve, e.g., the construction of a novel experimental rig or data collection method.

Design is the specification of a new thing, be it an object, process, material, or method. Design solves problems. In the same way that research begins from a place of ignorance, design begins with a blank slate. The bracket could have any shape, be of any material, and be manufactured in any number of ways. Parallel to how research may involve some design tasks, design often entails some personal research, such as looking up material properties, obtaining cost estimates, or testing the performance of prototypes for feasibility. *Professional skills* facilitate healthy and efficient teamwork in the design process and can include communication among team members, project management, leadership, time management, economic assessment, and understanding of customer wants, desires, and requirements. To paraphrase Theodore von Kàrmàn [2, p. 81], research discovers what is by answering questions, and design creates that which has never been by solving problems.

Engineering is a profession whose main objective is design, commonly accomplished in small teams within engineering firms. *Engineering education* is the process of preparing college/university students to enter the engineering profession via an undergraduate engineering curriculum. This paper focuses on undergraduate engineering education at Christian colleges and universities.

An engineering *project* involves research, design, and professional skills, in varying proportions. There are two common models for engineering projects in engineering education. First, a *focused design project* might occur in a sophomore- to senior-level engineering class and involve the application of course domain knowledge in a design activity. For example, a heat-transfer course may have a heat-exchanger design project. Focused design projects tend to be relatively well defined in the sense that student tasks are clear. Design work is usually restricted to technical considerations but could also include limited economic considerations. A focused design can often be accomplished through repeated analysis, also known as iteration. That is, the design process can consist of analyzing enough reasonable configurations and selecting the optimum. In a focused design project, there may be little or no need for the students to do research. In contrast, an *open-ended design project* is one where the problem itself is unclear, perhaps only a question is known. Students may never encounter open-ended design projects in the undergraduate curriculum or, if they do, only in a senior design course. In any case, open-ended design projects are often introduced as problems to be solved, such as, “it is difficult for a person with only one hand to ride a bicycle on unpaved, rural roads” or “this village lacks sufficient clean water.” Open-ended engineering projects involve more research on engineering and non-engineering topics than focused projects.

Problem-based learning (PBL) is a pedagogical strategy that can motivate engineering students to engage with course material. In PBL, instructors expose students to inherently interesting and engaging problems, and students self-motivate to learn course content. Often, content is delivered just-in-time: students realize they need information, ask the professor, and the professor delivers. “PBL is considered to be the best option for designing integrated projects that solve real problems and simulate professional environments” [12, p. 8]. Koktosaki et al. [13] provide several recommendations for high-impact teaching with PBL. Five of the recommendations are (a) effectively guide and support students, (b) provide high-quality group work to ensure students share equal levels of agency and participation, (c) balance didactic instruction with independent inquiry, (d) emphasize reflection along with self and peer evaluation on assessments, and (e) provide elements of student choice and autonomy throughout projects.

Challenge-based learning (CBL) is another active-learning pedagogical strategy that engages students in real-world problem-solving. CBL focuses student attention on grand challenges such as the Sustainable Development Goals [14] and invites creative solutions to vexing problems [15].

High stakes teaching (HST) is the topic of this paper and has similarities to both PBL and CBL. HST has the following five important characteristics, not all of which are shared with PBL or CBL: (a) a large, semester-long, open-ended, engineering design project (b) for an external customer or client (c) in which students take primary ownership to (d) answer a single-sentence question (e) as a class together. “Large,” in this context, means that obtaining an answer to the question requires considerable effort due to many interrelated pieces and complex analyses required, suitable for 20–30 students. Unlike most open-ended design projects, an HST design project doesn’t start with a problem. Instead, it starts with a question. The problems are initially undefined but emerge during the project. The analyses of emergent problems involve much data and/or justifiable assumptions. Because the project is large and open-ended, much personal research is needed on the part of students to begin to define problems, construct solutions, and develop an answer to the single-sentence question. Because the class is required to develop a single answer to the one-sentence question together, students must coordinate efforts within the classroom setting. HST provides opportunities to implement the recommendations and instructional practices listed by Kotosaki et al. [13]. Many examples of HST projects are given at <https://matthewheun.com/posts.html#category=ENGR333>.

