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Developing the Critical Thinking, Creativity and Innovation of Undergraduate Engineering Students*

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We present the framework of a novel upper-division undergraduate course that was developed to deliver disruptive and innovative applications of commercial technologies to an external funding agency and simultaneously develop the critical thinking, creativity and innovation of undergraduate engineering students. The course is structured as a deliberate interactive engagement between students and faculty that combines the Socratic method with the Thayer method to develop an understanding of disruptive and innovative technologies and a historical context of how social, cultural, and religious factors impact the acceptance or rejection of technological innovation. We present an assessment of this new course based on a course-end survey, several external indicators, a post-graduation survey and faculty assessment.

Keywords: critical thinking skills; creativity; innovation; disruptive technology; Socratic dialog; Thayer method

1. Motivation and background

For decades there has been a seemingly continuous call for engineering education reform to improve critical thinking, creativity and innovation of engineering students. In 1968, D. V. De Simone from the U.S. Department of Commerce claimed that engineering education stressed the acquisition of knowledge and skills of analysis and effectively stifled creativity and innovation [1]. Others have noted that the rapid increase in scientific knowledge and emerging technologies have placed increased pressures on engineering curricula to expand technical content, often at the expense of creativity, critical thinking and innovation [2, 3]. J. A. Orr and B. A. Eisenstein suggested that innovations in engineering education are necessary to 'prepare engineers for the reality of the global marketplace' and that 'any engineering curriculum that does not address innovation is depriving its students of essential competencies.' [4] Increasingly in this global environment, engineers must possess critical thinking skills to understand the impact of social conditions, human health and the environment on sustainable design and manufacturing [5].

In 2002, the United Nations held the World Summit on Sustainable Development, which resulted in a vision of education 'that retains a commitment to critical analysis while fostering creativity and innovation' [6]. In 2004, the U.S. National Academy of Engineering published *The Engineer of 2020* [7], which envisioned various scenarios for the future of the engineering profession and identified the attributes of the engineer of 2020. The following year they published *Educating the Engineer of 2020* [8], which identified ways to improve undergraduate engineering education and increase innovation, creativity and critical thinking. During this same period in response to numerous curricular reforms to incorporate more hands-on design work into engineering curricula, J. C. Wise et al. conducted a four-year longitudinal study of the intellectual development of engineering undergraduates and found that without curricular innovation, students often lacked critical thinking skills, confidence and creativity [9]. Finally, in 2008 The Millennium Project published *Engineering for a Changing World* [10], which highlighted the importance of technological innovation to economic competitiveness and national security.

While the literature is replete with calls for engineering education reform, research on successful change is far sparser. Those reported can be categorized as modifications to curricula and courses, the addition of new courses, and pedagogical changes. Probably one of the most notable new approaches to engineering education is the engineering curriculum offered at Olin College, which is founded on four basic principles that state that students must have: (1) a superb command of engineering fundamentals and specialized knowledge in their field of major, (2) a broad perspective regarding the role of engineering in society, (3) the creativity to envision new solutions to the world's problems, and (4) the entrepreneurial skills to bring their visions into reality [11]. A model electrical and computer engineering curriculum was proposed in [12] that merges the disciplines of mathematics, science, engineering and computing and includes exposure to human, cultural and professional aspects of the engineering career. C. J. Steiner outlined an optional year of study for engineering and

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science students at Deakin University in Australia with courses focused on traditional and contemporary roles of engineering in science and society, commercial innovation issues, values and practice, innovation skills, and commercial project planning and management [13]. D. H. Cropley and A. J. Cropley reported results from a course entitled: Engineering Innovation and Practice, which included three lectures on creativity and incorporated case studies of creative breakthroughs in engineering [14]. Problem Based Learning is a pedagogical approach that has been integrated into a number of courses to help encourage creative thought [15–17]. Another relatively recent approach to teaching invention, innovation and entrepreneurship centers on the E-Team concept (here 'E' denotes both Excellence and Entrepreneurship) where multidisciplinary design teams include students from outside of engineering [18]. Finally, journal writing and learning essays have been incorporated into a variety of courses to develop creativity, independent thought and a deep understanding of the material [19–21]. This last approach, which is effectively a pedagogy of written dialog, most closely parallels the new course reported in this paper.

