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Incorporating a Product Archaeology Paradigm Across the Mechanical Engineering Curriculum

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ABSTRACT

Historically, the teaching of design theory in an engineering curriculum has been relegated to a senior capstone design experience. Presently, however, engineering design concepts and courses can be found through the entirety of most engineering programs. Educators have recognized that engineering design provides a foundational platform that can be used to develop educational strategies for a wide array of engineering science principles. More recently, educators have found that product archaeology provides an effective platform to develop scalable learning materials, strategies, and educational innovations across these design courses. This paper presents and discusses how product archaeology has been incorporated at a large research university in two design-related courses for mechanical engineering students: (1) a sophomore-level course and (2) a senior-level class. More specifically, details are reported regarding how and how easily global, societal, economic, and environmental factors were emphasized in the curricula of these courses. Next, the paper shares the qualitative and quantitative assessment tools and methods used to determine the impact of incorporating a product archaeology paradigm in the courses. Finally, the results are reported which demonstrate a significant increase in the students' perceptions across a number of skill and knowledge areas related to ABET-required Outcome h without negatively impacting other important academic areas. Results demonstrate a significant increase in student perception across a number of skill and knowledge areas critical to the next generation of engineers.

Key Words: product archaeology, design theory

INTRODUCTION

Even though design education historically has been incorporated into the engineering curriculum in upper level mechanical design courses or in senior capstone design experiences, there have been recent trends to incorporate activities that promote engineering design concepts through the entirety of most engineering programs [1]-[4]. The promotion of engineering design across the curriculum provides educators more opportunities to address the global, societal, economic, and environmental (GSEE) factors in designing engineering solutions. Globalization, economic turmoil, environmental resource limitations, and interconnected societal concerns are creating challenges that require engineers to have a much broader perspective on their profession than they needed even ten years ago.

Since 1996 the ABET Outcomes Assessment Criteria have offered a set of guidelines to assure that engineers are equipped to be successful leaders able to meet the challenges of this new world [5]. Among the most vital of these criteria is Outcome h: the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context. Properly understood, Outcome h goes far beyond contextual awareness. It provides the bond between virtually all other ABET outcomes, linking the profession's traditional strengths in scientific knowledge (Outcome a) with design (Outcomes b and c), multidisciplinary teamwork (Outcome d), and knowledge of contemporary issues (Outcome j). Outcome h is more important than ever for engineering education because such GSEE issues have become critical for preparing, engaging, and retaining the nation's best students [6]-[7].

Yet, many engineering departments still find it challenging to meet the requirements of ABET Outcome h. Providing engineering students with useful and engaging educational experiences targeting the GSEE impacts of engineering solutions is a difficult task that entire teams of faculty are working to address. Possible course approaches include early cornerstone design courses aimed at engaging students in their freshmen and sophomore years, or later synthesis-level design courses targeted at juniors or seniors. However, a number of other ABET outcomes are typically being fulfilled in those courses, resulting in an ineffective "catch all" course with limited exposure to these increasingly important topics. For example, a first-year design course at Trinity College is used to assess all ABET outcomes except Outcomes h and i [8]. At Purdue no courses, only extra-curricular activities, were used to assess each of the ABET outcomes; however, those conducting research were not able to make any conclusions for Outcomes h and decided there was a need for "further analysis" of this outcome [9]. While study abroad has also been another common response to provide a more global, socially sensitive context, current economic conditions have impacted students' and universities' ability to engage in such experiences [10]-[12].

Briedis noted that the assessment of Outcome h was "less straightforward" than the other professional outcomes and as a result a new course was to address this outcome directly [13]. This strategy was employed instead of using humanities and social sciences general education courses to assess Outcome h. However, most departments do not have the flexibility or room to develop a new course specifically to address any single ABET outcome, much less Outcome h. As a result, most departments relegate this requirement to their senior capstone design experience along with many other ABET outcomes [14]. The end result is a course that often does too little while trying to do too much. The importance of the GSEE issues is being heightened by the emergence of design innovation as a critical capability in addressing a number of technical, economic, environmental, and societal challenges around the globe [15]-[16]. This paper addresses the challenges of teaching and assessing the required materials to fulfill Outcome h, leveraging *product archaeology* as the core curriculum paradigm.

PRODUCT ARCHAEOLOGY

The concept of *product archaeology* (PA) was first introduced by Ulrich and Pearson [17] as a way to measure the design attributes that drive cost through analysis of the physical products themselves. Shooter and colleagues advanced the archaeological aspects of dissection by combining excavation (literally "digging in the sand to find parts") with a WebQuest they developed to enhance middle school students' awareness of and competency in engineering [18]. More recently, PA was defined as "*the process of reconstructing the lifecycle of a product—the customer requirements, design specifications, and manufacturing processes used to produce it—to understand the decisions that led to its development*" [19], and others have adopted PA as a pedagogical paradigm. By considering products as designed artifacts with a history rooted in their development, engineering educators are able to synthesize concepts from archaeology with advances in cyber-enhanced product dissection [20]. This synthesis enables the implementation of new educational innovations that integrate GSEE factors into multiple engineering design-related courses using PA.

Archaeology is at the intersection of science and humanity; like engineering, it uses practical observations and scientific experimentation to observe, experiment, and draw conclusions. The imagery typically associated with archaeology is of archaeologists in the field, using tools to dig in the dirt hoping to recover and analyze artifacts that help them understand the sociocultural history (i.e., the beliefs, practices, technological capabilities, etc.) of the location's previous inhabitants. An archaeologist creates an archaeological record "to reconstruct life and culture of past ages through the study of objects created by humans, known as artifacts" [21]. Although archaeologists use a variety of tools and methods in their work, their approach to working on a new site can be generalized into four phases: (1) *preparation*, (2) *excavation*, (3) *evaluation*, and (4) *explanation* [22].

Typical *preparation* activities for an archaeologist include researching the known history of the inhabitants and taking photographs to assess the layout of the site. The *excavation* phase is associated with the stereotypical image most hold for archaeology; this phase often includes time spent digging and exploring the site. During this exploration an archaeologist looks for artifacts and other relevant evidence of its previous inhabitants. The *evaluation* phase includes the analysis and testing (e.g., chronological analysis via carbon dating) of the artifacts. Based on the evidence that is obtained, archaeologists conclude the study by developing suitable conjectures to form an *explanation* of what transpired at the site drawing from a wide range of existing theories (e.g., migration, diffusion) [22]. These conclusions consider the GSEE factors that shaped the community and artifacts. A similar approach can be leveraged in engineering education if consumer products are taken as the artifacts under investigation. Students first determine and consider the time period in which the product was developed, and then dissect the product. Once dissected, students can conduct material tests, look for signs of specific manufacturing processes, identify how components interact, etc. Once this information is gathered, students then identify which GSEE factors likely influenced the final product design along with technical reasons. The pedagogical analogy between archaeology and product dissection as an engineering education tool is summarized in Figure 1.

