The Engineer of 2020 is Here: Using Innovative Kinesthetic Activities as Tools to Fulfill the NAE Vision

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Abstract—**With the arrival of the 2016 freshmen class on college campuses, the Engineer of 2020 is here. In the 13 years since the NAE's initial publication, many innovative engineering programs and initiatives have taken root across the United States. Many of these programs are rooted in experiential learning for technical mastery, and have demonstrated success in developing strong technical experts. The vision for the Engineer of 2020 goes beyond technical knowledge and deep into the human elements of engineering. We describe the use of innovative, kinesthetic activities to support the broader realization of the NAE vision. We draw from two unique courses, a communication course with a multidisciplinary engineering student enrollment, and a course for both engineering and non-engineering students that explores the implications of engineers as people. While different in context, the elective courses share a similar ideology and approach in emphasizing communication, human relationships, focus on the engineering process, opportunities for reflection, and growth mindset. Many of the activities described require students to play a role in a non-technical or abstract scenario which forms the basis for discussing engineering principles. The underlying philosophies of these non-technical courses also permeate our approaches to teaching technical material in core classes. Student feedback has been positive, with students recognizing the absence of this kind of learning in their broader education.**

Keywords—Engineer of 2020, kinesthetic experiential experience

I. Introduction

In 2004, the National Academy of Engineering (NAE) articulated its vision for upcoming generations of engineers in its book, "The Engineer of 2020" [1]. This vision addressed the broadening complexity and scope of future societal challenges, calling upon the need for "collaborations with multidisciplinary teams of experts." What characteristics describe the Engineer of 2020? The ability to communicate to diverse audiences with/without technology use, the perspective to recognize the social and economic context of engineering problems, the ability to work with a broad range of interdisciplinary knowledge, adaptability, and respect.

The NAE vision for the Engineer of 2020 does not hinge on technical content, but rather focuses on the human element of engineering. Numerous engineering programs and initiatives are working to achieve this vision, including Olin College of Engineering [2], The Cooper Union [3], and James Madison University's (JMU) College of Engineering [4]. At Olin and JMU, students forgo specific disciplinary degrees, building an engineering degree program around a societal challenge (e.g., clean water) of interest instead.

These curricula do not represent the large majority of engineering programs. We have taken steps to infuse our curricula with elements of the NAE vision through our teaching, and here we describe two independently-developed elective courses that utilize kinesthetic experiential learning to achieve the NAE vision for our students. To be effective, these ideas must permeate how we approach all of engineering and permeate our "traditional technical" courses as well [5-7]. Thus, we will also touch upon unique approaches in our technical courses that work to achieve the NAE vision.

II. Implications of Kinesthetic Activities

We see engineering as a process that involves a continual exchange of information, ideas, knowledge, constraints, solutions, and feedback between engineers working with other experts, stakeholders, users, and society, all in an attempt to provide value to society [6, 7]. Thus, engineers must interact, both physically and abstractly, with a broad range of individuals. In these interactions, engineers bring with them a toolbox, the set of ideas, concepts, and skills they provide. This is more than just technical knowledge, and may be influenced by an individual's personal experience, identity, etc.

The kinesthetic activities we use in our classrooms allow us to have students engage with this perspective of engineering in ways that are difficult to achieve through other methods. Active learning is widely accepted as an effective mode of increasing student engagement and learning outcomes [8]. These kinesthetic activities focus on the "active" in "active learning," by having students actively play roles in creating a live scenario. Students directly experience various aspects of the engineering process, and are also introduced to the concepts and ideas that will form their toolbox by having a more "full body experience" [9]. We have found these activities especially useful for difficult to grasp concepts, where the opportunity to see the system in action can shed a great deal of light on what is happening. In many cases, it is impossible or infeasible to show our students a real-life system in action in our classrooms. Simulations and videos can help, but kinesthetic activities that simplify concepts to achieve a particular learning objective can bring these to life.

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III. Courses Designed For Critical Engineering Skills

We describe two independently-developed courses designed to focus exclusively on essential engineering skills that lie outside the technical content of degree programs. Developed by different faculty, and originating at separate institutions, both courses rely heavily on looking beyond technical information to the human element and skills that are critical to a successful engineering process. Additionally, both courses frequently include kinesthetic experiential learning activities that immerse students in the topic at hand. Individual reflection coupled with post-activity debrief ensures that learning objectives are met, and allows students to learn from their peers' experience as well.