2. Overview of the course and course construct

Disruptive and Innovative Commercial Technology Ideation is a 3.0 credit, upper-division undergraduate elective course that initially began with electrical engineering and computer science honors majors and has recently expanded to include information technology and life sciences majors. The course is structured as a deliberate interactive engagement between students and faculty that combines the Socratic method [22] with the Thayer method [23]. Developed from Plato's Socratic dialogues, the Socratic method of teaching is a student-centered approach that develops critical thinking skills by engaging in analytic discussion. The Thayer method is attributed to Sylvanus Thayer, who served as the Superintendent of the U.S. Military Academy from 1817 to 1833 and is considered the Father of the Military Academy. During his tenure, he made a number of foundational changes to Academy standards and procedures including creating a teaching method known today as the Thayer method, which emphasizes self-study and daily homework, as well as small class size. One of the cornerstones of the Thayer method required that every cadet be prepared to answer questions or solve problems in every class every day.

The enduring theme of the course is to develop an understanding of disruptive and innovative technologies and a historical context of how social, cultural, and religious factors impact the acceptance or rejection of technological innovation. To develop this framework, the course is grounded in four classic texts: *The Innovator's Dilemma* [24] by Clayton M. Christensen, *The Structure of Scientific Revolutions* [25] by Thomas S. Kuhn, *The Discoverers* [26] by Daniel J. Boorstin, and *The Two Cultures* [27] by C. P. Snow. Each student independently researches potentially disruptive technologies and prepares a compelling argument of why they believe the specific technologies are disruptive so they can defend their choice and rationale. During course meetings students discuss the course readings and specific technologies found during their independent research. As part of the course, each student is also given the opportunity to interview forward-thinking technology leaders in their respective fields of interest. During the six semesters that the course has been conducted, students have met with the Director of the Defense Advanced Research Projects Agency (DARPA), the Chief Scientist of the CIA, the Chief Technology Officer of MIT Lincoln Laboratory, the Director of Disney's Imagineering, the Chief Scientist of the U.S. Army, and the Vice-President of Research of iRobot, to name a few.

2.1 Socratic dialog and the Thayer method

Unlike most courses in a traditional science or engineering curriculum, this course is structured as a dialogue between students and faculty. Much like the construct of a social science course, each class meeting engages the students in a dialog about the course readings and the specific technologies that each student is researching. This construct, based on the Socratic method, is a dialectic method of inquiry that uses cross-examination of an individual's claims in order to reveal contradictions or internal inconsistencies. Many argue that Socratic questioning is at the heart of critical thinking. Socratic questioning challenges accuracy and completeness of thinking and deepens individual insights and understanding. Additionally, this approach serves to strengthen the student's skills at formulate a logical argument and their ability to effectively engage in a rational, oral debate. Throughout the course, the students are expected to use this approach as they engage in dialogs with other faculty and the technology leaders. Questions like: 'How do you define disruptive technology?' and 'Why do you believe that specific technology is disruptive?' set the stage for a common vernacular from which to then continue the dialog.

In this course, we also incorporate select components of the educational reforms that Sylvanus Thayer brought to West Point in the early 1800s. During his time as Superintendent, Thayer introduced a number of foundational changes that spanned organizational structure, entrance testing, curriculum, small class size, and teaching techniques. Thayer's educational philosophy demanded that every cadet be responsible for his own learning. However, not all of the pedagogical changes that he introduced encourage critical thinking, innovation and independent thought. He required daily grades, rigid recitation protocols, and rote, hard skill-oriented standards of accomplishment rather than encouraging original thought. However, small class size, self-study and daily recitation are mutually supportive of the Socratic method and support the objectives of the course.