Project definition, scope, constraints, and parameters require considerable thought and effort by the students. In high-stakes learning, students take ownership and invest in the engineering design project by:

- Answering a question that is intrinsically important to both students and the external customer/client. One technique to ensure meaning is to pose a question that relates to a geographical location relevant to the students (such as their campus, their city, or their watershed) and is connected to global grand challenges (e.g., environmental sustainability and climate change).
- Partnering with an external stakeholder who serves as the customer or client for the project, such as the college or university president, the VP of campus facilities, the mayor of the city, or a local chapter of a non-governmental organization.
- Dividing into teams with each team responsible for a piece of the overall project. Students are motivated to do their part because they have a personal responsibility to the rest of the class.
- Giving public account of their work. Public accounting can involve check-in meetings with the customer several times throughout the semester and public presentation of results at the end of the semester.

The single-sentence question is an important organizing principle and a key orienting device in the high-stakes classroom. The one-sentence question reinforces the open-endedness and research aspects of the project. The question gives students agency to take the question in their desired direction to develop their own answer. Students understand the project to be important because they are answering a question the customer cares about (and, therefore, they are motivated).

LESSONS LEARNED AROUND HIGH-STAKES TEACHING

This section discusses lessons learned from multiple decades of high-stakes teaching. First, the mechanics of HST are discussed. Second, evidence of the effectiveness of HST is provided from the point of view of both student and professor.

Mechanics of high-stakes teaching

The classroom is an environment constructed by not only physical space and technology but also by the words, actions, habits, and mores of both students and professor. All factors contribute to and/or detract from learning. This section explores choices and practices to construct a high-stakes classroom that fosters effective teaching and learning. The example for this paper is the fourth-year thermal-systems design course taught by author MKH at Calvin University. The actions taken by the professor before, during, and after the semester are covered in the sections that follow.

Before the semester

Several months prior to the start of the semester, the professor is on the lookout for project topics and potential customers during meetings, in discussions on campus, while working on research, and at conferences and workshops. Projects that work well for high-stakes teaching are associated with a *place* of interest to students, involve a customer with meaning for the students, and connect the students to an important global issue. Past topics include solar farms, campus heating technology, and energy-efficient homes for low-income families.

After the topic is selected, the professor works with the customer to define the one-sentence question to be answered by the students. Questions are more effective when they are short, simple, and clearly stated. Iteration with the customer is necessary.

In addition, the professor sets expectations with the customer. Expectations can include (a) that students won't spend as much time on the project as an employee would, due to other courses; (b) that it always takes students longer than expected to get organized for meaningful progress; (c) that early progress report presentations are unlikely to be professional and organized; and (d) that student improvement is the goal through the semester.

Additional support personnel are identified and contacted by the professor to assess their interest in the project and to secure their participation. The customer often provides suggestions for who could serve as support persons. The customer and professor decide an initial structure for student subgroups (typically four each) to encourage communication and other professional skill development both within student groups and across student groups.

When the one-sentence question is decided, the schedule for the semester is developed and confirmed with the customer and support personnel. Dates and times of all student deadlines are determined. All interactions with the customer and support personnel (kickoff meeting, in-class updates, and seminar presentation) are agreed and entered into calendars. The interactions among students, customer, and support personnel are front-loaded in the semester, thereby providing early guidance to the students to reduce, but not eliminate, time spent moving in unhelpful directions.

Finally, an assignment document is developed, typically 6–7 pages long. The first page of the assignment document starts with an introduction to the topic, establishes its importance to the students, and ends with the single-sentence question. Further pages provide additional technical considerations, introduce the

customer, clearly define end-of-semester deliverables, give contact details for the customer and support personnel, and outline the schedule for the semester. The schedule includes opportunities for students to practice four modes of technical information dissemination: oral progress reports for a review panel consisting of the customer and support personnel, a written final report, presentations at a poster session, and a departmental seminar. About 20–30 hours are invested in pre-semester preparation.

During the semester

Topic, question, and customer are revealed to students on the first day of the semester, often prior to distributing the syllabus for the course. Throughout the semester, the professor facilitates relationships among the students, the topic of the project, and the customer. Much of this work involves translating customer feedback into both actionable ideas and concepts the students have seen in previous or current courses. The professor asks leading questions of the students and avoids supplying answers. “Where have you seen something like that in your previous courses?” “When the customer says X, they’re thinking about Y. What do you know about Y?”