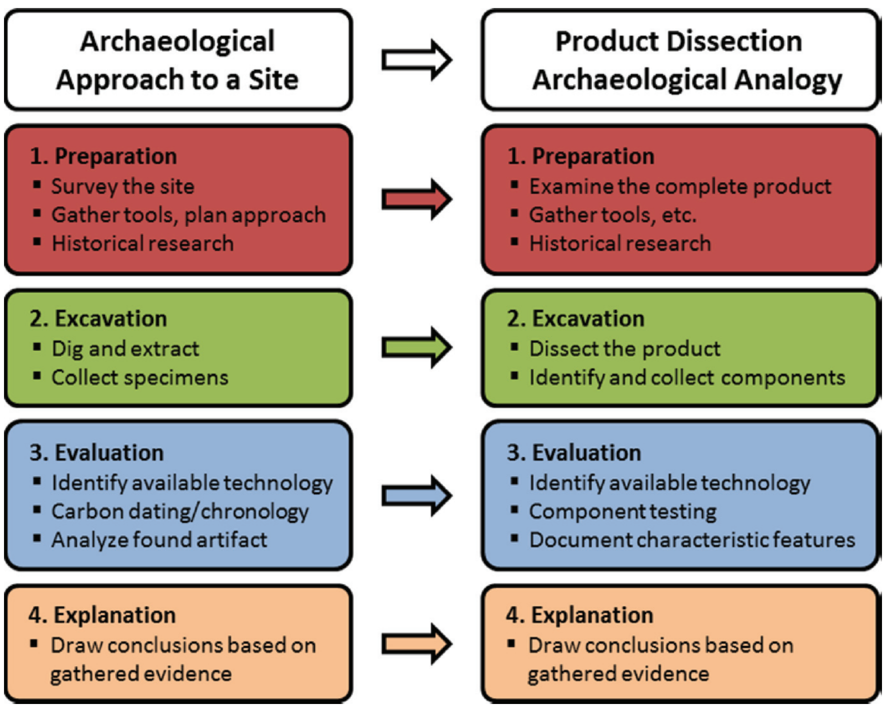


Figure 1. Product dissection Archaeological analogy.

The PA paradigm provides an opportunity to study not only the development and manufacturing cost (i.e., economic issues) of a product but also the global and societal context that influenced its development. It also provides a context for studying the environmental impact of a product by considering the product's energy and material usage throughout its life cycle. When implemented in an engineering classroom, PA allows students to place themselves in the minds of designers during the time a specific product was developed to try to recreate the conditions that influenced the development process.

Before studying how GSEE factors can be integrated into introductory engineering courses using the PA paradigm, the pedagogical framework is presented in the next section, and the PA paradigm is established in the context of this framework. Then brief summaries of the two implementation courses are presented and the results of the assessments are discussed.

PEDAGOGICAL FRAMEWORK

There is a logical analogy between product dissection and PA activities. This analogy is used to create an educational framework for PA that relates PA activities based on the level of the students involved in the activity. An overview of this framework is shown in Figure 2, first presented in [19] and then studied and implemented in more depth in [23]-[26].

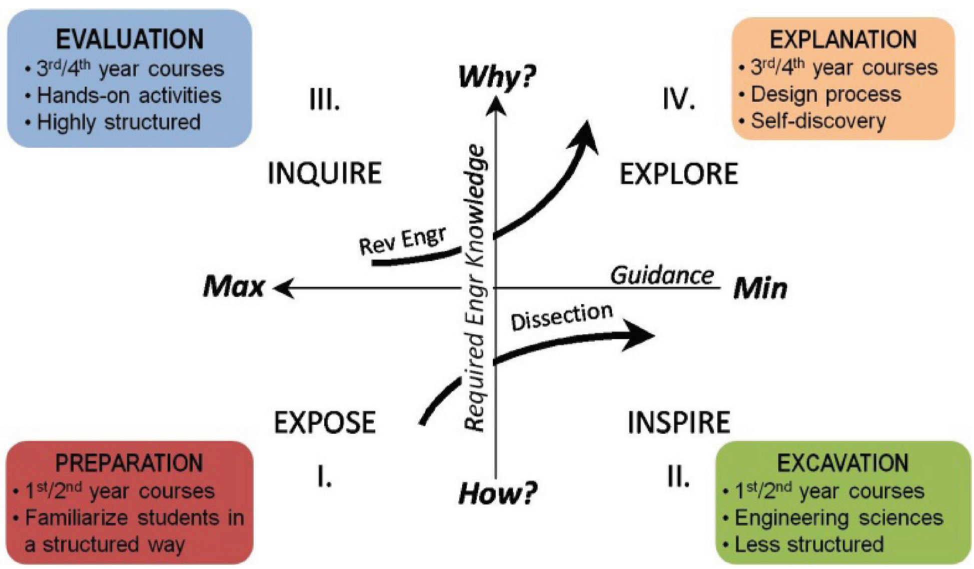


Figure 2. Product archaeology framework.

The framework utilizes a two-dimensional axis system. One dimension represents the amount of instructor guidance, ranging from minimal to maximal. The other dimension represents the student's knowledge of engineering, ranging from students being able to answer procedural questions (e.g., *how* does the device work?) to more explanatory, contextual questions (e.g., *why* did designers choose this material?). The *Expose-Inspire-Inquire-Explore* quadrant lexicon is based upon the original product dissection-based framework presented in [27]. The level and type of activity for each quadrant are described as follows:

1. ***Expose*** – These activities are best suited for lower undergraduate courses so students become familiar with products, learn engineering vocabulary and terminology, and overcome any anxiety with engineering; such activities must be highly structured to ensure proper progress through the activities.
2. ***Inspire*** – These activities are useful in lower undergraduate courses to introduce students to design, including computer-aided design tools or to reinforce fundamentals from engineering courses such as statics and mechanics of materials; such activities are usually less structured to promote self-discovery.
3. ***Inquire*** – These activities are primarily used in upper undergraduate courses to provide students' experience with hands-on activities that reinforce engineering principles and theory; such activities are usually highly structured to ensure that the material is covered properly.
4. ***Explore*** – These activities are appropriate for upper undergraduate design courses to support students' idea generation, redesign, and benchmarking as well as their application of 'core' engineering knowledge; such activities usually require very little supervision since they are intended to foster self-discovery.