Taken together, the Socratic method combined with the Thayer method engages the students in an intellectual dialogue that improves their understanding of the subject material, improves their critical thinking and independent thought skills, and develops their ability to engage in technical debate.

2.2 Disruptive technology

Clayton M. Christensen first coined the term disruptive technology in his 1995 article 'Disruptive Technologies: Catching the Wave' [28]. Later in his book, *The Innovator's Dilemma*, Christensen asks the question: Why do well-managed companies fail? He concludes that they often fail because the very management practices that have allowed them to become industry leaders also make it extremely difficult for them to recognize and develop the disruptive technologies that ultimately capture their markets.

He concludes that well-managed companies are excellent at developing sustaining technologies, those technologies that improve the performance of their products in ways that satisfy their customers. Disruptive technologies, however, are distinctly different from sustaining technologies. They are typically cheaper, smaller, simpler and frequently more convenient to use. Disruptive technologies fundamentally change the value proposition in a market according to a distinct pathology. Christensen suggests that value networks are responsible for disruptive effects. A value network is a hierarchy of component producers and consumers, each operating at price points determined by economic forces within the network. The network as a whole produces a category of finished products, for example, disk drives, earthmoving equipment, or financial software. Disruption occurs when a value network concerned with cheaper products advances, through its own sustaining improvements, to a point where it becomes capable of adequately meeting demand in an entirely different network where price points are significantly higher. When this occurs quickly, which it often does, the disrupted network has insufficient time to adjust, and it usually perishes. Consider the Linux operating system (OS) as an example of a disruptive technology. It employed a new development methodology—Open Source—that was widely viewed as inferior to proprietary forms of software engineering for complex systems. When originally introduced, its performance was also considered inferior to other server operating systems like Unix and Windows NT. But the Linux OS was inexpensive compared to other server operating systems. After years of improvements to its technology, rooted in refinements and the ultimate success of Open Source methods, Linux is now installed in 81.00% of the worlds 500 fastest supercomputers [29].

While *The Innovator's Dilemma* develops the broad framework for thinking about disruptive technologies and understanding the business aspects necessary to recognize and successfully take advantage of them, students gain a deeper understanding of the lessons of the book by applying the concepts to specific applications. In this course, we ask the students to view disruptive technologies through the lens of military applications.

2.3 The structure of scientific revolutions

In *The Structure of Scientific Revolutions*, Thomas Kuhn argues that science does not progress through a linear accumulation of new knowledge, but instead undergoes periodic revolutions, or paradigm shifts in which the nature of scientific inquiry within a particular field is abruptly transformed. He suggests that science can be categorized in three distinct stages. The *pre-paradigm* or *prescience pha*se, which lacks a central paradigm, comes first. In this phase, there is generally no consensus on a single unifying theory and there are multiple incompatible or incomplete theories which scientists pursue. As the scientific community begins to converge and develop consensus on a theory a paradigm emerges. This is followed by *paradigmatic* or *normal science*. During this stage, a paradigm has been accepted by the scientific community and subsequent research consists of applying shared methods to refine and expand the central paradigm. Normal science is characterized by Kuhn as 'puzzle-solving.' Over time, advances in normal science may reveal anomalies, facts that are difficult to explain within the context of the existing paradigm. While these anomalies are generally resolved, in some cases they may accumulate to the point where weaknesses in the paradigm are revealed. Kuhn refers to this as a crisis. At this point, science enters the third phase, that of *revolutionary science*, in which the underlying assumptions are re-examined and a new paradigm that addresses the anomalies is established.

After the new paradigm is established, scientists return to normal science, solving puzzles within the new paradigm.