There are moments when intervention is helpful or necessary. “Did you know that another group was also analyzing that? Maybe you should chat with them to decide who is responsible for what.” When students schedule a longer, out-of-class session to discuss differences between teams, the professor brings pizza. When it becomes clear that one group will be “in the middle” of the project (often a team responsible for economic analysis), the professor meets with them to identify and name the emerging team dynamics and class structure.

An important part of facilitating the relationship between students and customer is providing feedback to students on mid-semester oral progress report presentations. The professor combines offline comments from the customer and support personnel with extensive notes to provide feedback in class periods following in-class oral progress reports. Fast feedback improves presentation style, structure, and delivery throughout the semester. Feedback can also reinforce the high stakes of the project.

To facilitate the relationship between students and the topic of the project, the professor provides suggestions for resources to consult and people to meet. For example, when a customer asked for a quantification of the value of the visibility of a project, the professor brainstormed with students and wondered aloud if billboard advertising rates would be a good analog. Students investigated and developed a financial model that quantified the value of visibility, thereby satisfying the customer’s request while deepening their engagement with the topic.

Throughout the semester, students complete weekly timecards to account for their time on task, similar to timekeeping for real engineering projects. On the final day of the semester, the professor presents a teamwork award to a student with exemplary contributions to the project. Peer evaluations are the basis for selecting the awardee.

In short, the professor observes, guides, and supports the students in their quest to answer the question posed on the first day of the semester. The professor constrains him/herself to act more like a coach than a player. Although the professor *could* do the work, the professor stays on the sidelines to observe and provide feedback. The professor intervenes only in high-leverage situations. This approach is aligned with Sukackè et al. who state “[i]t is important that teachers welcome the shift from teacher-[centric] to student-centered education, where instead of the main knowledge provider, they become facilitators and learn together with students” [15, p. 25].

After the semester

At the conclusion of the semester, grading is an unfortunate necessity. The professor consults with the customer or client to identify exceptional performance by individual students. The professor reads the final report and checks notes from in-class progress reports, the poster session, and the end-of-semester seminar. Then, individual student grades are assigned. Because of the extensive observations and interactions throughout the semester, grading individual contributions to the project takes less time than one would think, only 1–2 hours.

The professor posts student artifacts (reports and posters) at <https://matthewheun.com/posts.html#category=ENGR333> and communicates with the customer for any follow-up conversations or presentations.

Evidence of HST effectiveness from student focus groups and professor reflection

In this section, we provide evidence of the effectiveness of high-stakes teaching. The evidence comes from two sources: students and professor. Student evidence was obtained from focus groups. Professor evidence is derived from reflections on two decades of high-stakes teaching.

Student evidence (focus groups)

Motivation: Students reported several sources of motivation. *Italics* in the list below indicate key sources of motivation.

- “The prospect of an *end product* was very motivating, as opposed to a ‘normal’ project where I write a report or some paper. The product [in our case] was something that would be used by the mayor! There’s good motivation to do well because [our work] will have an impact.”
- The end-of-semester, open-to-the-public *seminar* also provides motivation. “The success of the project will be seen by everyone, because we have a seminar at the end. [We are] trying to show that [our work is] worthwhile and how much we are learning in the engineering program. ... Not only the grade, but also how people will perceive [the seminar] sparks a lot of [effort].”
- The *open-ended nature* of the project leads students to take ownership of the planning, work, and results. One student said, “[w]e started off with an open-ended question. The open-endedness [made] us take ownership, ... because we weren’t given a ‘how-to’ guide.”
- Students mentioned that working on *coordinated teams* provides motivation. “Working in teams: ... just by its nature you want to do well, and you do not want to let your team down. There’s an aspect of working in a group that motivates you to do well.”
- *Environmental sustainability* makes HST projects both valuable and meaningful to students. A student commented, “I think the sustainable aspect gave it more leverage to be an actual project, because the very idea that it was sustainable gave it value to Calvin University.”

Learning: Students reflected on factors that drove learning.

- One student said, “I would say the two most important things [are] ... the fact that there is a *real customer* and the fact that there is *limited guidance*. [T]hose two things ... drove the learning outcomes the most.”