The four phases of the PA framework act as a roadmap for curriculum developers as they attempt to employ tangible strategies that allow opportunities for students to be exposed, be inspired, inquire, and explore new products. In this way instructional tasks can be assigned across the curriculum allowing students to learn how GSEE factors play key roles in how products are designed and manufactured. This framework has been integrated with the Kolb model of experiential learning to guide future pedagogical developments. Kolb argues that learning is a four-stage process involving: *reflective observation*, *concrete experience*, *abstract conceptualization*, and *active experimentation* [28]. It was originally proposed in [19] and studied further in [23]-[26] that Kolb's four stages of learning can be mapped to the four phases of archaeological exploration as shown in Figure 3.

During the *preparation* phase students engage in *reflective observation* about products, their designs, and the GSEE factors that impact their design. The *excavation* activities serve as *concrete*

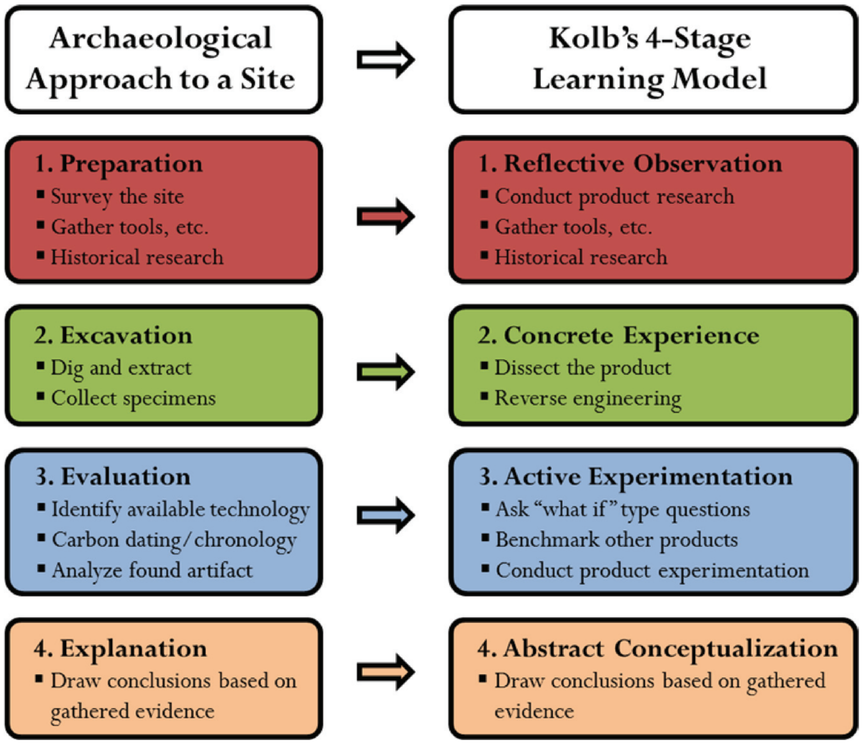


Figure 3. Mapping archaeological exploration to Kolb's model.

experiences where students physically dissect products and begin to develop well-reasoned answers to specific design-related questions. In the *evaluation* phase students engage in *active experimentation* with products and materials; they ask "what if" questions (often prompted by GSEE factors) and then explore possibilities, many times comparing and benchmarking products in the process. The *explanation* phase provides opportunities for students to engage in *abstract conceptualization* as they theorize meaning from their research, the research of others, pertinent theories, and their concrete dissection experiences all the while reflecting on the product in the context of how GSEE factors influence design decisions.

It is important to embed explicit opportunities for students to reflect on their experiences and, based on these reflections, abstract ideas regarding how components function, the reasons for their geometry, and how they were manufactured, considering both technical and GSEE factors. In this way, our pedagogy and assessment mechanisms provide a holistic learning experience with equal emphasis on the four learning modes in Kolb's model. In the remainder of this paper the application and assessment of this model in both a sophomore level introduction to mechanical engineering course and a senior level engineering design course are discussed.

COURSE DESCRIPTIONS

The two courses selected for implementation represent the bookends of the required mechanical engineering curriculum at the University at Buffalo-SUNY. The lower level course is the first required mechanical engineering core course while the upper level course is the final required mechanical engineering course (outside of a design project experience).

Lower Level Introductory Course

MAE277: *Introduction to Mechanical Engineering Practice* is a sophomore-level course with an annual initial enrollment of approximately 140 students (see Table 1 for respondent details). The purpose of this lower-level course is to introduce the basic tenets of professional and ethical practice as a mechanical engineer while emphasizing the role of engineers in making system level decisions; this is grounded by introducing the concept of engineering design and the design process. It is through the lens of engineering design that students are introduced to basic estimation, modeling, and analysis techniques. While these concepts are reinforced through in-class exercises and homework assignments, the core of the course is a semester-long product dissection project.

MAE277 includes both a large lecture component and a laboratory component. In the laboratory, students perform their dissection projects in groups of four to six members. The group members dissect and analyze their assigned products, presenting major findings to their peers at the end of the process. These products range from consumer electronics to automobile engines. The project follows a gated process which is aligned with Kolb's four-stage learning model. This relationship along with the corresponding PA phase for each gate is shown in Table 2.

	Year	
	2009	**2010**
Total Respondents	126	102
Male	101	86
Female	14	7
Not Reported	11	9

Table 1. MAE 277 respondent variety.

Kolb's 4-Stage Learning Model	Project Gates
Reflective Observation	**1: Preparation and Initial Assessment** Students research their assigned project and perform an initial assessment of the product, how it works, and the tools needed to dissect it.
Concrete Experience	**2: Product Dissection** Students dissect the assigned product, gather and document detailed information on the components it utilizes, the connectivity of components, and the overall assembly of the product.
Active Experimentation	**3: Product Analysis** Students analyze components, their materials, shapes, etc. in relation to other possible options and in relation to the functionality and performance of the product.
Abstract Conceptualization	**4: Product Explanation** Students synthesize the information they gathered to draw higher-level design decision conclusions.

Table 2. Project gate alignment to Kolb's stages.

Upper Level Design Course

The senior design course, MAE451: *Design Process and Methods*, is a required upper undergraduate course with an annual initial enrollment of approximately 170 students. MAE451 is a lecture-only course, focusing on teaching the fundamental theories of a design process, starting from problem clarification to product support. The design process representing the core of the semester activities is shown in Figure 4. Half of the course grade is based on individual homework, a final exam, and a design portfolio. The other half of the grade is based on group project work.

The groups engage in a set of month-long design projects developed to address GSEE factors leveraging three of the global issues outlined in the National Academy of Engineering's Grand Challenges [29]. The pedagogical focus is on the *explanation* phase of the PA framework, although in the process of designing and drawing conclusions, the students must perform tasks and experience opportunities related to the other three phases: *preparation, excavation,* and *evaluation*.