There are a number of reasons for including this text as one of the foundational components of this course. First, the text allows the students to gain an understanding of the scientific enterprise and process of scientific discovery not present in traditional textbooks. It introduces the concept that scientific knowledge is dependent on the culture and historical circumstances of groups of scientists rather than on their adherence to a specific, definable method. In fact, Kuhn portrays textbooks as a key reason that most people, including scientists themselves, have an artificially simplified and orderly view of scientific progress. Our scientific culture educates next-generation practitioners using these highly refined end products of previous research, wherein the messy human details of development have been scrubbed away. Kuhn, on the other hand, depicts science as a human process—mistake-prone, competitive, argumentative, with personalities and propensities of the researchers themselves playing a significant role in the rate, if not the end results, of progress. His ultimate claim is that we all benefit by recording and studying these details in order to gain a widespread meta-understanding, so that the future road of science might be smoothed and straightened. The *Structure of Scientific Revolutions* probably represents some of the best thinking on how transformation occurs, who drives it, why it is resisted, and what it really asks of people. It is a challenging book for undergraduate students that requires careful and critical reading and thinking. Finally, it is considered one of the hundred most influential books since the Second World War by *The Times Literary Supplement*.

2.4 Social, cultural and religious roles in technology acceptance and rejection

The Discoverers is a non-fiction historical work by Daniel Boorstin, published in 1983. The book, subtitled *A History of Man's Search to Know His World and Himself*, is the history of human discovery. Within the broader context of human exploration, he traces numerous scientific and technical discoveries and identifies obstacles set up by opposing myths, traditions, religious dogma and the dictates of earlier authority. More broadly he includes cultural, societal, and religious influences in scientific discovery and advances. He does a masterful job of documenting discoveries by focusing on an individual and incremental approach to history. The purpose for including this text as a foundational course component is to help the student understand that acceptance or rejection of technological innovations depends on factors beyond the control of the technologist including social, political, economic, cultural and religious factors.

One striking example of technological innovation and its lack of widespread acceptance dealt with shipbuilding and exploration. During the period when Prince Henry the Navigator was just beginning to explore the West coast of Africa, the Chinese had already built massive flotillas consisting of as many as 317 ships and had advanced the state of shipbuilding art well beyond that elsewhere in the world. Bulkheads that divided the ship's hold into compartments to prevent flooding and fires, first employed by the Chinese are believed to have been inspired by the septa, the transverse membranes in bamboo. But the Chinese were not traders, conquerors or crusaders. While the purpose of most other navies was to explore, expand and conquer, the purpose of the Chinese navy was instead to display the splendor and power of the new Ming dynasty. After only a brief and limited seafaring excursion with the most advanced shipbuilding technology of its day, the Chinese reverted to an inward focus. While the Chinese developed the technological innovations necessary to position China as a seafaring nation, capable of exploration and expansion, the Chinese culture and beliefs prevented adoption and further development.

2.5 The two cultures

Charles Percy Snow—C. P. Snow—was an English physicist and novelist. In 1956 he published an article entitled 'The Two Cultures' [30] and later in 1959 delivered the Cambridge University Rede Lecture entitled 'The Two Cultures and the Scientific Revolution' on which the book *The Two Cultures* is based. Snow's thesis was that 'the intellectual life of the whole of western society is increasingly being split into two polar groups,' [31]. 'Literary intellectuals at one pole—at the other scientists. Between the two a gulf of mutual incomprehension—sometimes (particularly among the young) hostility and dislike, but most of all lack of understanding' [32]. Snow effectively argues that practitioners from the sciences and the humanities should build bridges to further the progress of human knowledge and to benefit society. This book reinforces a common theme in the course: to think more broadly about a topic, and particularly about technology innovation acceptance.

2.6 Engagement with forward-thinking technology leaders

An integral component of the course is to provide a venue to extend the dialogue outside of the classroom with forward-thinking technology leaders. The purpose of this component of the course is to provide the students an opportunity to engage in a dialogue with senior technology leaders about disruptive technology, technology innovation and business processes associated with technology development. This component is structured in a way to reinforce the foundational course content while simultaneously providing an opportunity for students to probe more deeply into select technologies. Some of the 'thought leaders' are leaders of commercial and governmental organizations that develop new technologies. From these leaders the students can probe business management and organizational structures that encourages innovation. Others are renowned researchers and professors who have deep technical insights in specific technologies. This second group is identified each semester according to student topical interest and provides the opportunity to gain additional insights about the specific technology that each is investigating.