- The students noted that *limited guidance* encourages students to learn to create and adapt “structure,” e.g. forming an executive team to coordinate activities and establishing information-sharing channels among the teams. “There were no executives starting off. It was just the separate teams. ... The next step [was realizing] we need[ed] executives, the interface [among us]. Then we ended up meeting more often. Part way through [the semester], we realized that we wanted to restructure for ‘external [energy efficiency] projects’ and ‘internal [energy efficiency] projects.’”
- Students perceive that the *open-ended* nature of the question prompted research activities that enhance learning. “We had to first do research to understand what a green revolving fund is. [We had to] research to understand the problem, and then there was a lot of research involved in [developing] solutions. ... It wasn’t a conventional class where you have a professor who knows all the answers, so the only way to learn is to research. ... I would say research was maybe one of the biggest parts of [the project].”

Participation:

- Students report that the *structure* of the project encouraged participation by everyone. “There were a lot of areas for people to excel in their own ways. People were able to find their niche.”
- Students realized that *workloads could be catered to individuals* based on skills. “Like most group projects, there will always be a few people that aren’t as motivated or aren’t as on top of things. But there was something for everyone to do, and you could cater the workload to what would be best for different individuals, what tasks they would be best at.” “There wasn’t anyone who didn’t have anything to do.”

Mechanics: Students observed that the constructed learning environment in the classroom provides space for checkpoints, inefficiency, and struggle.

- Regarding the classroom itself, students noted the value of *flexible space* compared to previous classes. “[In] [o]ur previous [class], we were seated in rows, and it felt more individual, more of a lecture. But the structure of this [classroom] was nice, because we had a large room [with] individual pods of tables. So [the classroom] already felt like a group [and] emphasized the group aspect of [the project].”
- “We had those *intentional checkpoints* [presentations], which I really think are essential. [They] allow the students to determine what the client wants to see at that point in the [project].”
- “I think [the project] was really *effective*. But it was *inefficient* in the time required to get the job done. Looking back at it, we could have done that so much faster! But I think it was necessary [to struggle].”

This evidence from students above correlates well with the literature on student motivation in innovative teaching practices and problem-based learning. For example, the explanatory factor analysis in Alvarez-Bell et al. [16, Table 3] shows that the instructional practices with highest correlation for student engagement are

- providing opportunities for students to build collaboration and communication skills (0.97),
- providing opportunities for students to take initiative and responsibility for their own learning (0.93),

- providing guidance and feedback during the active-learning class activities (0.93), and
- providing support to help students succeed academically (0.92).

Professor evidence and reflection

Reaching a different type of student: Nearly all engineering courses favor students with knowledge acquisition and application skills. In contrast, the high-stakes teaching environment favors students with interpersonal, organizational, synthesis, and evaluation skills. Different abilities are required to coordinate and communicate effectively among 20–30 peers compared to taking a one-hour, in-class test. (In a recent year, one student was lovingly nicknamed “HR” by peers, a tongue-in-cheek acknowledgement of their communication and interpersonal skills.) The high-stakes classroom provides opportunities for weaker students, according to traditional measures, to gain and apply professional skills throughout the semester.

Creating a different type of experience: Engineering undergraduates matriculate into a world in which two types of coordination are important. Engineers often coordinate their work within small teams of 3–5 people. Engineers also coordinate between such groups in a division or across a company toward a shared objective. The high-stakes classroom prepares students for both types of work by creating an environment in which small groups of students coordinate across the entire classroom to accomplish shared objectives. Before author MKH developed HST projects, there were no opportunities for students to coordinate between small groups in the Calvin University engineering curriculum.

It is impossible to struggle time-efficiently: At the end of a semester, students sometimes remark that they should have been able to answer the question in a few short weeks, much less than a full semester. When asked why they would need less time now to complete the project, they identify the excessive time (in their minds) spent understanding customer needs, establishing communication lines among groups, dividing labor amongst groups and within groups, learning the problem domain, and developing a shared online file structure.