The design projects addressed three topics. In the *Making Solar Energy Economical Project*, students have the opportunity to understand how GSEE factors impact customer requirements. The *Provide Access to Clean Water Project* offers students opportunities to understand the GSEE factors which impact the development of design concepts. As a part of the *Restore and Improve Urban Infrastructure Project*, students experience opportunities to understand how GSEE factors impact the process of embodying design solutions.

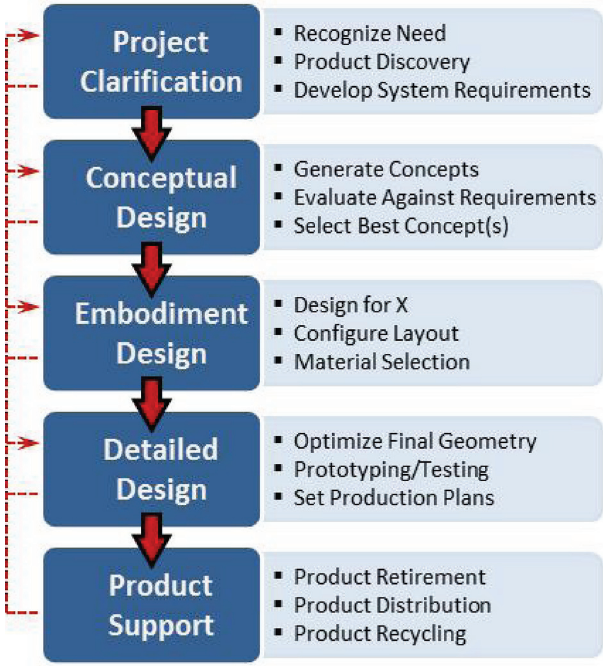


Figure 4. Design process.

The project descriptions can also be accessed with the teaching materials found at: www.productarchaeology.org. The projects progressively allow the students to experience more of the design process in Figure 3. For instance, in the solar energy project, the deliverable is simply the design problem including all the customer requirements and engineering specifications. Students must consider GSEE factors in the development of their customer requirements. In the clean water project, the students must perform all the same tasks as the solar energy project, but must also develop a conceptual solution to the problem. In the urban infrastructure project, the students must perform all the same tasks as in the clean water project but must also embody and detail their design solutions. All semester, emphasis is placed on innovative, multi-cultural, scalable, environmentally aware, economically feasible, and globally relevant solutions with significant social impact.

IMPLEMENTATION

Although there has been significant work to integrate GSEE factors into the engineering curriculum, these terms have a different meaning for different people. In this section the definitions for the GSEE factors are discussed to provide context for their integration into mechanical engineering courses. First, the structure of the sophomore-level course is discussed and the integration of the GSEE factors using PA as the driving paradigm is examined and then a similar treatment is applied.

Lower Level Introductory Course

This section highlights how the GSEE factors were integrated into the existing structure of the reverse engineering project. Additional emphasis was done through lectures, in-class activities, and course examinations; however, the focus of the course is on the reverse engineering project. In this section, how these factors were integrated into the project using the four project gates outlined in Table 1 is described.

Gate 1: Preparation and Initial Assessment

In the first set of project tasks, the student groups had to assess a number of product issues before dissecting their products. Analogous to preparing an excavation site for digging, the students were asked to define the history of the product (including when it was produced, its intended customer, and the companies involved in its development), to estimate the number of distinct components in the product, and to determine what kind of tools are necessary for the dissection.

In order to direct the attention of the students to the GSEE factors, the following prompt questions were included:

- *What were the key economic and global concerns at the time of development?*
- *In what countries or regions was the product intended to be sold?*
- *What was the intended impact on the consumer and the society in which it was used?*

Although the students were familiar with some of the issues related to global and economic factors, these terms have a different meaning for different people. Therefore, the following definitions were developed and made public for the global and economic factors used in this project gate.

> **Global Factors:** Global factors are defined as *the influences that result from cultural and geographic features specific to a region or originating from the interaction of two or more culturally/geographically distinct regions.* Global factors examine the cultural impact of a product that must be taken into consideration in the design process and the geographic features that influence the design of products and systems.

> **Economic Factors:** Economic factors are defined as *the influences that result from the economic conditions at the time of a product's development and its past, present, and projected sales as well as its support life cycle.* Economic factors consider the costs

associated with a product across the entire lifecycle of the product. Since economic decisions often involve externalities, student responses also tended to address the environmental factors associated with engineering design.

Gate 2: Product Dissection

In the next set of project tasks, the students had to methodically dissect their product, keeping careful journal notes of the steps, tools used, difficulties, and time required. They also had to submit a reflection of the dissection process, while noting insights regarding the GSEE factors from the following prompt questions.

- *How do global, societal, economic, and environmental concerns influence how subsystem connections are made?*
- *Is the product intended to be disassembled? Why or why not?*

While students were familiar with some of the issues related to environmental and societal factors, these terms also have a different meaning for different people. Therefore, the following definitions of these factors for use in this project gate have been developed.

Environmental Factors: Environmental factors are defined as *the influences that result from the product's environmental impact during development, manufacturing, sales, operation and disposal.* Environmental factors are often closely linked to global, societal, and economic factors in engineering decision making. This is because their impact on an organization is often felt indirectly through fines or changing public opinion. Many students recognized and noted in their responses that environmental factors were closely linked to global and societal factors.

Societal Factors: Societal factors are defined as *the influences that result from considering the impact like safety, ergonomics, and lifestyle on the people in a society within which a product is being used*. Societal factors are often closely associated with cultural considerations where culture summarizes the set of beliefs and traditions associated with a specific group of people; societal impacts examine their behavior and actions. Changes to lifestyle are possible within the same set of cultural values and norms.

Gate 3: Product Analysis

In the next set of tasks, the students had to analyze the individual components from the product dissection. They had to determine a number of parameters, including the function of each component, the material used, and how the product was manufactured.

In order to facilitate the consideration of GSEE factors in product function, the students created functional models for their product(s). However, instead of using standard functional models [30]-[31], the functional models were annotated as shown in Figure 5 to identify where there might be potential engineering concerns that arise from GSEE factors; the abbreviations in Figure 5 and Figure 6 are: global (G), societal (S), economic (E), and environmental (V). The students check the factor(s) that would impact a given function and provide further explanation in their report. A blank annotated functional model of a vacuum cleaner, which was created as an example, is shown in Figure 6; the colored boxes indicate which subfunctions contribute to the overall functions.