This last component takes several forms, but the underlying venue remains the same—a one-on-one conversation between the students and the forward thinking technology leaders. Each semester, several trips are organized to allow the students to meet select leaders at their respective organizations. In addition, to supplement these trips, a wide-range of prominent guest speakers are routinely available who can be enlisted to discuss similar business or technical subject areas.

2.7 Written communication skills

The culminating component of the course is a written paper suitable for submission to a conference or journal. The format is a five-to-seven page, two-column paper modeled after a traditional scientific or engineering journal article. Throughout the course, students submit one-to-two page papers on the primary course readings. These papers are critiqued by the faculty and are also peer-reviewed by at least one other student. The peer-review process is generally carried out by a student from a different disciplinary field and provides both students with additional insights into the common reading. These short papers then form the basis of the final paper, which also incorporates the specific technology that the student defines and defends as being potentially disruptive.

3. Course assessment

The first component used to assess the effectiveness of the course was an end-of-course survey with questions that specifically probed several of the course objectives. The following seven questions were included in the course-end-survey questionnaire and form the basis for course assessment:

1. The course caused me to think more broadly about science and technology.
2. I understand the role of society, culture and religion in technology acceptance and rejection.
3. The teaching style used in this course was effective.
4. My critical thinking skills have improved as a result of this course.

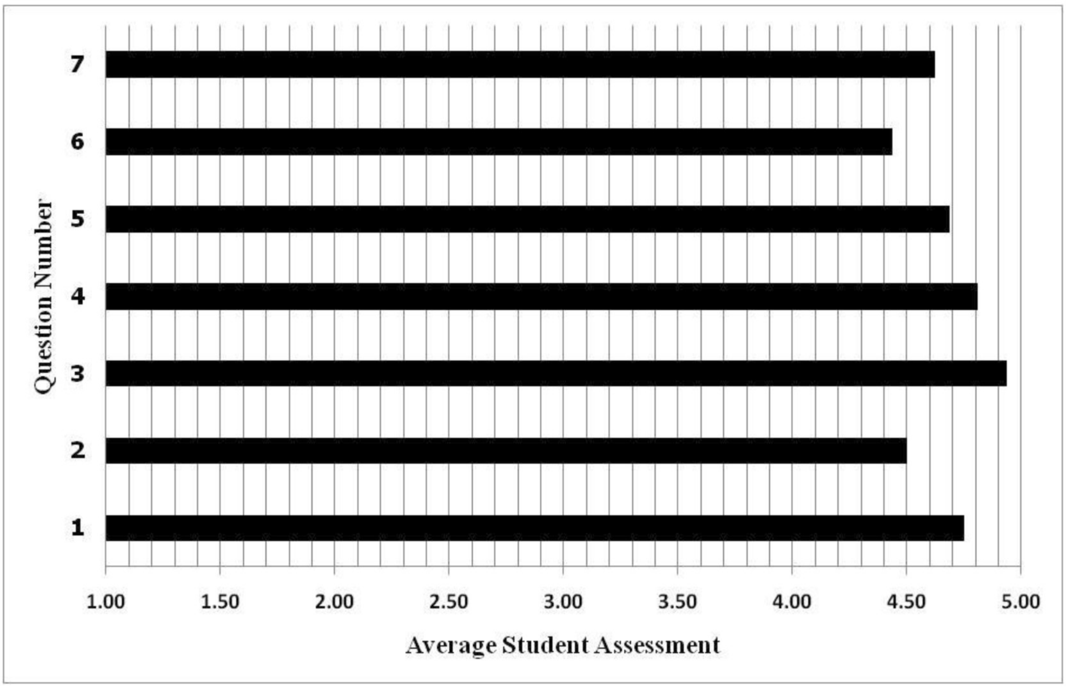

Fig. 1. End-of-course survey results.