Students don’t yet understand that it is impossible to struggle time-efficiently. Indeed, a benefit of the high-stakes learning environment is the struggle required to define the problems, to decide courses of action, and to make progress. Experiencing a high-stakes but safe environment provides students with a formational, pre-career exposure to the stages of the Tuckman Ladder: forming, storming, norming, and performing [17]. Although the experience has high stakes for the students (guided by the professor), no money is on the line, no one will be fired if they fail, and nobody will be injured if things go horribly wrong. In the moment, students don’t realize that the struggle is the very thing that develops the professional skills necessary to function effectively in future engineering teams. The HST instructor does well to understand that *inefficient* learning becomes *effective* learning when students are guided subtly through the process.

The rhythm of the semester: Learning is shaped by the classroom environment. The classroom environment is a created and emergent phenomenon, shaped largely by the professor and to a lesser extent by the students. One way the professor shapes the HST classroom is by weaving traditional lectures in and out of the project. Loading the early part of the semester with traditional lectures keeps storming on the project to a minimum. Front-loading presentations to the customer establishes the high-stakes character of the project. Ending traditional lectures a few weeks before the end of the semester allows time for the “norming” and “performing” rungs of the Tuckman ladder.

The question is important: Framing the project with a question is important for two reasons. First, a question is an effective way to attract the attention of potential customers. When in conversation with the non-profit Habitat for Humanity, I (author MKH) asked about a low-carbon house soon to be constructed. The question “Do you wonder about the *actual* carbon emissions savings from your ‘reduced carbon footprint’ house? If so, you would be a great customer for my students’ work in the coming semester!” proved to be enticing, because Habitat had not estimated the true carbon savings. I expect that saying “I will assign my students to design a net zero, two-bedroom house for a low-income family in our city. Would you be the customer for their work?” would have been less exciting.

Second, framing the project with a question forces the students to convert the question into problems to be solved. Moving from question to problems with clear objectives is an essential part of defining the project and foundational to the “storming” that occurs in the early weeks of the semester. Throughout their engineering careers, students will often move from “question to be answered” to “problem to be solved” as they interact with management, regulators, and other stakeholders. “Storming” in a safe classroom environment provides a first and (to many) seminal experience with this important aspect of engineering.

We have found that when the question presented to students is focused on environmental sustainability, creation care becomes more than platitudes or sentiments like “we should appreciate the trees, flowers, and rivers that God created” or “creation care is important for Christians.” Students experience, perhaps for the first time, that solving environmental sustainability problems as a unified body (the body of Christ, see below) takes pro-active effort, hard work, intentional coordination, and clear communication, all important professional skills.

Mindset: The mindset of the high-stakes professor should be confident of project success but not complacent toward it. Confidence can come from many sources: previous experience with rescoping or redefining projects that go awry, knowledge of the project’s domain, or similar HST projects in previous years. Complacency on the part of the professor would lead to missing critical moments for subtle guidance and steering of the project.

Grading: Assigning grades to student work turns out to be uncomplicated in the HST environment for a few reasons. First, the instructor is involved with students throughout the semester, which provides ample opportunities to observe and assess student interactions and performance. The instructor provides regular assessment to students after each progress report presentation to the customer, thereby providing feedback on student performance. Mental notes and written records can be kept on student performance as the semester unfolds during work times and in interactions with the customer. Conversation with the customer at the end of the semester is another way to obtain input on student performance.

Second, on peer evaluations, students tend to be frank and direct, effusive in their praise of some peers and unsparing in their criticism of others. Short, confidential conversation with a few students can often get to the bottom of problematic team interactions.

Third, presenting to the customer and facing critical questions is an excellent means of assessing depth of student involvement in the project and acquired domain knowledge. Again, notes and records can be consulted at the end of the semester when grades are decided.

High stakes for the professor: For several reasons, it is risky for the professor to teach in a high-stakes environment. First, the project question and structure are very important for a successful outcome. There

is a risk that the professor has not thoroughly considered those items, which could lead to a mid-semester pivot and student frustration. Second, it is inherently risky to place the professor's reputation in the hands of young, inexperienced engineers-to-be. Third, if the students were to fail to develop a satisfying answer to the question, it would be embarrassing for the department and the school. Indeed, the stakes are high for the students but also for the professor.

Metaphors: Metaphors can be illustrative when attempting to explain a new idea, such as HST. Below we list some metaphors that we use to describe high-stakes teaching. We also identify strengths and weaknesses of each metaphor.