A. Technical and Professional Communication for Engineers

Technical and Professional Communication for Engineers (TPC) originated as a chemical engineering specific communication course at The Ohio State University. Since 2015, it has been offered at Bucknell University as an elective course open to all engineering students. True to the course title, TPC covers both traditional aspects of technical communication such as writing, understanding audience, and oral presentations, but also important professional topics such as resume and cover letters, elevator pitches, prioritization, human interactions, and more. The course relies heavily on inductive methods, drawing from students' own communication experiences, practices, and beliefs to discuss topics. All class periods involve active student participation, and often kinesthetic experiential learning activities.

B. Engineering: A Humanist Enterprise

Engineering: A Humanist Enterprise (EHE) was developed and offered as a new course at Bucknell University starting Spring 2016. It is both a course in the Electrical and Computer Engineering (ECE) department and a University course open to any student who has fulfilled the first university-wide writing course requirement. The course premise is that behind every engineering feat is a human story. Disciplinary boundaries are blurred, and students consider the idea of engineering as a human activity, while exploring the implications of viewing engineering through this lens. The course is discussion-based and also relies heavily on the students' everyday experiences as human beings and ties these into how human nature and interactions can affect the work of engineering teams.

IV. Kinesthetic Experiential Learning Activities for Non-technical Concepts

As mentioned, both courses incorporate a variety of kinesthetic experiential learning activities to address non-technical concepts. While each activity has been designed with a specific purpose, they can be modified depending on specific learning objectives and time constraints.

A. Communicating Increasingly Complex Ideas

Contrary to popular stereotypes, engineering is a discipline highly dependent on communication [10, 11]. As technical experts, engineers are responsible for explaining complex ideas to a variety of audiences. This activity highlights the difficulties that can arise when describing increasingly difficult concepts to members outside of your peer group.

In TPC, each student is given a paperclip and asked to write down how they would describe its form, function, and mechanism first to a peer (without using the word paperclip), then to a non-peer kindergarten student (age 5). Next, students compare and summarize features of their descriptions in pairs. This is repeated for a binder clip and stapler. Each item has a similar end function, but as we move from paperclip to stapler the form and mechanism become increasingly difficult to describe to a non-peer audience. We can no longer rely on a shared lexicon or shared experience. At the end of the activity, the class creates a summary of description features based on item and audience, and assesses the difficulty of each.

The activity ends with asking the students, how does this all relate to communicating as engineers? While students are often told to "consider audience" in communication in technical classes, they are rarely given an opportunity to truly reflect on that communication might look like to different audiences. Using familiar everyday items, as opposed to technical concepts, allows students to make this comparison in an accessible example, and translate that experience into considering their technical communication.

B. Communicating Design

One of the most important technical skills for engineers is arguably communicating design. Communicating design is a complex process that involves multiple parties: those who need the design (the user/client), those who actually create the tangible design in final form (the builder), and those who create the conceptual/schematic design (the designer).

This activity focuses on the designer-builder communication, with the user/client interaction addressed in post-activity debrief. Student pairs sit back-to-back. One student, the *builder,* should have a flat working surface. The builder is given a Tangrams set, and their partner, the *designer,* is given a depiction of an unsolved Tangrams puzzle. Neither is to share materials with their partner. Tangrams are sets of geometric puzzle pieces that can be arranged to make a variety of figures. In an unsolved puzzle, the designer can only discern the final figure but has no information on how to assemble it. In a solved puzzle, lines provide indicators of how the different geometric shapes fit together to create the final image.

Depending on time constraints and final objective, the activity can be run any number of 5 distinct rounds, with differing guidelines for each. In the first 4 rounds, neither designer nor builder can look at what the other has. These rounds, in the order they are used in the TPC course, are as follows: (i) only the designer can speak, and the puzzle is unsolved; (ii) same conditions as round 1, but now the builder can also speak; (iii) designer and builder switch roles, otherwise the same rules as round 2; (iv) designer is given the solved version of the same Tangram puzzle; (v) designer and builder work together on an unsolved puzzle, where both can see what information the other has.

Designers and builders are asked to rate their confidence between rounds, and confidence generally increases with each progressive round. The post-activity debrief highlights successful, and unsuccessful, strategies, such as word choice in description. We also highlight how rounds 1-3 are especially difficult because the designer does not know the solution and is essentially "shooting in the dark." This is related to understanding the design problem, and realizing that sometimes the client/user, designer, and/or builder might not understand the problem or have the same perspective on it. We end with a discussion on how clear communication between all involved leads to the best outcomes.