5. My technical communication abilities (oral and written) have improved as a result of this course
6. I feel confident in my ability to survey the commercial technology horizon and identify potential military implications and applications.
7. I feel confident in my ability to frame an issue and formulate a logical oral argument.

The scale used to complete the survey was (5)—Strongly agree, (4)—Agree, (3)—Neither agree nor disagree, (2)—Disagree, and (1)—Strongly disagree. Figure 1 shows the average student assessment for these seven questions.

While the total enrollment of 25 students over the three-year history of the course was small, the student assessment of course objectives is positive. It is interesting that Question 3 received the highest evaluation, indicating that the students approved of the teaching style: the Socratic dialog. The two questions receiving the lowest ratings, Questions 2 and 6, are more likely attributed to student experience and the breadth of the question. All students believed that their critical thinking skills improved as a result of the course, one of the core objectives of the course.

An external indicator of student performance is the acceptance of paper submissions reporting research results. In the first two years of the course, students submitted their work to the National Conference on Undergraduate Research (NCUR), an annual conference dedicated to promoting undergraduate research, scholarship, and creative activity in all fields of study [33]. Of six student papers submitted, all six manuscripts were accepted and published [34–39].

Individually, one of the students who participated in the first offering of the course continued the development of his disruptive technology ideation—a low-cost version of the Street View feature of Google Maps—building a prototype that received the Lockheed Martin Award at the 2009 MIT Institute for Soldier Nanotechnology (ISN) Soldier Design Competition and later publishing the results of his work at the IEEE Consumer Communications and Networking Conference [40] and in *Spectrum* [41]. This work is now being developed into a fielded product.

Finally, a post-graduation survey has been conducted that asked the graduates the same seven questions asked in the course-end survey and also asked if the course has affected the way they think about technology and innovation. Figure 2 shows the results from the post-graduation survey.

The post-graduation assessment echoes the results from the end-of-course survey. It is interesting to note that Questions 1 and 3 received an increased average assessment, indicating that the graduates felt that the course caused them to think broadly about science and technology and strongly approved of the teaching style. It is also interesting that with temporal distance from their undergraduate education, graduates feel very confident in their ability to survey the commercial technology horizon and identify potential military implications and applications. Additionally, respondents identified