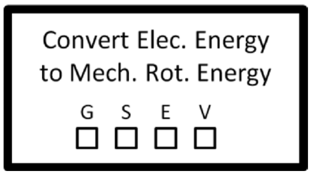


Figure 5. Annotated Function.

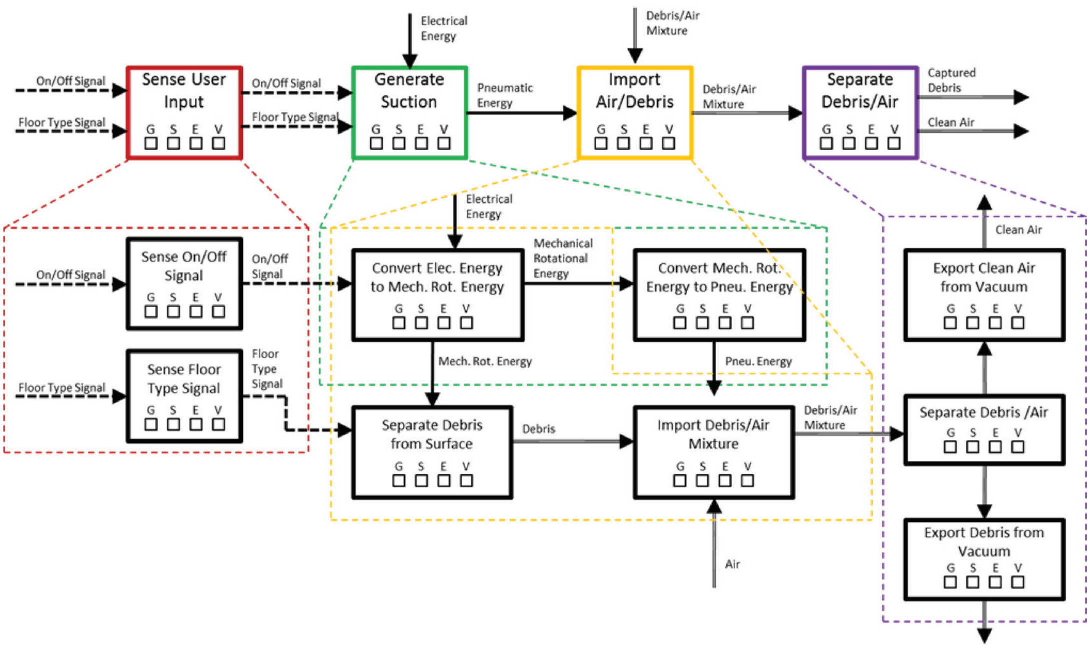


Figure 6. Functional model for a vacuum cleaner [23].

In order to emphasize the GSEE factors associated with the material and manufacturing choices, the following prompt questions were developed.

- *What operating environments do the components function in?*
- *What is the environmental impact of the material used for each component and did this influence the product function?*
- *What is the environmental impact of the manufacturing methods used?*
    - *What evidence supports this?*
    - *Did material choice impact this decision?*
- *What are the economic factors that influenced the choice of material and manufacturing?*
- *How did global and societal factors influence these decisions?*

In addition, the students were required to recommend at least three design changes for the product at the component or subsystem level, including features they would change or eliminate and components they would combine or eliminate. These changes needed to address one or more concerns stemming from GSEE factors, and were meant to improve performance, serviceability, cost, etc.

Gate 4: Product Explanation

In the final set of tasks, the students reassembled their products, following in reverse their documented disassembly process from Gate 2. Any deviations from the reverse of the disassembly process were to be noted and compared to how the students thought the product was originally assembled. Then, once the product was returned to its original state, the students in their report had to reflect on their Gate 1 assessment about product function and component count. This included a recommendation of three or more design changes for the product at the system level, including features they would change or eliminate. These changes needed to address at least one GSEE factor.

Upper Level Design Course

To foster the PA paradigm, a collection of competitive archaeological "digs" was implemented in the upper level design class. In each dig, the class was given "clues" one at a time, simulating an archaeological dig excavation. The clues described an unknown mechanical system and were either word descriptions or a picture of a component. A new clue was given to the entire class, on average, once a day for their evaluation. As a result, the pedagogical focus of these digs was on the *excavation* and *evaluation* phases of the PA paradigm.

For a given dig, each group was only allowed a single guess as to what the system was. These guesses specified the generic system type (*i.e.*, brand and model were not required) but contained no justification or rationale for the guess because it could assist competing groups. The winning group was awarded bonus points, typically 5-10 points on a homework or group project. If a group guessed incorrectly they were eliminated from contention for that dig. Therefore, there was a competitive tension between waiting for more clues and not being beaten to the right answer by another group. The digs were administered completely on Facebook using a page dedicated to the MAE451 course (http://www.facebook.com/pages/Mae451-University-at-Buffalo/266642943347409). Over a given semester, there are approximately ten competitive digs. In Figure 7, a screen shot of one of the semester digs is shown.

Each competitive dig was successfully identified by a student group, with the longest dig requiring 12 clues and 40 group guesses before it was correctly identified; on this particular dig, the first guesses from all the groups in the class were wrong, so the groups were all given a second guess. The history of the verbal clues and guesses for this dig is shown in Table 3 with the correct answer, ***wing flap/aileron system***, shown after clue 12**.** The shortest dig, a VCR, required only one graphical clue and was identified in the first group guess, as one of the students had been repairing his own VCR and recognized the part.

No.	Clue	Guesses	
1	shaft	• vacuum cleaner	
2	lever	-none-	
3	motor	-none-	
4	pulley	• mill/drill press • lawnmower • weed whacker	• onboard boat engine • motorized window blinds • operating crane
5	cable	• elevator • garage door opener	• clothes dryer • electric generator
6	actuator	• aircraft landing gear • automatic transaxle	• laser printer • car • winch
7	limit switches	-none-	
8	rollers	• treadmill	
9	tracks	• tank	• snowmobile
10	linkage	• conveyor system	
11	control rods	• escalator • rotary railcar dumper	• tow truck • forklift
12	bellcrank	• motorcycle • bulldozer • generator • satellite • retractable wheelchair lift/ramp • train locomotive • nuclear reactor	• inkjet printer • excavator • jimmy jib • gondola cable car • roller coaster • remote control car • power windows • ***wing flap/aileron system***

Table 3. The longest archaeological dig.

Figure 7. Facebook "dig".

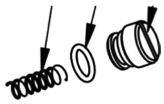
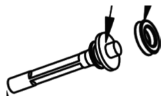
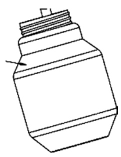
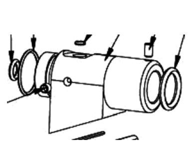
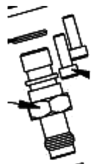
No.	Clue	Guesses
1		-none-
2		• flashlight • laser pointer • hot glue gun
3		• ***air spray paint gun***
4-6		 

Table 4. A graphical archaeological dig.