C. The Nature of Problem Solving

To many students, problem solving is equated to solving the "plug and chug" style problems they often encounter [12, 13]. This is a gross misconception, and this "River Game" activity is designed to highlight some of the realities of problem solving. It has been used in a variety of technical and non-technical courses, including senior design.

The purpose of the "River Game," adapted from a free online game, is to develop a process for getting a group of 10 people across a river with a boat, considering a variety of constraints. Participants are usually split into groups with enough people to represent each of the characters that need to get across the river. The large group serves two purposes: (i) participants must navigate working together and (ii) participants who recognize the mapping between the group size and number of people in the problem can try solutions by simulating the scenario in their group.

Students are given 10-15 minutes for problem solving. This is intentionally short to force participants to think hard about their solution strategy. Most groups usually do not finish, and the class works together with the instructor/facilitator to solve the problems. There is then a debrief at the end to discuss the main lessons: real problems have goals and constraints, real problems are ambiguous, changing assumptions and constraints opens up new solution possibilities, and problem solving is a non-linear process.

D. Recognizing Diversity and Adapting to Achieve Common Goals

The activity used to address diversity is a two-part process. The first is an adaptation of the culture game "Bafa' Bafa'" [14] where students are divided into two cultures that have clashing aspects. Both cultures are based on trading and strive to obtain currency. However, they have several cultural differences: (i) their methods of communication during trades, (ii) norms of interpersonal interaction, and (iii) the qualities they value in others. The students are divided into cultures and given about 10 minutes to privately (as a culture) learn and practice their cultures' behaviors. Each culture sends an observer to watch the other culture in action and report back. The groups then interact for about 15-20 minutes. At the end, the groups are debriefed first separately by culture, then together.

The main lessons of this activity are: (i) differences in background and culture can hinder attempts to achieve a common goal (in the activity, trade, in a professional setting, solving an engineering problem); (ii) the perceptions of culture shaped by our own experiences can misrepresent the aspects of the culture we do not understand. In the game, cultures have intentionally opposing standards for good and undesirable or offensive manners. Hence, during the separate group debrief, groups will tend to describe actions of the other culture as "rude" or "insulting" whereas these actions in the other culture are considered acts of politeness. In the TPC course, the activity usually concludes here with the aim of raising awareness and encouraging reflection on this issue that can be carried into professional life.

The EHE course takes the activity one step further to mitigate the issues identified with cultural differences. This is done through a think-pair-share-square where students seek common ground, first as pairs, then as pairs of pairs (square). The purpose of this activity is to emphasize that people often share some common ground that can be a starting point for dealing with conflicts stemming from differences.

V. The NAE Vision in Technical Courses

While effective and successful, these elective courses only reach a self-selected subset of students. To truly integrate the NAE vision into engineering education, these same philosophies need to appear in technical courses. Here we describe how the same philosophies manifest in some of our technical courses as we work to prepare the Engineer of 2020.

A. Description of Technical Courses

We describe two technical courses that incorporate some of the same philosophies from the non-technical elective courses described earlier to help students understand technical concepts. Both technical courses also make frequent use of kinesthetic learning experiences. These experiences become analogies that students can draw on as concepts are developed. The courses are described briefly below.

1) Embedded and Cyber-Physical Systems: This is a junior level core course in the ECE curriculum. It involves designing the computer-based systems that are "embedded" in many of the things we interact with, from household appliances like microwaves to more complex safety-critical systems like cars and aircraft. The course follows Fred Brooks philosophy[11] that

> the hard part [what he calls the "essence"] of building [systems] is the specification, design, and testing of the conceptual construct, not the labor of implementing it and testing the product [what he calls the "accidents"]; we will still make implementation mistakes, to be sure, but they are fuzz compared to the conceptual errors in most [systems].

The course helps students develop systems thinking skills and uses the same kind of kinesthetic learning experiences used in the other described elective courses to develop the ideas and concepts for the students.

2) Equilibrium Stage Processes: Otherwise commonly known as separations, this is a required core chemical engineering course that focuses on equilibrium-based separation processes. Taken the first semester of the junior year, it is a "half course" with two 52 minute lectures and one recitation each week. Separations are essential to any manufacturing process, and separation units are typically the largest cost in plant design. Thus, this course focuses on understanding principles of separation processes, with an emphasis on separator design applications. Students are evaluated on their general understanding and ability to achieve the stated goals of a given problem, with consideration of real-life consequences of any errors. This connection between the in-class problem and the potential real outcomes allows students to recognize the varying importance of error.