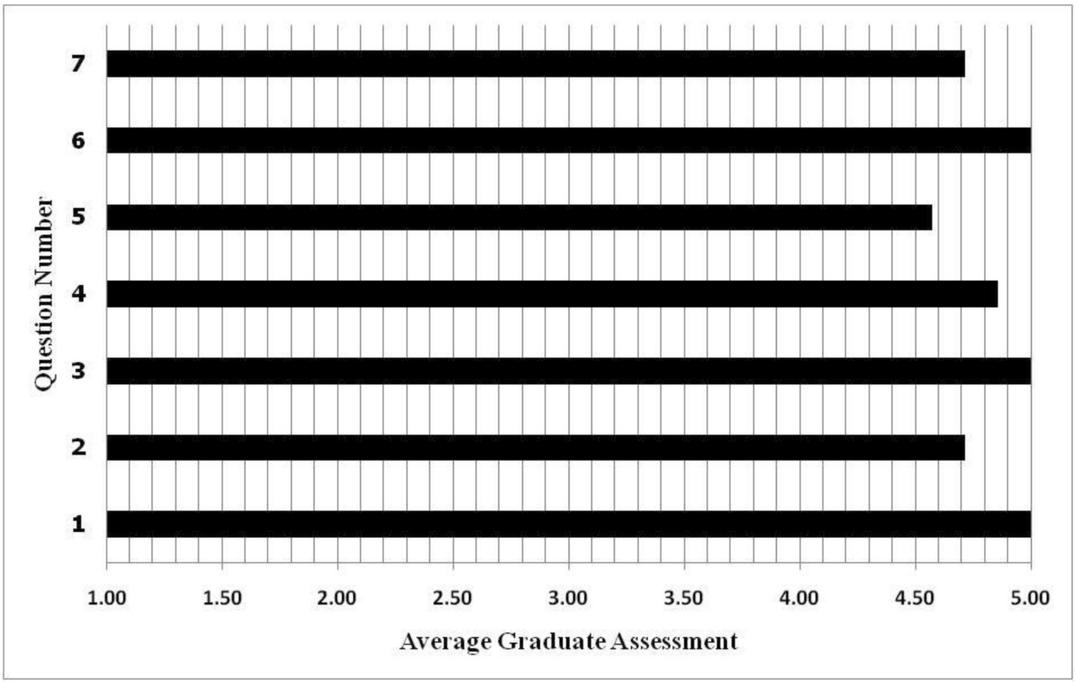

Fig. 2. Post-graduation survey results.

the Disruptive and Innovative Commercial Technology Ideation course as the best course they took during their undergraduate experience. The other common theme was that the course forced them to learn on their own. Specific free-text comments from the post-graduation survey included:

- 'The course made me feel sort of like a scholar because I was in charge of my own learning and required to produce my own critical thoughts instead of simply regurgitating thoughts of others.'
- 'I did feel that I learned more during the disruptive technology class than almost all of my others, as almost all of the learning was individual and covered new material.'
- 'I think more broadly about technology issues and have even started to appreciate humanities majors a little bit.'
- 'I think it is a great course because it forces us to take a step back from our detail-orientated, micro-level studies to take a broad look at technology.'

4. Course insights

There are a number of insights from the development and execution of this course that merit discussion. First, the Socratic dialog approach used in this course is, at first, foreign to the students and therefore they are initially not comfortable engaging in debate, especially with the faculty. However, as the course progresses and the students become more comfortable with the format, they begin to see the merits of the approach as they develop a deeper understanding of the subjects.

An additional advantage of the course construct stems from the diversity of the student's disciplinary backgrounds. This provides diversity of perspective during the class discussions but also presents a challenge for a single faculty member, requiring substantial preparation to engage in the discussions of a wide variety of specific disruptive technologies. This course also provides a tremendous opportunity for students to integrate knowledge of economics, politics, human psychology, historical study methods, and others. This is a strength of the core curriculum at West Point and is an important reason for the success of the course.

While the course as it is currently structured is successful in achieving its goals, the question of scalability must be addressed. Fundamentally, this course is resource intensive, requiring substantial faculty time to prepare and conduct the course. In order to support the Socratic dialog format, the course enrollment must necessarily be small: enrollment beyond about 8–10 students would reduce the impact of the dialog. Additionally, the breadth of the course topical discussions resulting from the diversity of student disciplines requires a senior, more experienced faculty member who is well-grounded in the foundations of physics, chemistry, biology, and their applications to a variety of engineering and science applications.

Finally, the course is substantially shaped by the selection of the course readings. One possible change under consideration is to supplement the course readings with excerpts from other, more contemporary books or books that address specific desired topical coverage such as *The Next 100 Years* [42] by George Friedman, *Diffusion of Innovations* [43] by Everett Rogers, *The World is Flat* [44] or *Hot, Flat and Crowded* [45] by Thomas Friedman, or *The Black Swan* [46] by Nassim Taleb, to name a few. These additional texts could be used to shape the course and the dialogs further and to provide an opportunity for students to apply their critical thinking skills to more contemporary works.

5. Conclusions

We have presented the framework and assessment of a novel course offered at West Point over the last three years that develops the critical thinking, creativity and innovation of undergraduate engineering students. This course provides students with the opportunity to step back from the routine of homework, laboratories and examinations where they are focused predominately on disciplinary depth and think more broadly and critically about their disciplines, innovation and societal implications. Results from a course-end survey, several external indicators, a post-graduation survey and faculty assessment all indicate that course objectives are being met and that critical thinking, creativity and innovation are being improved. The fact that external funding has continued and additional funding agencies are participating is another indicator of the value of the course.

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