In Table 4, another of the competitive digs with graphical clues is shown. The correct answer was guessed after the third clue. The next three clues if the correct answer was not guessed are also shown.

RESULTS

In this section the results of incorporating the GSEE factors into the lower and upper level courses are discussed. To assess the implementation of the materials in Section 5, items from the national Prototype to Production (P2P) Engineer of 2020 (E2020) study [32] based on the Engineer of 2020 report [33] and additional course-specific items were used to create a survey.

Lower Level Course Assessment

In this course, the survey was administered at the end of the fall 2009 and 2010 semesters. The fall 2009 students had the same course requirements and grades but were not directly introduced to GSEE factors. The 2009 results were used as a control to compare to the 2010 class who were introduced to GSEE factors as part of the course curriculum as described in the Implementation Section. Some of the course-specific items measured the effectiveness of cyber-enhanced product dissection, the results of which are discussed in [17]. In this paper, the focus is on the portions of the survey that targeted GSEE factors.

The surveys were anonymous and were collected by an individual not associated with the course; this individual also recorded and analyzed the students' survey results. The students were asked to evaluate the extent to which two sets of courses had emphasized four groups of learning objectives: 1) Applying Math & Science, 2) Topics in Engineering, 3) Professional Skills, and 4) Problem Solving Skills. The learning objectives for each group are shown in the Appendix.

Two rounds of surveys were used to isolate the impact of MAE277 on these learning objectives. The first set of items evaluated how much *all other engineering courses besides MAE277* emphasized the objectives; the second set evaluated how much *MAE277 alone* emphasized them. As shown in the Appendix, the items all employed a five-point Likert scale where students were asked to respond based on the emphasis of the course (1 representing little/no emphasis up to 5 representing a very strong emphasis) for the topic in each item. In the surveys there were 4 items directly related to assessing Outcome h, as they address the students' understanding of GSEE factors related to engineering practice. These items are summarized in Table 5 along with two items that were included regardless of GSEE factors instruction; the last two serve as a quality control check to see if the introduction of GSEE factors instruction detracted from other important course topics.

The student items listed in Table 5 were formulated to examine the factor(s) shown in the right hand column. The abbreviations in this column are: global (G), societal (S), economic (E), and environmental (V).

Figure 8 shows the mean response to the items outlined in Table 5, with one standard deviation shown as an error bar. Items 7, 8, 10, and 18, which are aligned with the GSEE factors, show increased positive responses in the 2010 offering of MAE277 compared to the 2009 offering. This suggests that the introduction of the GSEE factors helped emphasize the multidisciplinary topics. The responses for Items 20 and 23 are shown to indicate that the emphasis on GSEE factors did not negatively impact other important areas. While there was a moderate increase in the last two items, it was not statistically significant.

Item #	Survey Item	Related Factor
7	Examining my beliefs and values and how they affect my ethical decisions.	G
8	The value of gender, racial/ethnic, or cultural diversity in engineering.	G
10	Current workforce and economic trends (globalization, outsourcing, etc.).	G, E
18	Understanding how an engineering solution can be shaped by environmental, cultural, economic, and other considerations	G, S, E, V
20	Systems thinking	Quality control
23	Generating and evaluating ideas about how to solve an engineering problem	Quality control

Table 5. GSEE factors survey items.

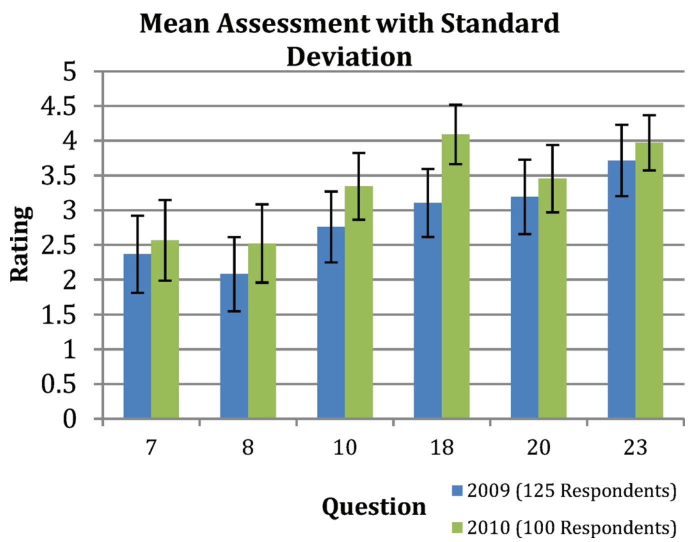


Figure 8. Student response to survey items (Table 5).

Of the 23 topic areas shown in the Appendix, the 2010 offering of MAE277 had a statistically significant impact (with *p*-values of less than 0.05) relative to the other engineering courses on 6 items as shown in Table 6. Paired samples t-tests were used to compare student's responses to items regarding the two sets of courses. To control for multiple comparisons, a post hoc Bonferroni correction was administered. The communication differences noted in Item 14 were likely a result of the semester-long project, which includes a presentation to the class and which requires intra-group coordination and communication. The impact of the GSEE factors is clearly shown in the difference in response to Item 18. To further understand the impact of the GSEE factors, the survey results were compared with the results from the previous year.

Item #	Item	Other courses (mean)	MAE 277 (mean)	*p*-value
5	Ethical issues in engineering practice	2.57	3.94	< 0.001
13	Professional skills (knowing codes and standards, being on time, meeting deadlines, etc.)	3.16	4.04	< 0.01
14	Written and oral communication skills	3.45	4.35	< 0.001
15	Leadership skills	3.05	4.16	< 0.05
18	Understanding how an engineering solution can be shaped by environmental, cultural, economic, and other considerations	2.72	4.27	< 0.05
22	Defining a design problem	3.22	4.64	< 0.05

Table 6. Statistical significance of GSEE factors (MAE277 data for 2010).

Item #	Item	MAE 277 (avg)		p-value
5	Ethical issues in engineering practice	2009	2.71	> 0.05
		2010	3.94	< 0.001
13	Professional skills (knowing codes and standards, being on time, meeting deadlines, etc.)	2009	3.61	> 0.05
		2010	4.04	< 0.01
14	Written and oral communication skills	2009	3.91	< 0.001
		2010	4.35	< 0.001
15	Leadership skills	2009	3.56	< 0.01
		2010	4.16	< 0.05
18	Understanding how an engineering solution can be shaped by environmental, cultural, economic, and other considerations	2009	3.10	> 0.05
		2010	4.27	< 0.05
22	Defining a design problem	2009	3.78	> 0.05
		2010	4.64	< 0.05

Table 7. Comparison of MAE277 data for 2009 and 2010.