B. Kinesthetic Activities for Learning Technical Content

The central theme of the activities described is that the students play a physical role as a part of a system to simulate its behavior. These role plays serve as analogies that students can draw from when thinking about the engineering ideas [15, 16]. We draw on this experience of "being the system" to discuss the engineering ideas that surface and their application to the technical problems they will encounter.

1) Examining systems concepts: This activity helps students understand various ideas in systems thinking by simulating two familiar systems. The first system is a restaurant where there are guests, a waiter, and a cook. Each role has specific instructions governing resources and interactions. The second system is a fast food establishment in the style of a Chipotle or Subway where guests construct their meal from a number of available items. Students not playing a role in the activity are asked to make note of interactions. Those playing a role are also asked to take note of their interactions with others and to write their observations down at the end of the role play. Through guided questions, the role play allows students discover a number of concepts, including that systems consist of entities that produce outputs (e.g., food) by reacting (e.g., preparation and delivery of food) to inputs (e.g., orders). The other main point of the exercise is to impress upon students that sometimes humans can be considered part of (or the full solution to) a problem. Since this is a course in the ECE department students are inclined to think that the solution to any design problem must be a circuit or a piece of software, which may not always be true.

2) Be the system, know the system: In equilibrium stage processes, students often struggle with grasping the differences between dilute and concentrated systems. A highly non-traditional activity has proven to be useful in clearing this up. Students model a "mixer-settler" liquid-liquid extraction system by physically being the system components (diluent, solvent, or solute), and get to experience firsthand the difference between a dilute and concentrated case. "Mixing" is simulated by having students move around when music is playing, and then "settling" by reorganizing by phase when the music stops. The actual separation occurs in the mixing phase, when solute particles move from associating with diluent, to associating with solvent. This activity is used after dilute extraction has been discussed in detail, but before solution methods for concentrated extraction has been introduced.

VI. Student Responses

While we do as a general practice collect student responses to activities for our own use, we can only report very general sentiments from students because we did not originally intend to publish results on these courses and hence did not seek prior IRB approval for sharing student data.

In some instances, particularly in the technical courses, there has been some initial student resistance to these techniques. In the technical courses, such approaches conflict with student perceptions of "technical" content. We also hypothesize that this resistance is, in part, aggravated by the fact that we are young faculty, and relatively new to the institution. In the elective courses alternative pedagogy is not as surprising and better received.

Overall, students do come to see the value, even in the technical courses. Students have commented that this approach has helped them to think in new ways and found it to be an engaging way to learn. For many, the benefits of these approaches may not manifest until after the course is complete and their personal engineering experience catches up with aspects of the philosophy we have tried to instill.

The elective courses have been well received by the students who take them, and the courses particularly benefit from both a small class size and an early establishment of "course culture." We make it clear from day one that this is not your typical course, and it requires a great deal of active participation and engaged thought. Students from both elective courses have commented that the course should be a requirement, rather than an elective—the highest compliment we can ask for.

VII. Recommendations for Implementation

There are a number of considerations when deciding whether to use a kinesthetic activity to supplement student learning. These include: (1) *What are the main ideas or points you are trying to get across in your lesson or course?* We have found that these activities work best when there are several main points that can be extracted from the students' kinesthetic experience. These can then be referenced throughout the course to underscore the underlying concepts. (2) *Would having the students go through a particular experience they can refer back to work better than some alternative?* We have found that kinesthetic activities work best for: (i) difficult to grasp concepts that can be "brought to life" and (ii) fundamental principles or concepts that we want to be able to reference throughout the course. A kinesthetic activity tends to be a more memorable experience, and thus more easily referenced than other course experiences. (3) *What is your class size, and what resources do you have to be able to manage such a session?* Some activities may require more facilitators for larger classes, or may be infeasible in a specific classroom space. (4) *How much classroom time do you have for the activity and follow up?* Some activities require in-class prep (e.g., setup). In general, the activities we have described here take anywhere from 10-15 minutes, to the full 52 minute class period. Several can be adopted for different time constraints and learning objectives.

In our classrooms kinesthetic activities are typically used to introduce an idea and serve as a reference point. We start a particular topic with the activity, pull out the takeaways with the follow up and continue to expand on the topic, referring back to the relevant parts of the activities as analogies to help explain particular concepts/ideas. We believe they have been useful in engaging our students in difficult and abstract concepts, as well as broadening their perspective as we teach the Engineer of 2020.

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