- *Shepherd* (lead from behind). When sheep are led from behind, the shepherd's leadership goes unnoticed. The professor in a high-stakes classroom should appear from the students' point of view to provide very little direction on the project. Consequently, the students take more ownership. In focus groups, students reject this metaphor for good reasons. Students are not unthinking sheep; sheep don't take ownership of their project; and students have more agency than sheep in a pasture.
- *Coach* (lead from the sidelines). In some ways, the professor in HST is a coach for students. It is not the professor answering the one-sentence question and performing the design tasks at hand. Instead, the professor (coach) observes "from the sidelines" and offers advice and/or correction. A student in a focus group likened the professor to a coach who offers "tools to overcome problems" in sports such as soccer or lacrosse where coaches are not directly involved on the field of play. Such coaches decide which players are on the field and oversee training, but mostly the game unfolds under their observation but without their direct participation. The coach metaphor is apt because it captures the HST professor's facilitation of group performance and success by arranging details of the project even before the semester begins.
- *Team athletics* (athletes strive under the guidance of a coach toward a common goal). Students liked the metaphor of team athletics, an expansion of the coach metaphor. Several aspects of team athletics describe HST well. Each student has a role on the team, and each student develops expertise on a piece of the project. A good coach will put their athletes in the best positions for success. HST projects enable quieter students to make significant contributions in the background. (Students reported that the visibility for seminar presenters was unfair because, actually, all class members contribute.)
- *Improv comedy* (be prepared, but make it up as you go along). Professors prepare for classroom teaching and, without question, preparation facilitates student learning. That said, no amount of preparation provides complete control over the classroom, nor would that be desirable. Although the HST professor prepares ahead of time, the high-stakes classroom is spontaneous, with active and reactive give-and-take among the students, the customer, and the professor. Similarly, improv comedy works best when there is give, take, and trust between audience and comedians. Improv comedians "go for it" to find comedy gold. Similarly, the HST professor and customer must trust the students to "go for it" to find an answer to the question. In focus groups, students liked the improv comedy metaphor, especially the trust aspect. They noted that to tell a funny joke, improv comedians need to take risks. So, too, students need to take risks to achieve good outcomes. Students also noted that they needed to adapt (improvise) the management structure of their project in response to customer suggestions. Finally, improv comedians need to "read the room"

to communicate well with their audience. Similarly, students need to learn to communicate well with peers, with the customer, and with the professor.

- *Warfare* (in the trenches). It is said that no battle plan survives contact with the enemy and that planning is everything but plans are worthless. The warfare metaphor is apt in that the professor may have a plan at the beginning of the semester, but an HST project never goes exactly according to plan. This metaphor is less apt in that the HST classroom has very little hierarchy, just professor to student, unlike the lengthy chain of command in armies. Furthermore, the project itself is not necessarily an “enemy” or even adversarial.
- *Body of Christ* (1 Corinthians 12). The HST class is like a body in that each student (and the professor) has a role to play. Even more so than a team sport, the whole cannot have success without everyone contributing to the best of their abilities, whatever the level of ability. With class-wide projects, each student has a role and responsibility on their own team, and each team has a role and responsibility to the broader project. The high-stakes classroom provides an environment in which (a) students can become members of a well-functioning body of Christ and (b) Christian virtues can be developed. (See below for more on virtues.)
- *Teaching a teen to drive* (teen driving is a high-stakes necessity). A new driver needs guided opportunities for driving on real streets before driving on their own. So, too, engineering students need opportunities to develop professional skills before becoming real engineers. Professional skills are best developed under a mentor, just like driving skills are best developed under the watchful eye of a parent who is not driving. Further, like the road is a high-stakes environment with serious consequences for mistakes, so, too, the engineering profession has high stakes for designing bridges, appliances, and machines. In both teen driving and engineering, there is no shortcut for gaining experience other than having experiences.

HIGH-STAKES TEACHING IS BENEFICIAL FOR SHAPING CHRISTIAN ENGINEERS OF THE FUTURE

The sections above (Definitions and Lessons learned) form the basis of the contention that HST is beneficial for shaping engineers and Christian engineers of the future.