Table 7 compares the results from 2010 (when the GSEE concerns were included) to 2009 (before GSEE factors were included). Since the sample sizes differ, Table 7 does not report the difference of means or significance between the two groups. However, the information recorded in Table 6 provides evidence that item means were higher for the 2010 group than the 2009 group. By displaying the information, as is done in Table 6, there are also other nuances that can be noted. For example, the mean in 2010 was higher for item 5 than in 2009. The same is true of item 15. Yet, the difference in *p*-values supplies information on how the means for each year compared to the means for those items when students reported on their other engineering courses.

These results demonstrate that the introduction of GSEE factors improved the emphasis of key concepts related to ABET Outcome h, as can be seen in the responses to Item 18. One additional difference that was not necessarily expected was the difference in response to Item 22, which focuses on defining a design problem. While the course was taught by different instructors, the curriculum did not change significantly enough for this result to be expected. One possible explanation for this is the discussion of GSEE factors helped emphasize the multidisciplinary nature of design. Since the results for females and males were consistent, no gender comparisons are included.

Upper Level Course Assessment

For this course, the survey was administered to the students at the end of the fall 2010 semester. Of the 163 students in MAE451, 100 submitted surveys (survey completion was optional.) Since this was an upper level course, only three of the groups of learning objectives, shown in the Appendix, were studied: 1) Topics in Engineering, 2) Professional Skills, and 3) Problem Solving Skills. As with the MAE277 survey, surveys were anonymous and results were recorded and analyzed by individuals not associated with the course.

The survey was similar in structure to the survey given to the lower level class in that students were asked to respond to items first in terms of *all other engineering courses besides MAE451* and then in terms of *MAE451 alone*. This was done to isolate the impact of MAE451 on these learning objectives. The same five-point Likert scale was used. Paired samples t-tests were used to compare student's responses to items regarding the two sets of courses. To control for multiple comparisons, a post hoc Bonferroni correction was administered. In Table 8, the analysis of the data is shown. The columns display respectively the average score for all the other courses except MAE451, the average score for MAE451, the *p*-value from the hypothesis test, and the rank of the issues in each group based on their statistical significance level within the group. While only the GSEE-relevant issues from the lower level course are presented in the previous section, a broader sampling of issues from the upper level course is presented to ensure that other summative knowledge areas were not adversely affected by the emphasis on GSEE issues. What is evident is that MAE451 placed a greater emphasis on almost every issue compared to the other courses in the curriculum. The only issue that did not have a significant difference was 'How theories are used in engineering practice' in the "Topics in Engineering" set. Each other issue had a significant difference corresponding to a *p*-value of less than 0.001, with the exception of the 'Systems Thinking' issue in the "Problem Solving Skills" set which had a *p*-value of less than 0.01.

Further, the bolded items in each topic represent issues directly relevant to GSEE factors in ABET's Outcome h, demonstrating how significant an impact the new PA modules introduced in MAE451 had on the students' understanding of GSEE issues in engineered solutions. The top-ranked topic in each set directly relates to ABET's Outcome h criteria:

- For "Topics in Engineering", the topic 'Current workforce and economic trends (globalization, outsourcing, etc.)' aligns with the global and economic criteria.
- For "Professional Skills", the topic 'Project management skills (budgeting, monitoring progress, managing people, etc.)' aligns with the social and economic criteria.
- For "Problem Solving Skills", the topic 'Understanding how an engineering solution can be shaped by environmental, cultural, economic, and other considerations' aligns with the social, economic, and environmental criteria.

Item	Other courses (mean)	MAE451 (mean)	p-value	Rank in group
TOPICS IN ENGINEERING				
Current workforce and economic trends (globalization, outsourcing, etc.)	2.70	4.03	< 0.001	1
Creativity and innovation	3.17	4.59	< 0.001	2
Ethical issues in engineering practice	2.57	3.94	< 0.001	3
Emerging engineering technologies	3.26	4.52	< 0.001	4
The value of gender, racial/ethnic, or cultural diversity in engineering	2.16	3.43	< 0.001	5
Examining my beliefs and values and how they affect my ethical decisions	2.48	3.61	< 0.001	6
The importance of life-long learning	3.13	3.94	< 0.001	7
How theories are used in engineering practice	3.79	3.96	0.268887	8
PROFESSIONAL SKILLS				
Project management skills (budgeting, monitoring progress, managing people, etc.)	2.88	4.39	< 0.001	1
Working effectively in teams	3.53	4.62	< 0.001	2
Written and oral communication skills	3.45	4.35	< 0.001	3
Leadership skills	3.05	4.16	< 0.001	4
Professional skills (knowing codes and standards, being on time, meeting deadlines, etc.)	3.16	4.04	< 0.001	5
PROBLEM SOLVING SKILLS				
Understanding how an engineering solution can be shaped by environmental, cultural, economic, and other considerations	2.72	4.27	< 0.001	1
Generating and evaluating ideas about how to solve an engineering problem	3.17	4.64	< 0.001	2
Defining a design problem	3.22	4.64	< 0.001	3
Applying knowledge from other fields to solve an engineering problem	2.70	3.87	< 0.001	4
Understanding how non-engineering fields can help solve engineering problems	2.45	3.81	< 0.001	5
Systems thinking	3.37	3.91	< 0.01	6

Table 8. Impact results and statistical significance for MAE451.

While the P2P survey focused on student perceptions, further evaluation was conducted using an objective assessment of the students' performance. As part of the Department of Mechanical and Aerospace Engineering's preparedness strategy for ABET review, a set of learning objectives for each of the ABET outcomes are assessed. For Outcome h, MAE451 was used to assess the following learning objective: "understand the role and relevance of global and societal concerns in developing engineering requirements." Starting in 2010, this learning objective was accomplished using the PA-based strategies presented in the Implementation Section. Previous to 2010, a completely different set of assignments and group exercises, not based on PA, were used.

In Figure 9, the scores of a sampling of 15 student groups (representing approximately 80 students) from 2010 are compared to a sampling of 15 student groups from 2006 and 2007. In 2006 and 2007, the class did not include the grand challenge mini-projects or the Facebook "digs", and the instruction focused primarily on the major phases of a design process. Reference was

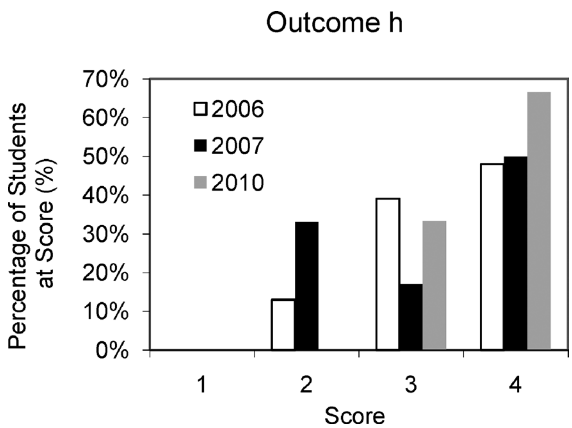


Figure 9. Multiyear comparison.

made to GSEE factors but not in an active learning format as in the 2010 class. While some of the instructional content overlapped between the course offerings, our focus was on measuring the impact of the PA driven pedagogical framework. Data from 2008 and 2009 were not used, as the course was transitioning to its new instructional format. A team of two faculty members collaboratively evaluated the student work each year. Professor Lewis was the common member of this team every year. The evaluators used the following scoring criteria:

- Able to identify societal issues to be considered during development of a given product.
- Able to identify how societal and global issues influence development of requirements and technical specifications.

The evaluation team used the following four-point scale:

4 Meets all or nearly all the criteria
3 Meets most of the criteria
2 Meets some of the criteria
1 Meets few or none of the criteria

Clearly, the students from 2010 scored higher on the Outcome h criteria, quantitatively demonstrating the effectiveness of the PA perspective taken in the instructional materials.

Anecdotally, Figure 10 illustrates the geographic locations where the student groups focused their design and development work across the three projects related to solar energy, clean water, and sustainable infrastructures. The students, through their own research and sharing their findings with the class, were exposed to a wide range of global, social, cultural, economic, and environmental issues. As evidence of the impact of the exercise, one of the groups from the course

Figure 10. Locations of course design projects.

decided they wanted to actually implement their design and raised enough money to send two of their members to Haiti to implement their clean water storage and distribution system outside an orphanage.

CLOSURE

This paper summarizes an effort to incorporate GSEE considerations into lower and upper level mechanical engineering courses. This was accomplished by synthesizing concepts from archaeology with advances in cyber-enhanced product dissection to implement new educational innovations that directly address the challenges of teaching students the GSEE factors associated with ABET Outcome h. Rather than relegating this requirement to an early cornerstone or a later capstone design experience, this issue has been addressed by providing scalable learning materials, strategies, and educational innovations for both lower and upper level courses that develop students' understanding of the broader context of engineering. In doing so, PA has been found to serve as a scalable and sustainable pedagogical foundation for engineering that provides a platform to enrich the limited exposure that students currently receive to GSEE-related issues.

A key contribution of GSEE factors is that they effectively highlight the current state of engineering. Engineering is no longer a profession driven solely by technical issues – engineers must now understand the global implications of their decisions on society, corporate economics, and the environment.

Our activities have revealed some valuable insights that are listed below.

- PA activities provide valuable opportunities for students to experience, evaluate, and implement GSEE factors in an engineering design context.
- At the lower level, exposure to GSEE factors early in the curriculum offers the additional advantage of providing context for more specialized courses which will be taken later in students' academic careers.
- Not only do the PA activities impact the GSEE factors identified in ABET outcome h, they also positively impact many of the other knowledge areas that have been identified as vitally important for the engineers of 2020, as shown in Table 4.
- Qualitative feedback from the students was extremely positive. Representative comments from the upper level course include:
  - *"Most interesting class of the past two semesters. Shows a real application of engineering in the 'real world' and the direction that design is heading."*
  - *"I think this course is a must-have course to be a successful engineer, and it really opened my mind to all the ideas behind innovation and design."*

Current work includes continued development of instructional materials, course plans, and assessment strategies across the entire undergraduate mechanical engineering curriculum and studies aimed at identifying multi-year trends in the results. The PA materials are also being expanded to other fields of engineering. These materials will be disseminated through continuing workshops for faculty and students as well as through the product archaeology website: www.productarchaeology.org.

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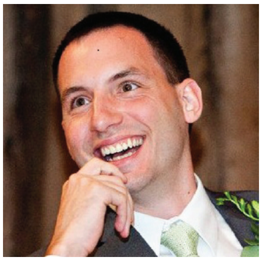

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APPENDIX

#	APPLYING MATH & SCIENCE	Little/no emphasis	Slight	Moderate	Strong	Very strong
1	Math to engineering problems	❍	❍	❍	❍	❍
2	The physical sciences to engineering problems	❍	❍	❍	❍	❍
3	Computer tools and applications to engineering problems	❍	❍	❍	❍	❍
4	Life sciences to engineering problems	❍	❍	❍	❍	❍
	TOPICS IN ENGINEERING	**Little/no emphasis**	**Slight**	**Moderate**	**Strong**	**Very strong**
5	Ethical issues in engineering practice.	❍	❍	❍	❍	❍
6	The importance of life-long learning.	❍	❍	❍	❍	❍
7	Examining my beliefs and values and how they affect my ethical decisions.	❍	❍	❍	❍	❍
8	The value of gender, racial/ethnic, or cultural diversity in engineering.	❍	❍	❍	❍	❍
9	Creativity and innovation.	❍	❍	❍	❍	❍
10	Current workforce and economic trends (globalization, outsourcing, etc.).	❍	❍	❍	❍	❍
11	Emerging engineering technologies.	❍	❍	❍	❍	❍
12	How theories are used in engineering practice.	❍	❍	❍	❍	❍
	PROFESSIONAL SKILLS	**Little/no emphasis**	**Slight**	**Moderate**	**Strong**	**Very strong**
13	Professional skills (knowing codes and standards, being on time, meeting deadlines, etc.)	❍	❍	❍	❍	❍
14	Written and oral communication skills	❍	❍	❍	❍	❍
15	Leadership skills	❍	❍	❍	❍	❍
16	Working effectively in teams	❍	❍	❍	❍	❍
17	Project management skills (budgeting, monitoring progress, managing people, etc.)	❍	❍	❍	❍	❍
	PROBLEM SOLVING	**Little/no emphasis**	**Slight**	**Moderate**	**Strong**	**Very strong**
18	Understanding how an engineering solution can be shaped by environmental, cultural, economic, and other considerations	❍	❍	❍	❍	❍
19	Understanding how non-engineering fields can help solve engineering problems	❍	❍	❍	❍	❍
20	Systems thinking	❍	❍	❍	❍	❍
21	Applying knowledge from other fields to solve an engineering problem	❍	❍	❍	❍	❍
22	Defining a design problem	❍	❍	❍	❍	❍
23	Generating and evaluating ideas about how to solve an engineering problem	❍	❍	❍	❍	❍