In Lavado et al. [18], the problem-based learning (PBL) literature was reviewed in several categories, including integration of curriculum and sustainability. PBL that integrates disparate aspects of the engineering curriculum were found to “make students more responsible for their learning process and provide in-depth understanding of the subjects involved.” Further, teamwork is fostered “when more theory-oriented students are mixed with other more practice-oriented ones.” PBL that incorporates sustainability themes was found to generate “students feel[ing] more motivated and encouraged to do a good job, driven by the recognition of the social or environmental impact of their work. The ethical values [were] perceived [to] contribute to the learning experience.” There is ample evidence that PBL is beneficial for students.

This paper does not assert that HST is better than PBL or CBL; we do not have evidence for that claim. Rather, we note that walking beside students is an authentic way to bring Christian students into the engineering profession. Indeed, for Christian engineering faculty engaged in educating Christian engineers, there should be a desire to develop Christian virtues in students both in the classroom [19, 20]

and outside of it [21]. We contend that HST extends problem-based learning and challenge-based learning to provide myriad opportunities to develop Christian virtues under the guidance of the professor in the context of Christian engineering education. There are many lists of virtues, but we think the list provided in Plantinga's *Engaging God's World* [22] is particularly appropriate for the Christian education context: diligence, patience, honesty, courage, charity, creativity, empathy, humility, stewardship, compassion, justice, faith, hope, and wisdom.

Evidence for our claim that HST provides opportunities to develop Christian virtues in students was presented in the student and professor evidence sections above. *Courage* is required to take risks and participate fully in a high-stakes engineering project, similar to the improv comedy metaphor. *Diligence*, *patience*, and *humility* are necessary to "storm" through the confusing early weeks when students come to grips with the question and form structures in a class with 20–30 students to pursue an answer. *Creativity* is required to develop solutions to problems that emerge from the question. *Honesty* with one another, *empathy* and *charity* toward one another, and *compassion* for one another are necessary to develop strong working relationships within the class. *Stewardship* can emerge when high-stakes projects are focused on environmental issues and include economic components. When guided well, students can be motivated by the desire to make the world a more *just* place animated by *faith* in God's plan for all creation. A successful outcome for a high-stakes project can engender a sense of *hope* within the students that the future can be better than today. Finally, a successful experience in a high-stakes project can be a small part of a long life dedicated to developing *wisdom*.

Finally, we address some obvious questions. Should HST be a part of every Christian engineering curriculum? The answer hinges on what sort of engineering students we wish to develop in our teaching and learning. If we want to develop students who take responsibility for their work, function well in teams, are comfortable with high levels of ambiguity, are unafraid to enter new areas with appropriate levels of support, and demonstrate Christian virtues, HST is fit for purpose. Either the engineer's first "real" experience comes on the job, or it occurs in the undergraduate classroom. We contend that, like learning to drive, the only way to become an experienced engineer is to actually do real engineering. In short, we contend that HST is a risky but worthwhile endeavor for both students and professor.

Is HST more work than a "normal" class for students? Does HST result in "better" learning? Yes, to both questions. In part, HST results in better learning precisely because it requires more and different work from the students. Is HST more work than a "normal" class for the professor? Yes. The professor must be pro-active well before the first day of classes to find the customer, set the question, and prepare resources for the students. During the semester, the professor must be alert to opportunities to guide the project and coordinate with customer and support personnel. In some ways, the professor's role in the project is more like management than teaching.

What sort of engineering courses are amenable to HST? Courses where a large, open-ended project would be appropriate, such as upper-level courses with design elements as opposed to engineering-science elements.

What mindset is needed by the instructor? Expertise is needed, certainly, but instructors must be comfortable with risk and ambiguity and with ceding control to students. The instructor must trust the students and the design process so that minimal, necessary interventions are taken.

CONCLUSION

To conclude, consider this question inspired by HST itself: *what would it take* to try HST in readers' classrooms? Two things are required.

- First, instructors need to be convinced that HST is worthwhile. The previous sections entitled “Student evidence (focus groups)” and “High-stakes teaching is beneficial for shaping Christian engineers of the future” provides evidence that HST is worthwhile.
- Second, instructors need to know how to implement HST in the classroom. The section entitled “Mechanics of high-stakes teaching” provides suggestions for actions to be taken before, during, and after the semester.

In summary, this paper provides answers to the requirements for adopting HST. How can instructors implement high-stakes teaching? The only way to gain experience is to “go for it.”

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